Early-Stage SEP Acceleration by CME-Driven Coronal Shocks with Realistic Seed Spectra

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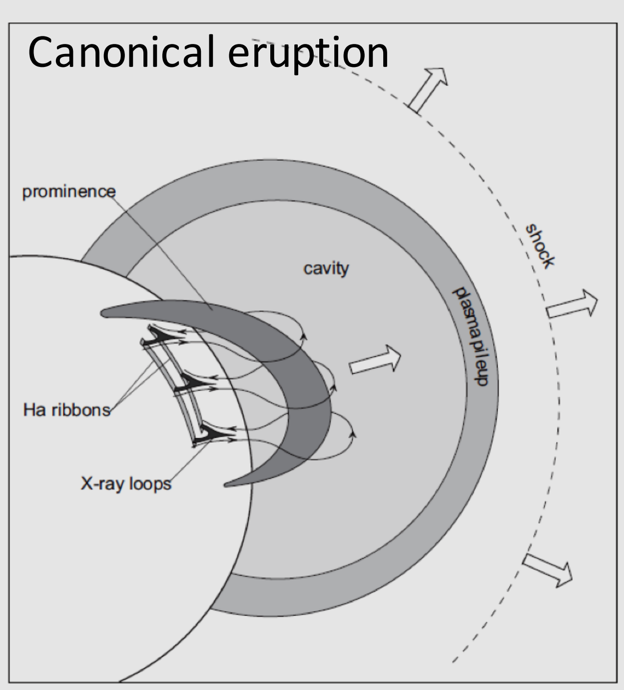
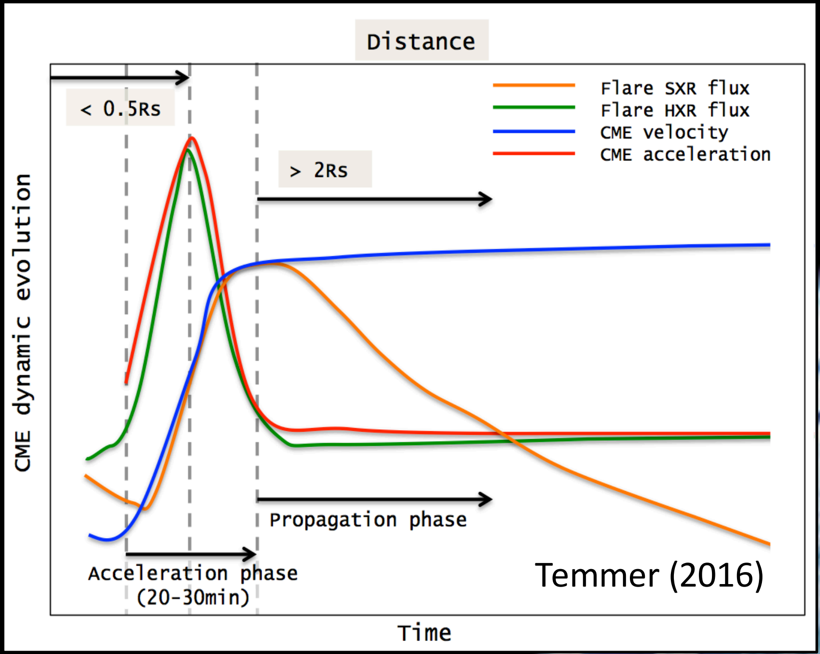
Motivation

- Most dynamic region for CME evolution within 5 R_{sun} (Temmer 2016, Bein et al. 2011)
- Shocks can form as low as 1.2 Rsun in the solar corona (Gopalswamy et al. 2013)
- MHD+kinetic modeling shows protons can be accelerated up to 1 GeV in strong coronal shocks (Kota et al., 2005; Roussev et al., 2004; Kozarev et al., 2013)
- Many shock-like EUV waves observed in the corona (Veronig et al., 2010; Kozarev et al., 2011, Nitta et al. 2013, etc.)
- **Can these accelerate SEPs?**

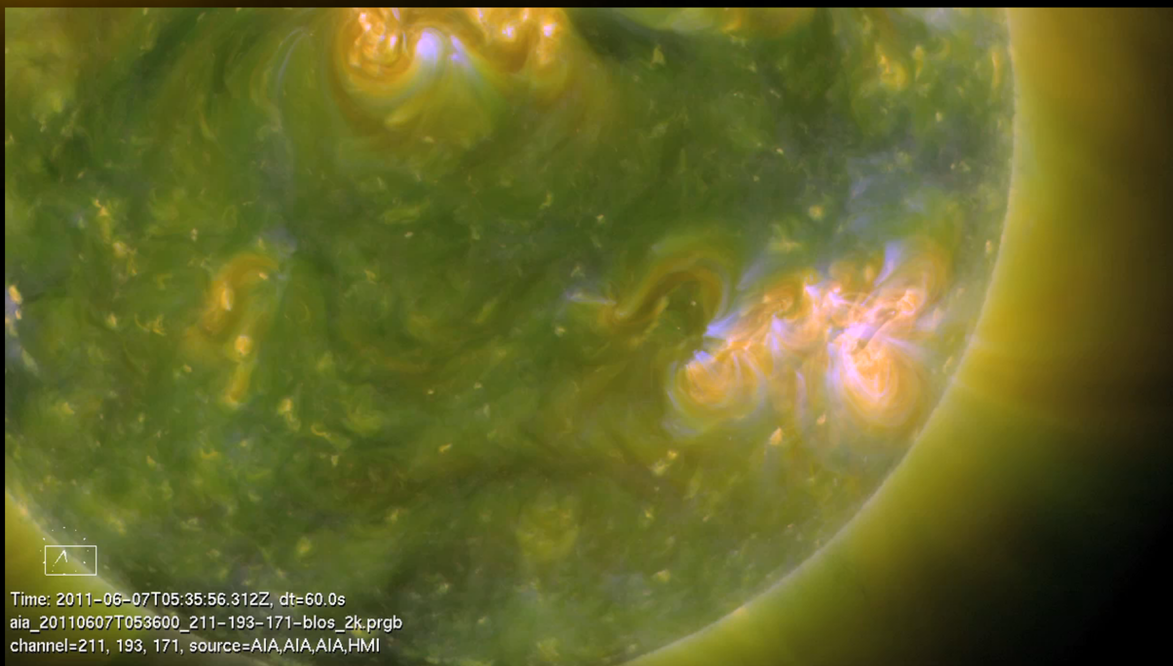


Forbes, 2000

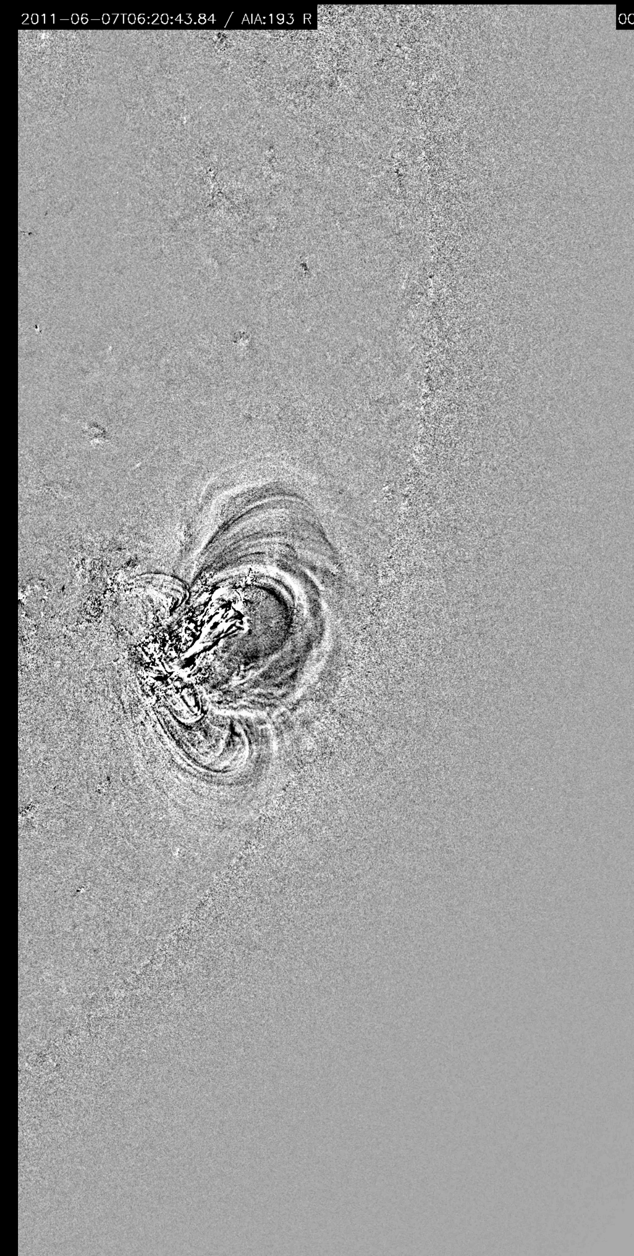


Temmer (2016)

