Non-neutralized currents and flaring activity in solar active regions

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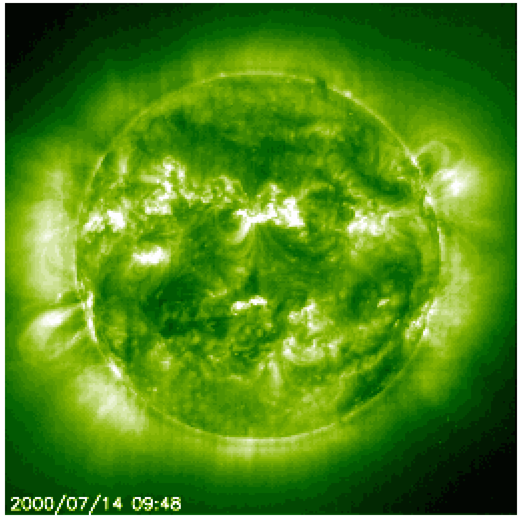
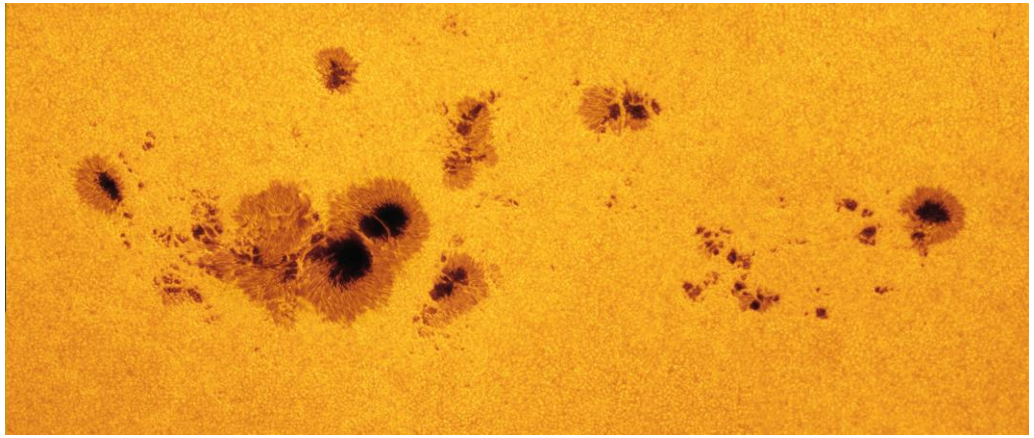
Outline

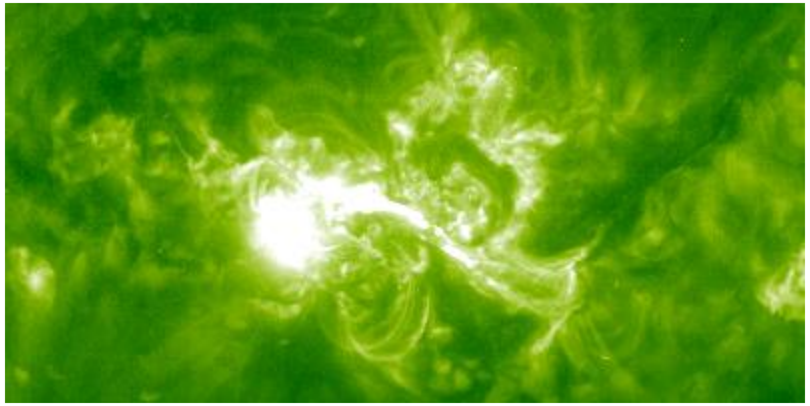
- Introduction - Motivation
- Non-neutralized currents, method
- Data
- Results: Merit as predictors
- Work in progress: non-neutralized currents and CME characteristics