Coronal Mass Ejections and EUV Waves



June 07, 2011 event



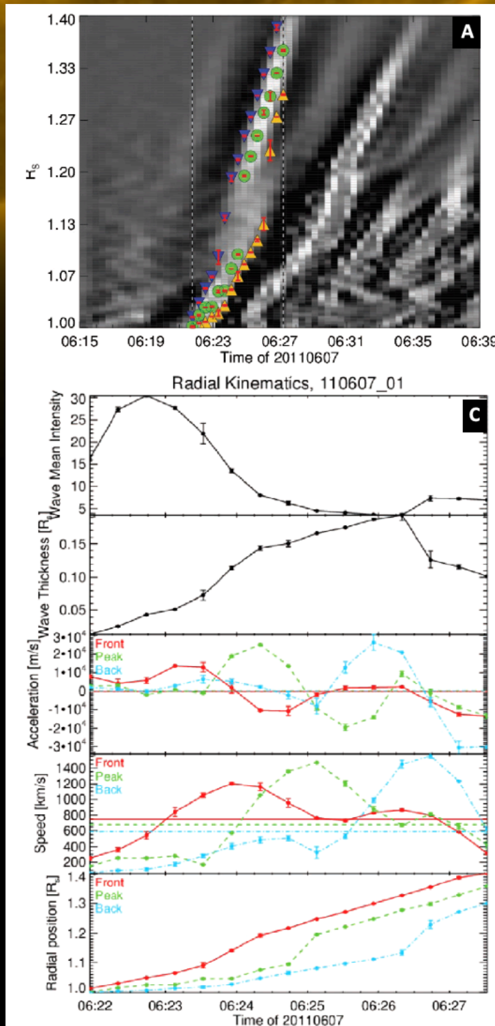
Data-Driven SEP Acceleration Modeling

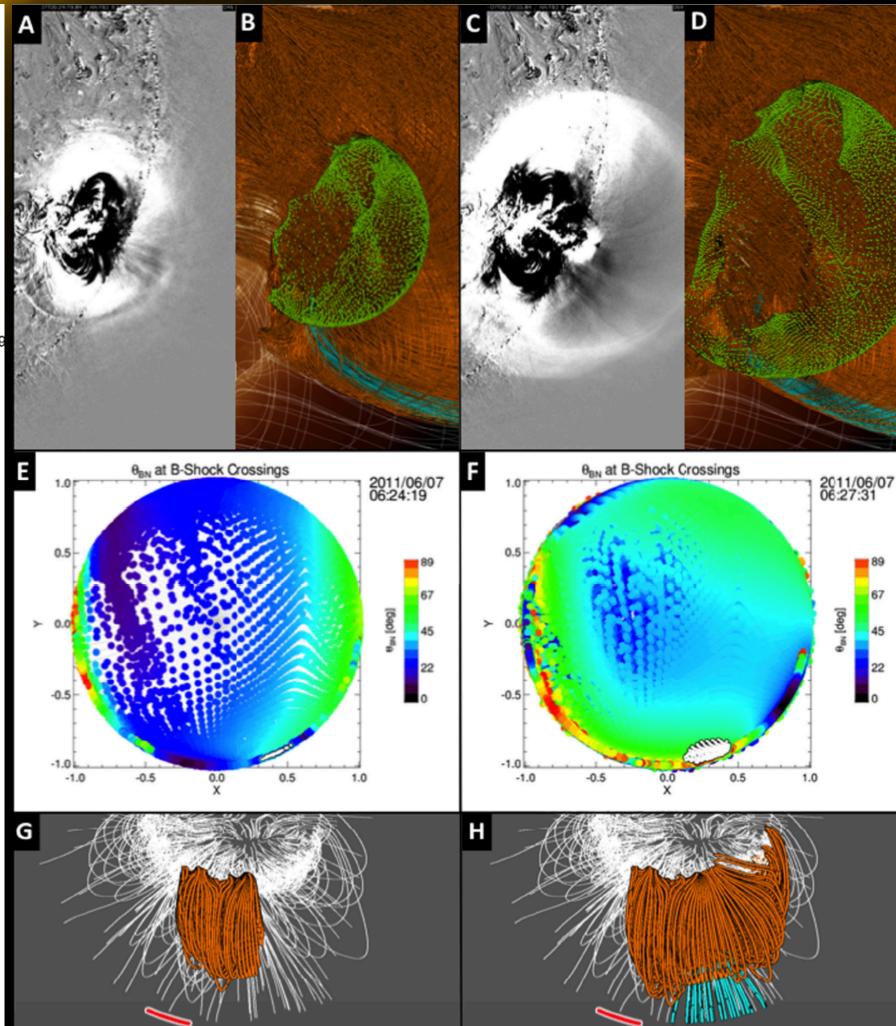
- Global MHD and kinetic models are great – we know everything about the system
- However, hard to constrain eruption driver and coronal conditions
- Difficult to apply to routine multi-event analysis
- Instead, use simpler models, driven by remote observations, for relatively quicker characterization

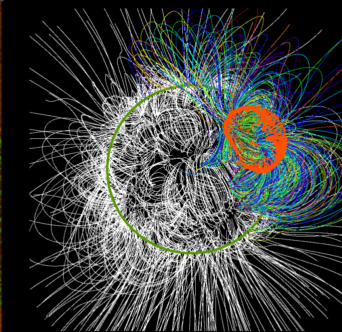
What do we need to model shock particle acceleration?

- Shock Kinematics and geometry
- Magnetic field strength & orientation upstream of shock
- Density & density change at shock
- Scattering conditions
- Source particle populations

Off-limb CBF Characterization – CASHeW Framework







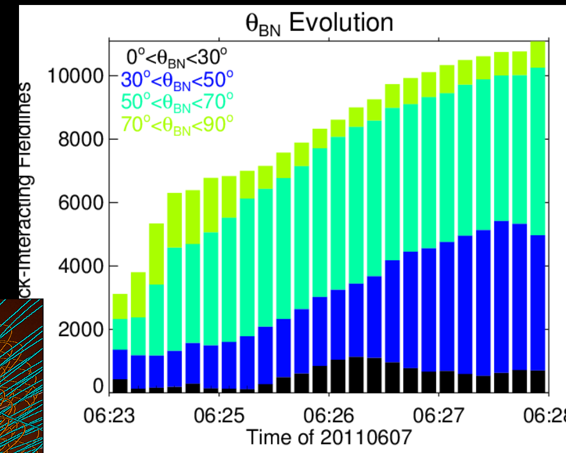
PFSS model from Schrijver & De Rosa, 2003