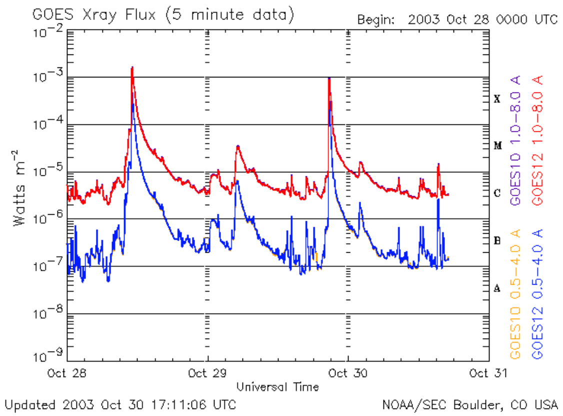
Solar Flares

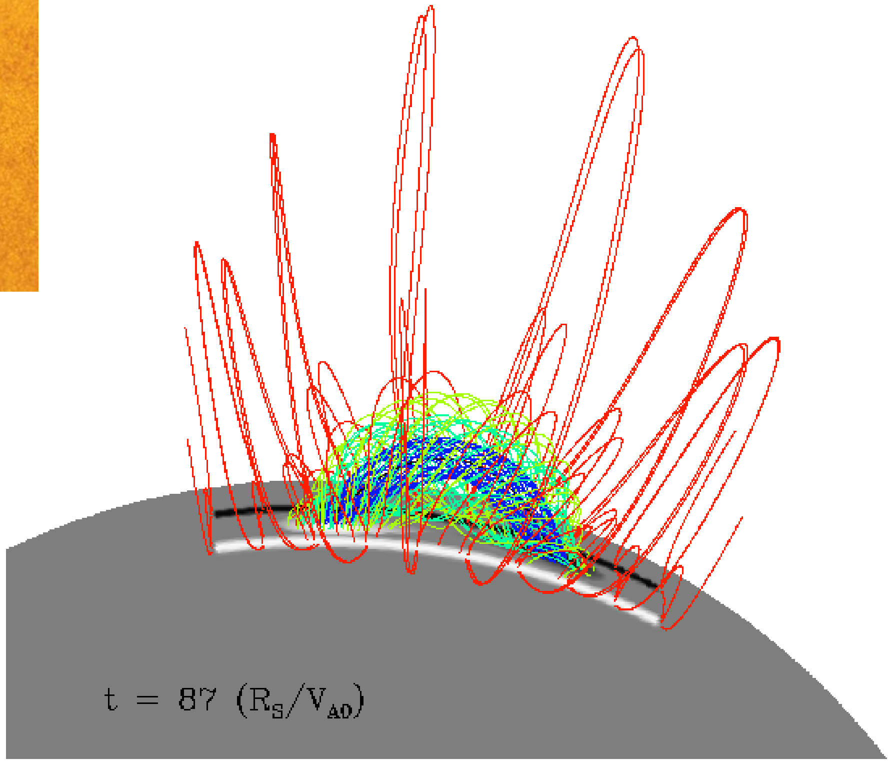
Energy is stored in the magnetic field







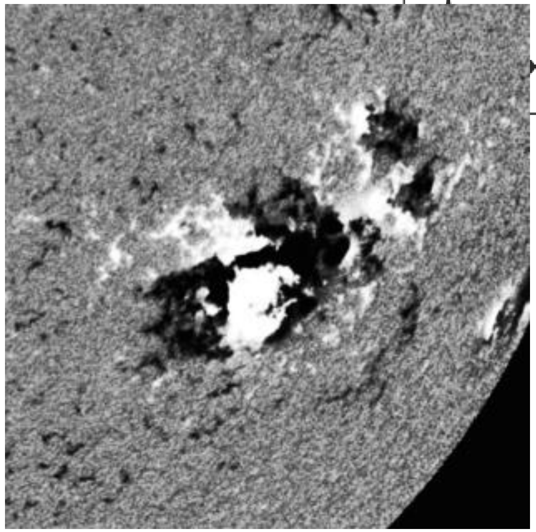


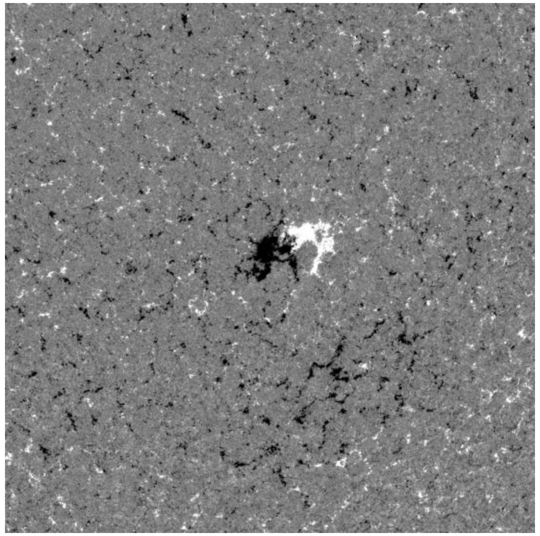


High Altitude Observatory, Boulder, CO

How do we predict solar flares?

- Use systematic observations of the magnetic field* of the solar disk
- Parameterize magnetic field complexity and measure physical quantities involved in flaring activity of active regions (AR)
- Produce large samples of values with the associated flaring activity (yes/no, flare class)
- Use statistics (Poisson, Bayesian etc) or machine learning algorithms to predict