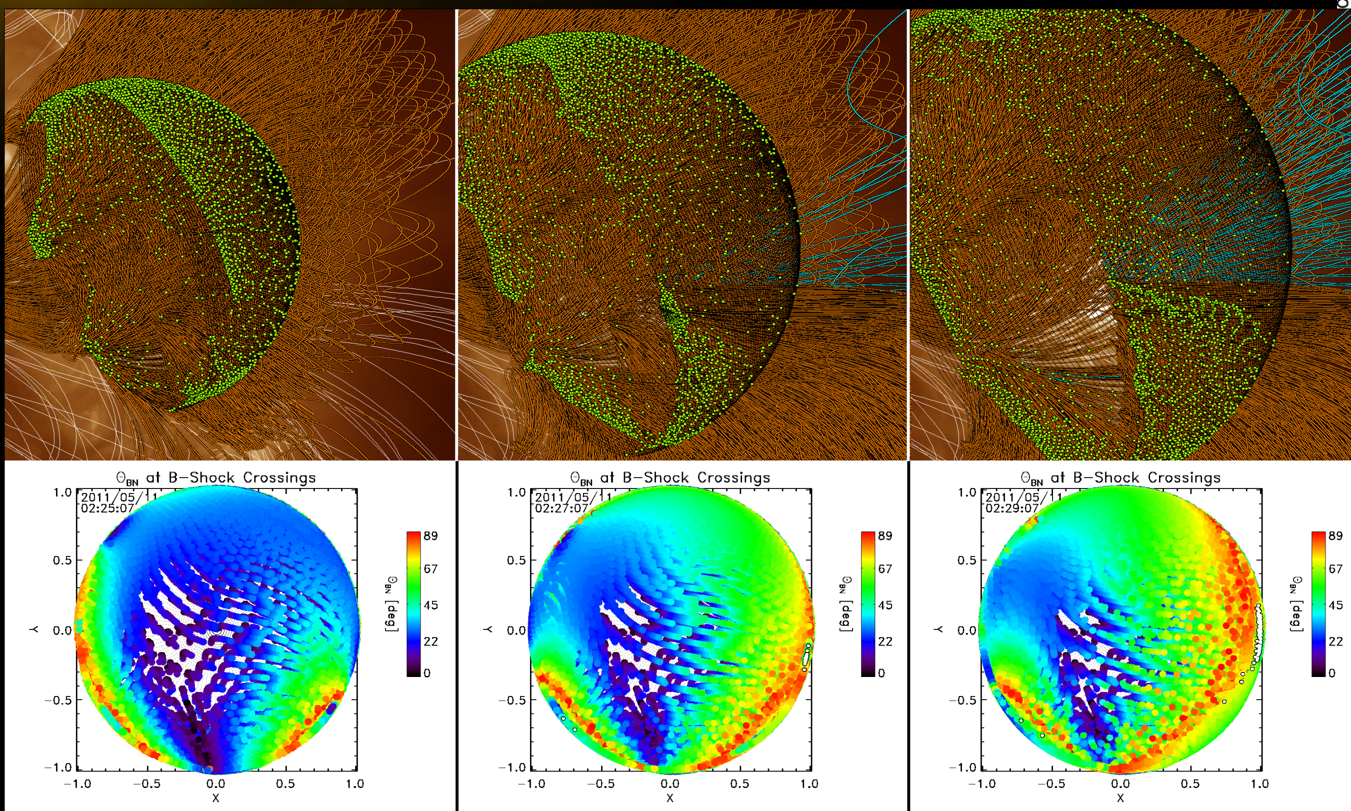
Kozarev et al., JSWSC, 2017

Current CASHeW methodology:

- Radial kinematics estimation (within AIA field of view)
- 3D Coronal Shock Geometric Surface (CSGS) model – spherical (from single-view)
- Determination of field-front crossing point locations, and angle $Theta_{BN}$
- B field, Density change estimation (DEM model of Aschwanden et al. 2011)

OCBF Characterization

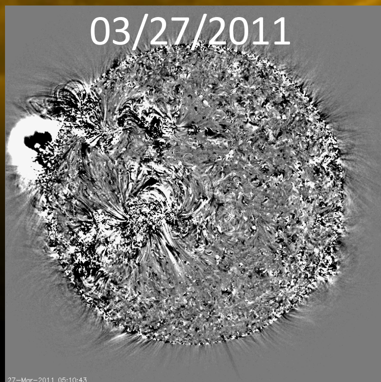


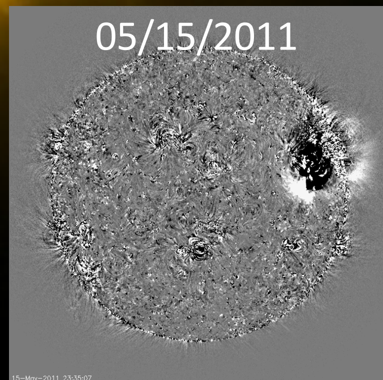


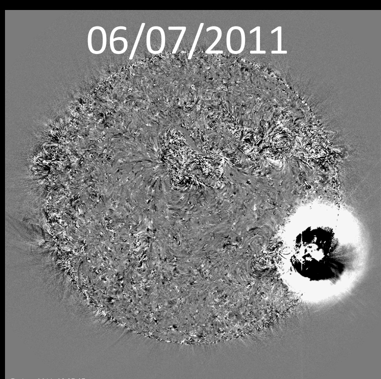
The coronal shock parameters can be / have been used to drive shock acceleration models (as in Kozarev & Schwadron, 2016)

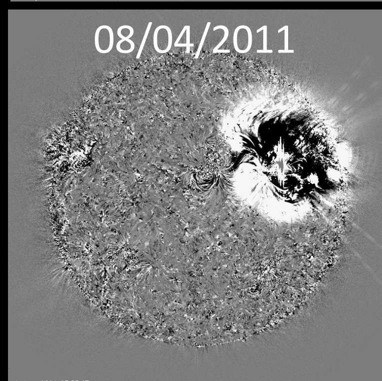
Multi-OCBF Event Study

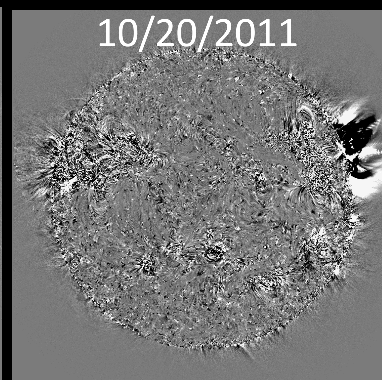
Date	CBF Start	Source Location	Flare Class
03/27/2011	05:02	E78N14	–
05/15/2011	23:30	W44N09	C4.8
06/07/2011	06:20	W44S21	M2.5
08/04/2011	03:50	W38N20	M9.3
10/20/2011	03:05	W88N20	M1.6
05/26/2012	20:30	W89N24	–
11/19/2013	10:15	W71S19	X1.0
12/07/2013	07:15	W47S15	M1.2
12/12/2013	03:03	W60S27	B2.2



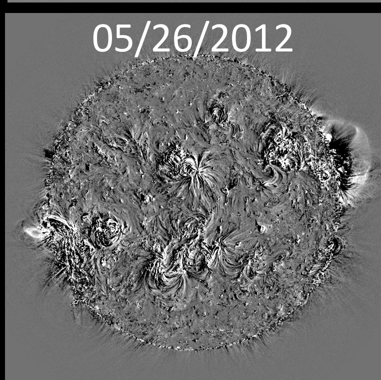


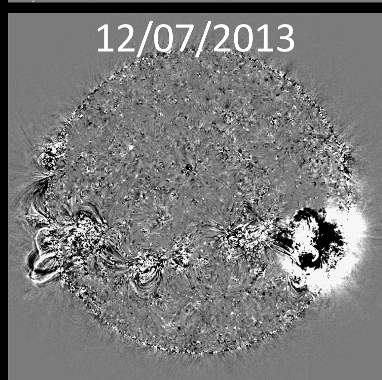


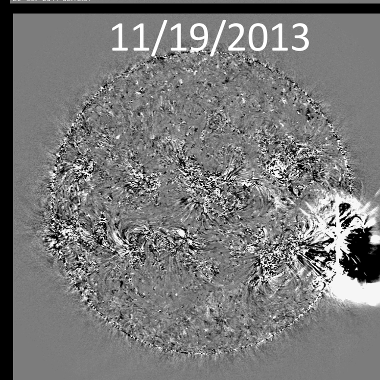


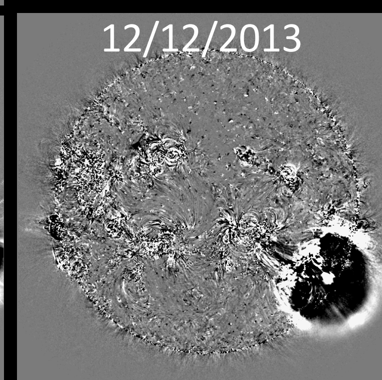


Events selected on basis of OCBFs present and source beyond 40 degrees from Sun center

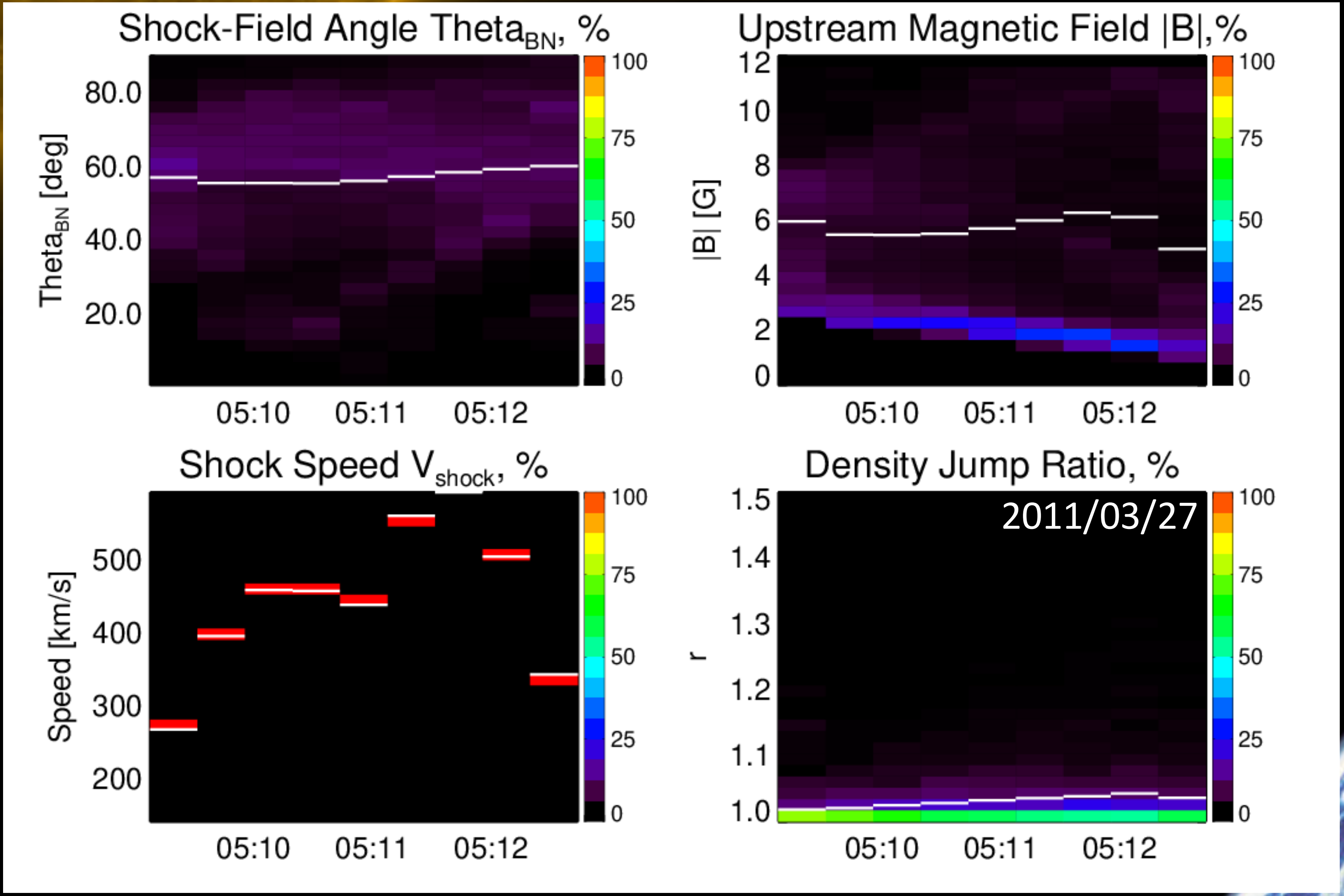




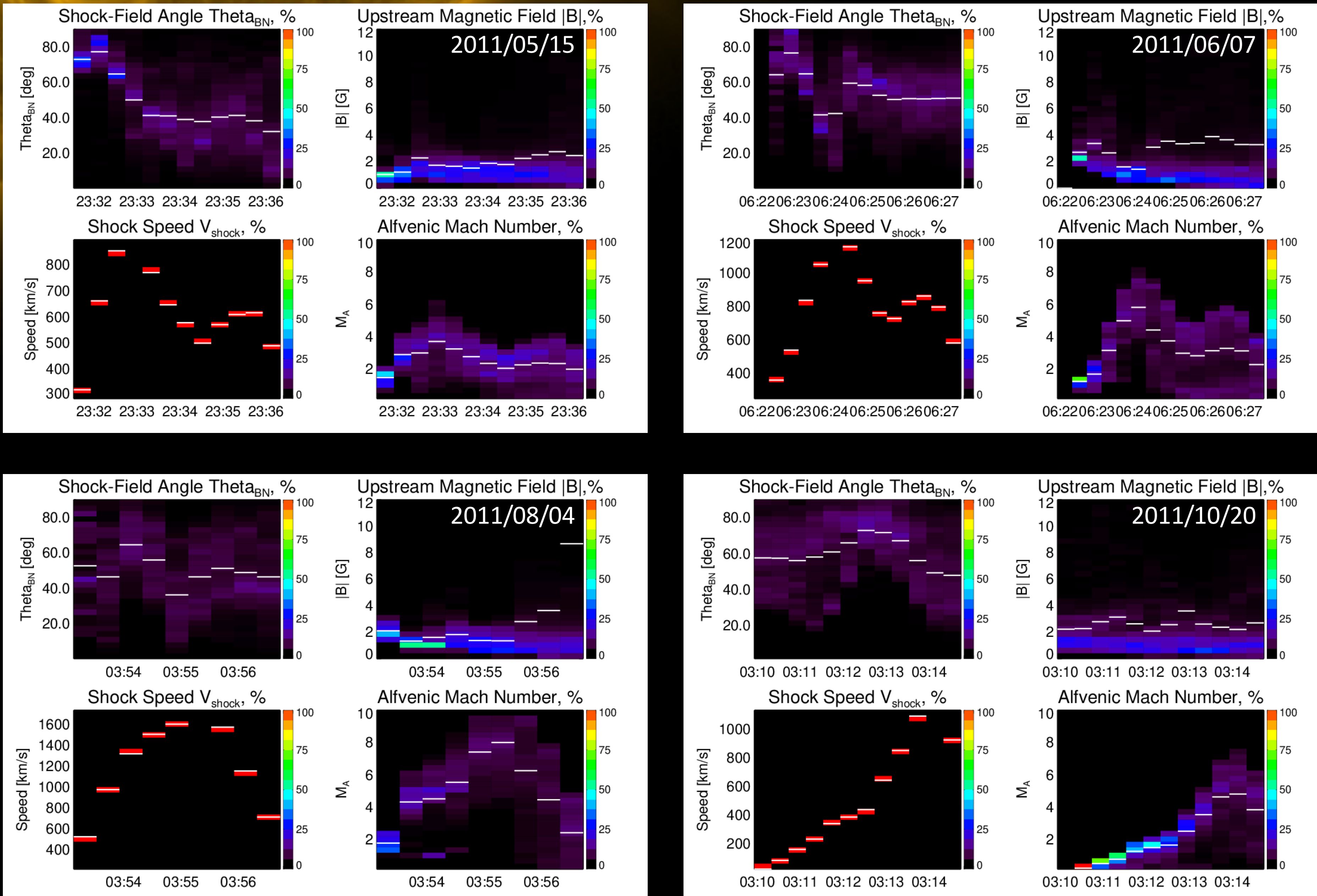




OCBF Parameters



Kozarev et al, 2018, in prep.



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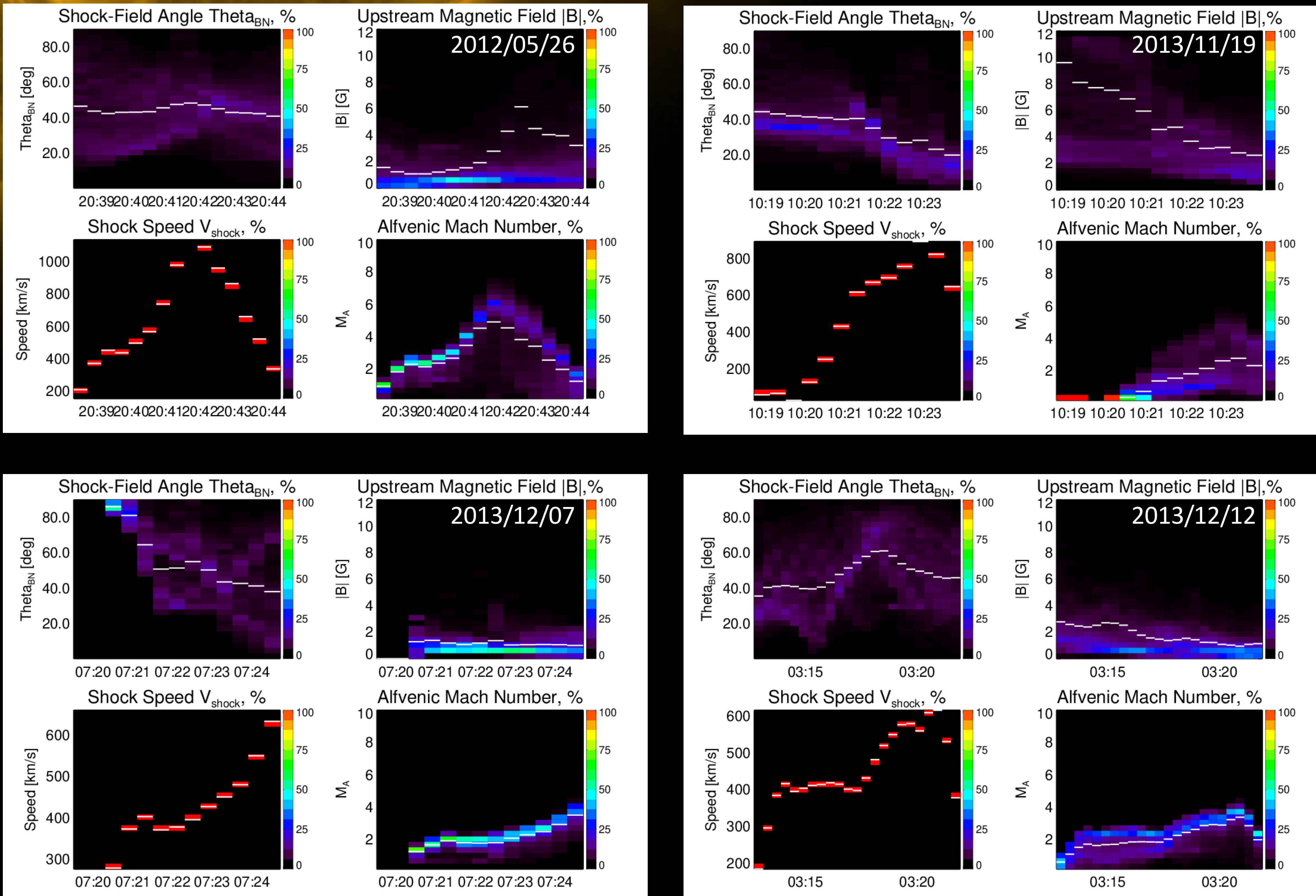


Kozarev et al, 2018, in prep.