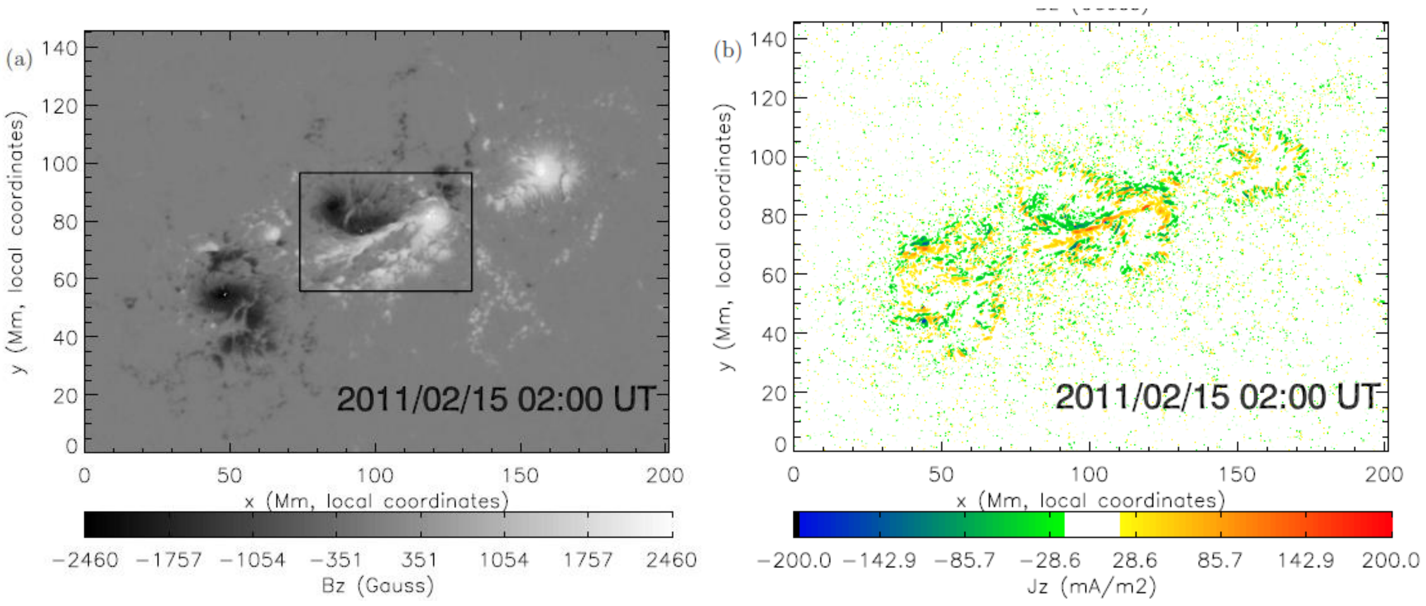


* Or do the same with continuum/UV/X-ray observations

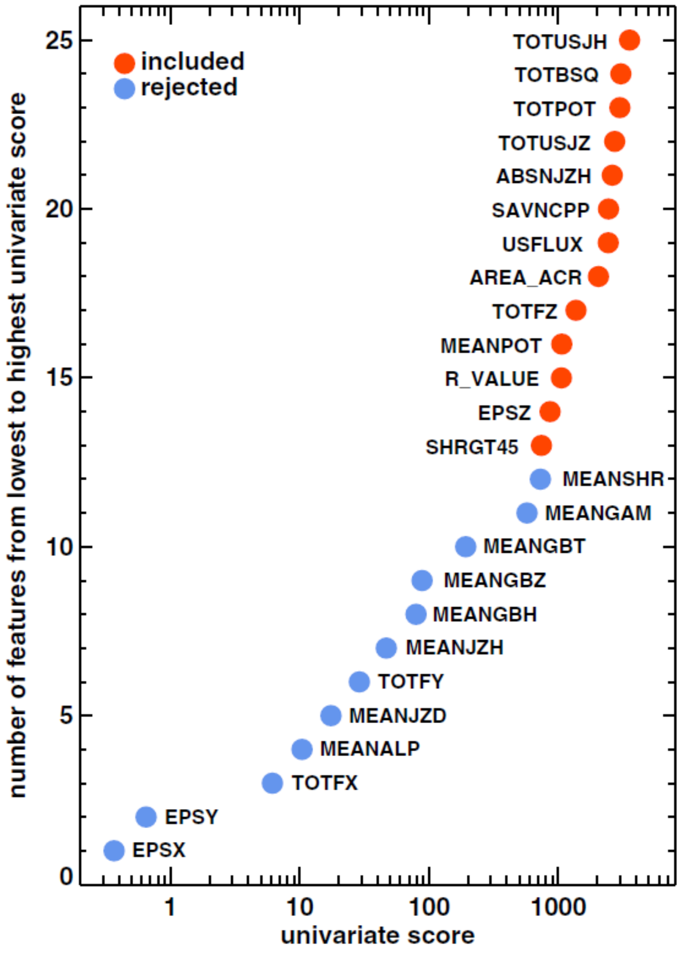
Why currents?

Non-potentiality of magnetic field = currents

Currents, shear and polarity inversion lines