Analytical data-driven DSA model

A first step towards remote data-based early-stage SEP prediction

$$\frac{\partial f}{\partial t} + u\frac{\partial f}{\partial x} - \frac{\partial}{\partial x}\left(\kappa\frac{\partial f}{\partial x}\right) + \delta x\frac{u_1 - u_2}{3}\frac{\partial f}{\partial \ln p} = Q_0 \delta x \delta(p - p_0)$$

$$f_1 = \frac{3Q_0}{\Delta u p_0}(p_1/p_0)^{-\gamma_1}$$

$$f_i = f_{i-1}\left(\frac{p_i}{p_{i-1}}\right)^{-\gamma_i}$$

$$p_1 = p_0 \exp\left(\frac{\Delta t \Delta u_1}{3\delta x_1}\right)$$

$$p_i = p_{i-1} \exp\left(\frac{\Delta t \Delta u_i}{3\delta x_i}\right)$$

$$\gamma_i = 3r_i/(r_i - 1)$$

$$r_i = u_1/u_2$$

$$\kappa = \kappa_{\parallel}\cos^2(\theta_{BN}) + \kappa_{\perp}\sin^2(\theta_{BN})$$

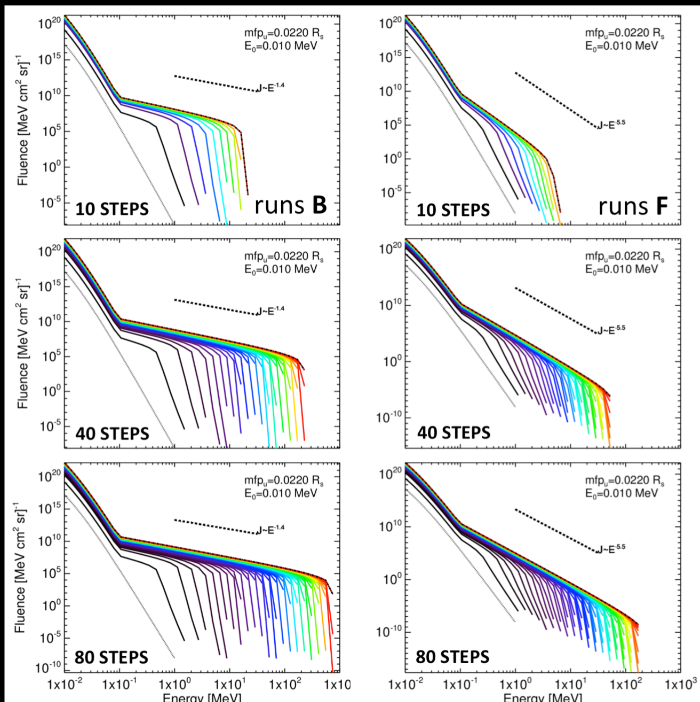
where $\kappa_{\parallel} = v\lambda_{\parallel}/3$, and $\kappa_{\perp} = \kappa_{\parallel}/[1 + (\lambda_{\parallel}/r_g)^2]$

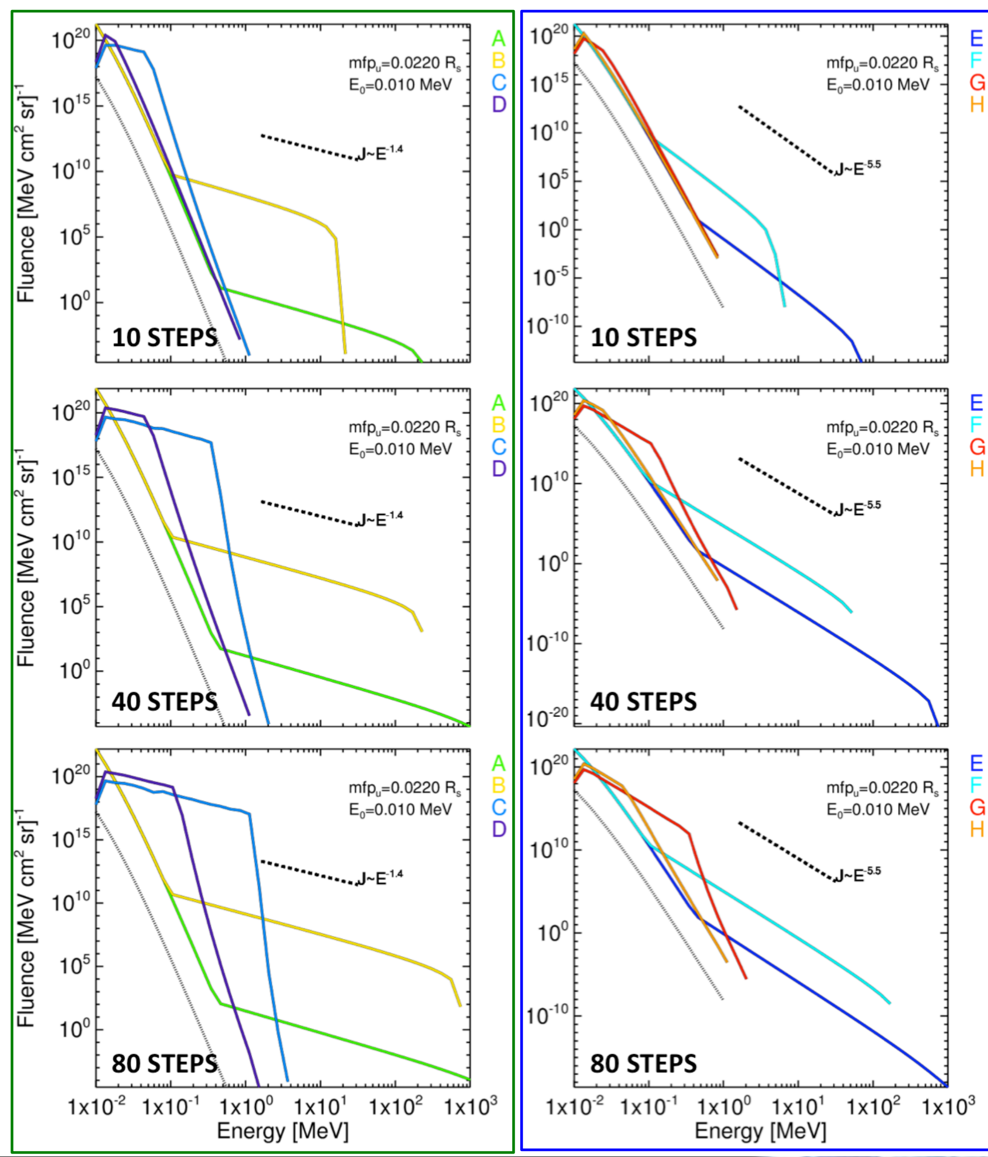
- Solves analytically for the diffusive shock acceleration of ions
- Developed specifically to take parameters from the CBF characterization
- Accounts for minimum injection momentum
- Ad-hoc scattering conditions (constant mean free path currently)
- Source population taken from coronal kappa distribution

Kozarev & Schwadron, 2016

Data-driven DSA model - Validation

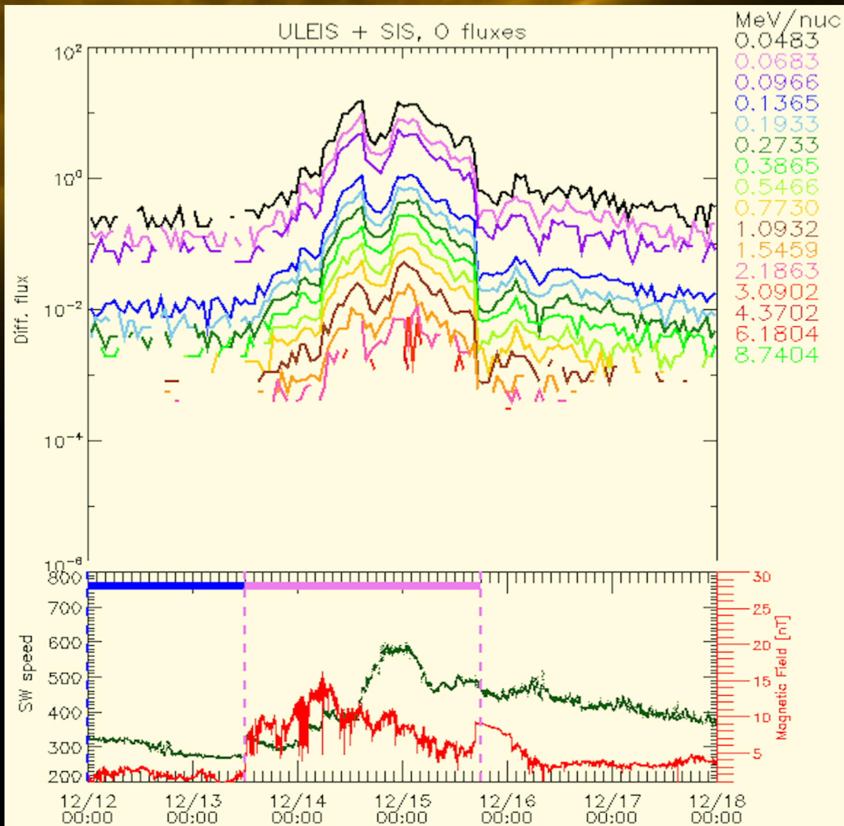
Run Name	V_{shock} $[km/s]$	$\|B\|$ $[G]$	θ_{BN} $[deg]$	r
A	800	5.0	85.0	2.6
B	400	5.0	85.0	2.6
C	800	5.0	5.0	2.6
D	400	5.0	5.0	2.6
E	800	5.0	85.0	1.3
F	400	5.0	85.0	1.3
G	800	5.0	5.0	1.3
H	400	5.0	5.0	1.3



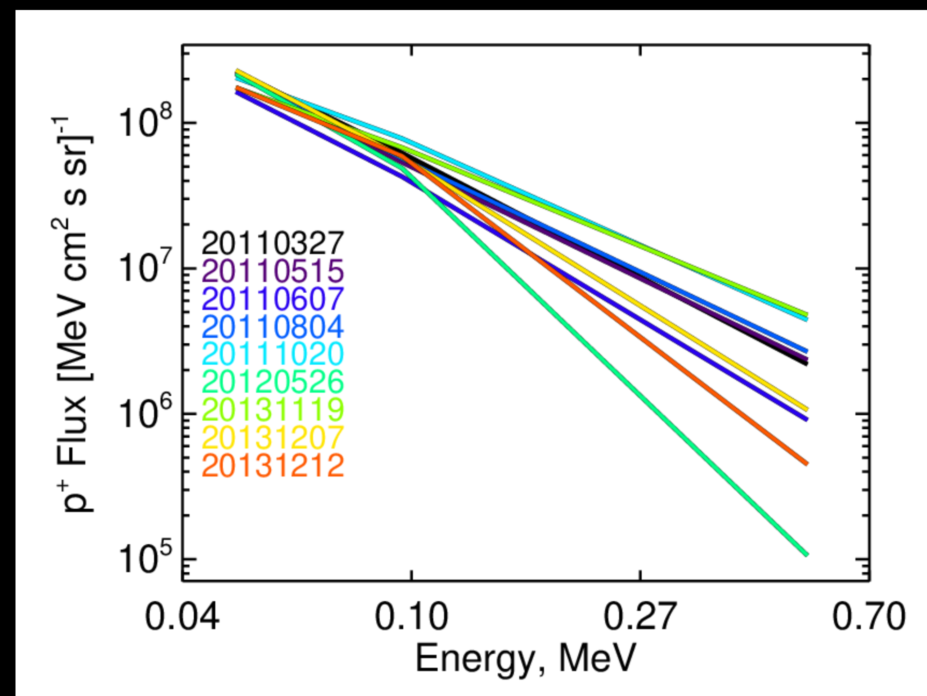


Kozarev & Schwadron, 2016

Input Suprathermal Spectra



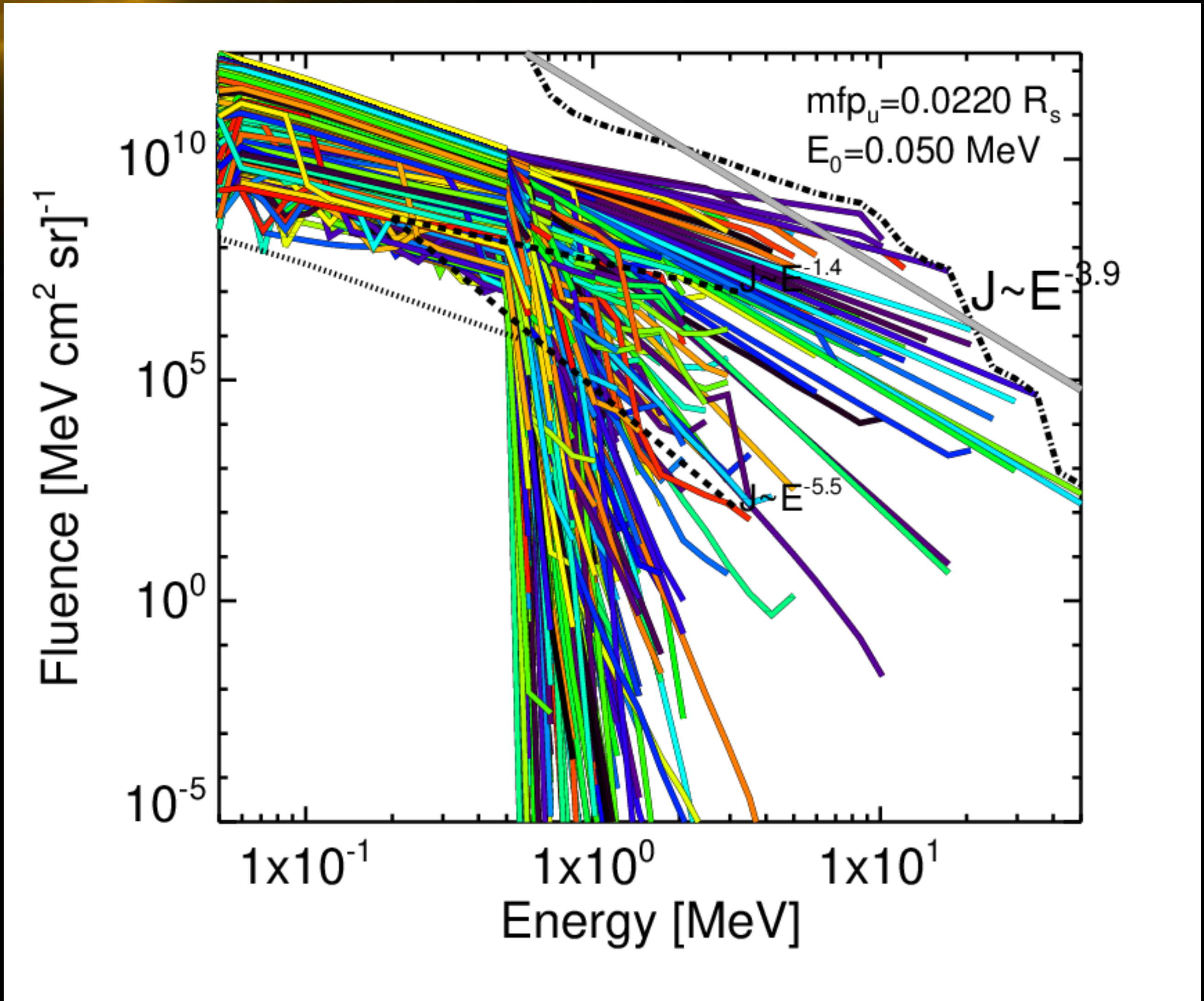
Date	CBF Start	Source Location	Flare Class	P[0]	P[1]	P[2]
03/27/2011	05:02	E78N14	–	3.58	1.86	1.98
05/15/2011	23:30	W44N09	C4.8	3.47	2.03	1.85
06/07/2011	06:20	W44S21	M2.5	2.6	1.94	2.28
08/04/2011	03:50	W38N20	M9.3	3.49	1.95	1.81
10/20/2011	03:05	W88N20	M1.6	3.25	1.39	1.70
05/26/2012	20:30	W89N24	–	3.46	2.16	3.63
11/19/2013	10:15	W71S19	X1.0	2.78	1.37	1.57
12/07/2013	07:15	W47S15	M1.2	3.65	1.98	2.37
12/12/2013	03:03	W60S27	B2.2	2.79	1.57	2.89



- ACE/ULEIS+SIS Oxygen observations from a recent study (Dayeh et al., 2017)
- Quiet-time, pre-event suprathermals (0.05-0.55 MeV); no source particles beyond 0.55 MeV
- Scaled to p^+ fluxes, assuming relative O abundances of 0.064 +/- 0.01% (Reames 2014)
- Scaled to 1.05 R_{sun} assuming $1/R^2$ flux dependence

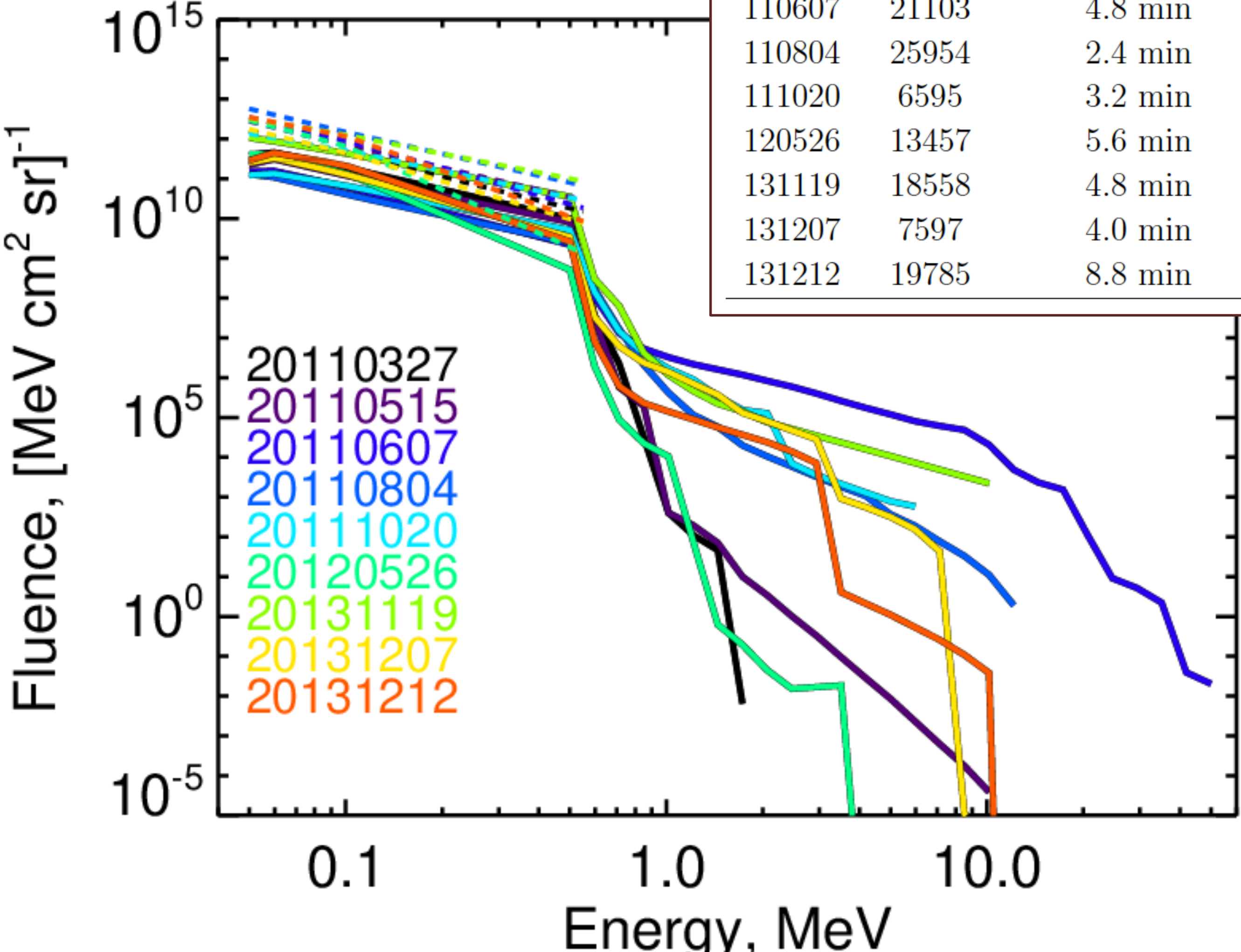
Kozarev et al, 2018, in prep.

Resulting Spectra – 06/07/2011 event



Resulting Spectra

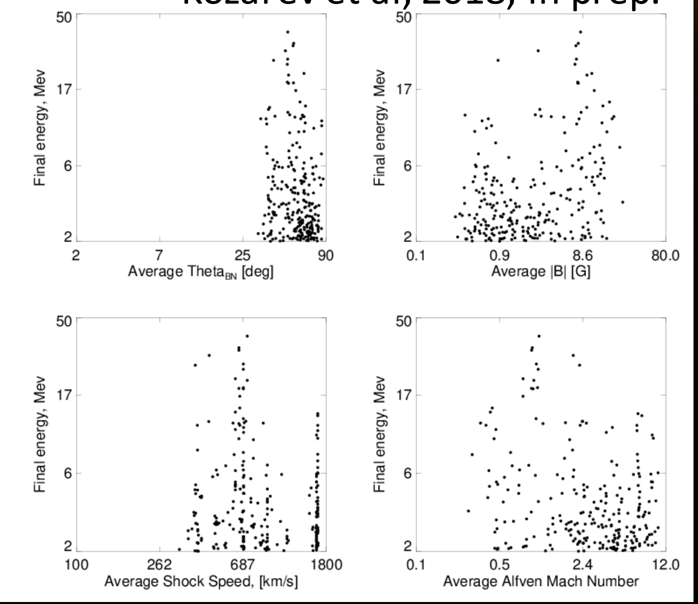
Date	# Lines	Max. Acc. Time	Max. Energy	Spec. Index
110327	7091	3.2 min	1.7 MeV	19.1
110515	12729	4.0 min	10.2 MeV	8.7
110607	21103	4.8 min	50.0 MeV	4.2
110804	25954	2.4 min	12.1 MeV	5.1
111020	6595	3.2 min	6.0 MeV	5.3
120526	13457	5.6 min	4.2 MeV	14.1
131119	18558	4.8 min	10.2 MeV	3.6
131207	7597	4.0 min	29.4 MeV	16.4
131212	19785	8.8 min	24.6 MeV	20.1

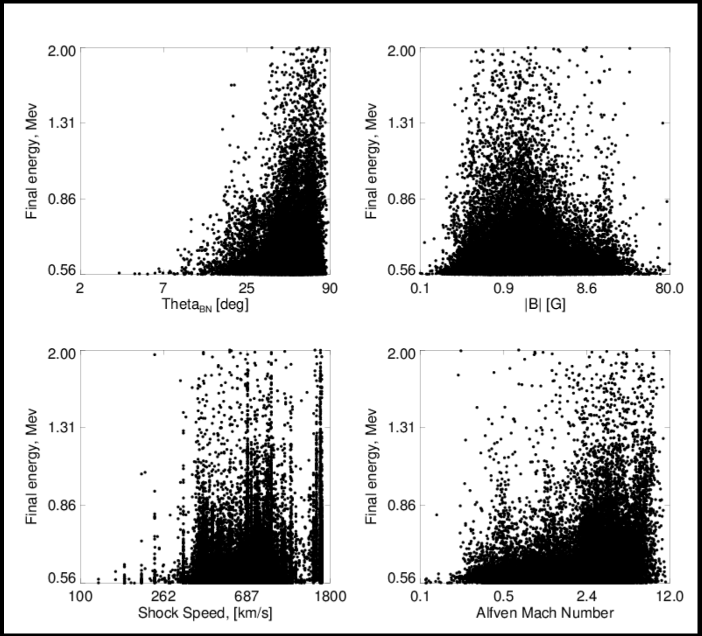


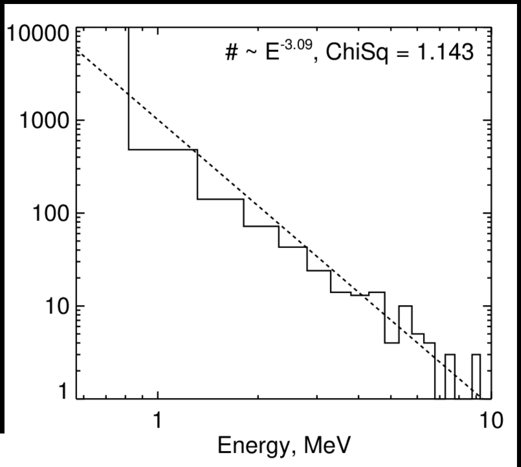
Kozarev et al, 2018, in prep.

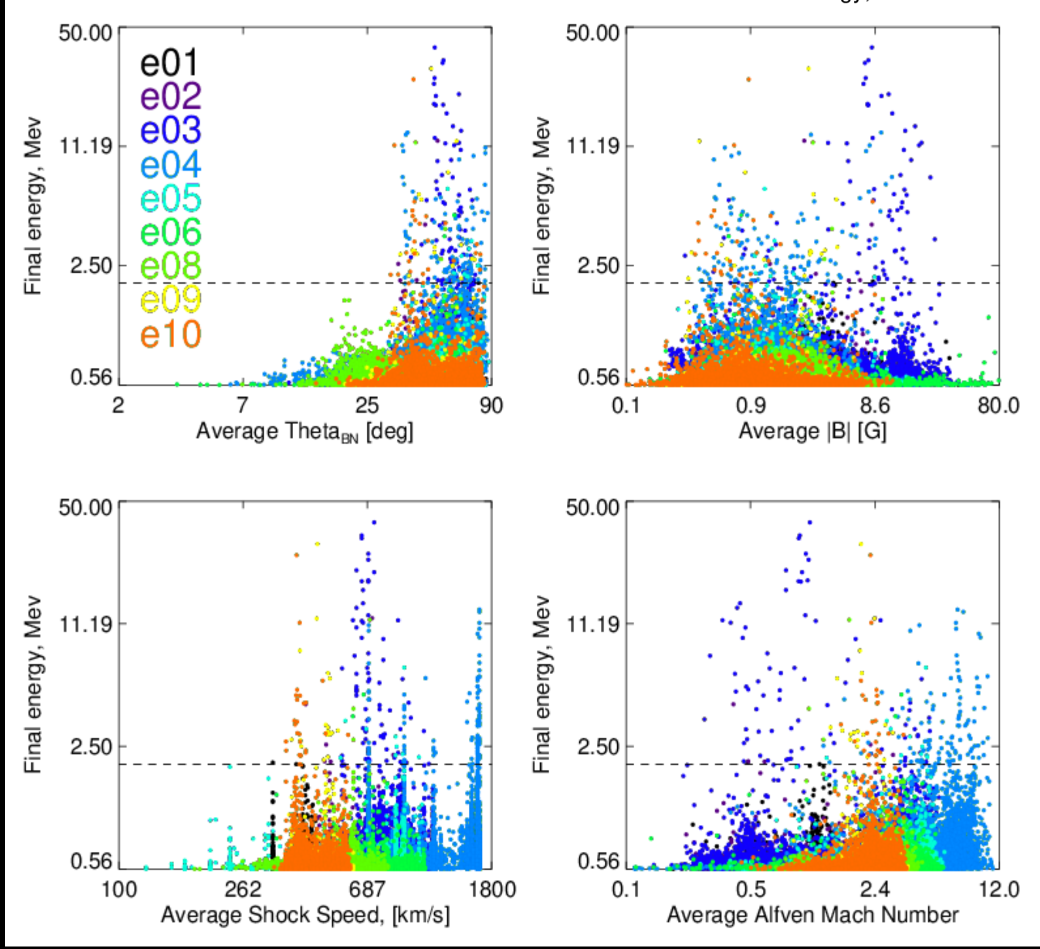
Shock Parameter Dependence

Kozarev et al, 2018, in prep.









Conclusions and Prospects

- High-cadence, high-resolution remote observations with AIA, combined with data-driven models allow estimation of wave/shock kinematics, density changes, magnetic field. These can be used to drive SEP acceleration models.

- A multi-event study of OCBFs has been carried out to estimate the amount of acceleration on protons during the very early stages of 9 eruptions;

- We have used the time dependent properties within the AIA FOV to drive directly a DSA particle acceleration model

- We find a range of maximum energies reached and spectral indices

- Strong acceleration results from stronger shocks and longer acceleration times

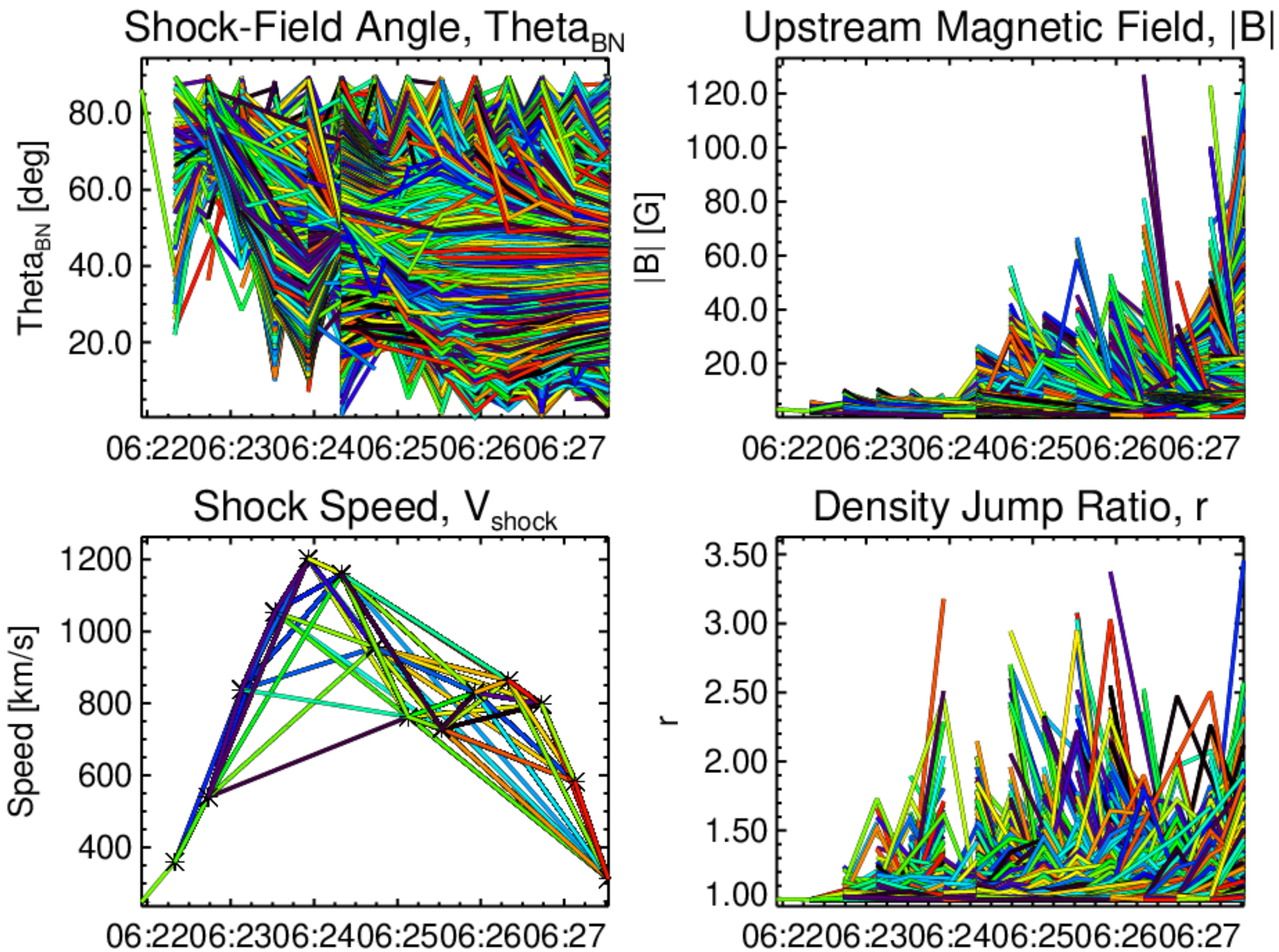
Where we are headed:

- Improve the description of shock geometric shape, include lateral measurements

- Improve determination of shock scattering conditions

- Extend OCBF characterization to beyond AIA FOV (LASCO), include interplanetary transport to 1 AU for validation of SEP modeling results

Extra Slides


Shock-Field Angle, $Theta_{BN}$
$Theta_{BN}$ [deg]
80.0
60.0
40.0
20.0
06:22
06:23
06:24
06:25
06:26
06:27
Upstream Magnetic Field, |B|
|B| [G]
120.0
100.0
80.0
60.0
40.0
20.0
06:22
06:23
06:24
06:25
06:26
06:27
Shock Speed, V_{shock}
Speed [km/s]
1200
1000
800
600
400
06:22
06:23
06:24
06:25
06:26
06:27
Density Jump Ratio, r
r
3.50
3.00
2.50
2.00
1.50
1.00
06:22
06:23
06:24
06:25
06:26
06:27