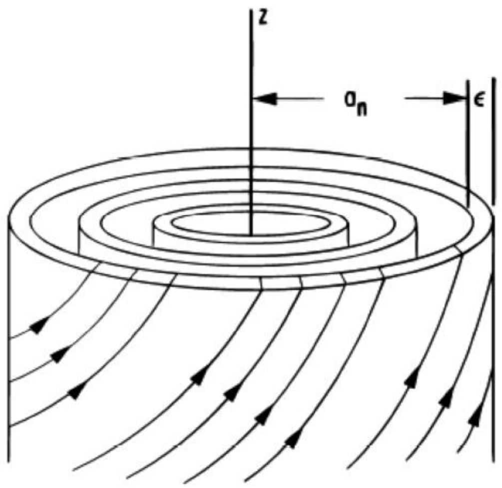


Janvier+ 2014

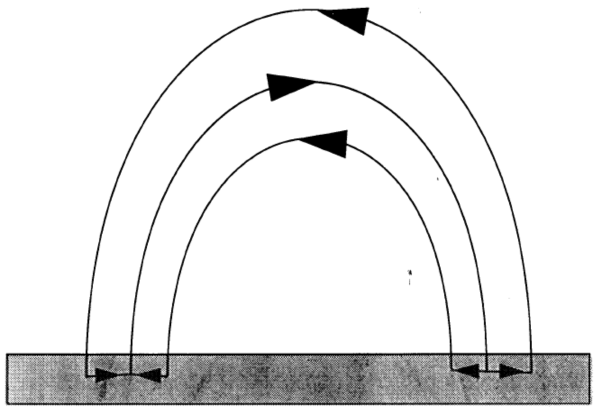


Bobra & Couvidat 2015

Non-neutralized currents



Parker 1996



Melrose, 1991

Currents may build-up either by photospheric motions or due to current-carrying emerging flux

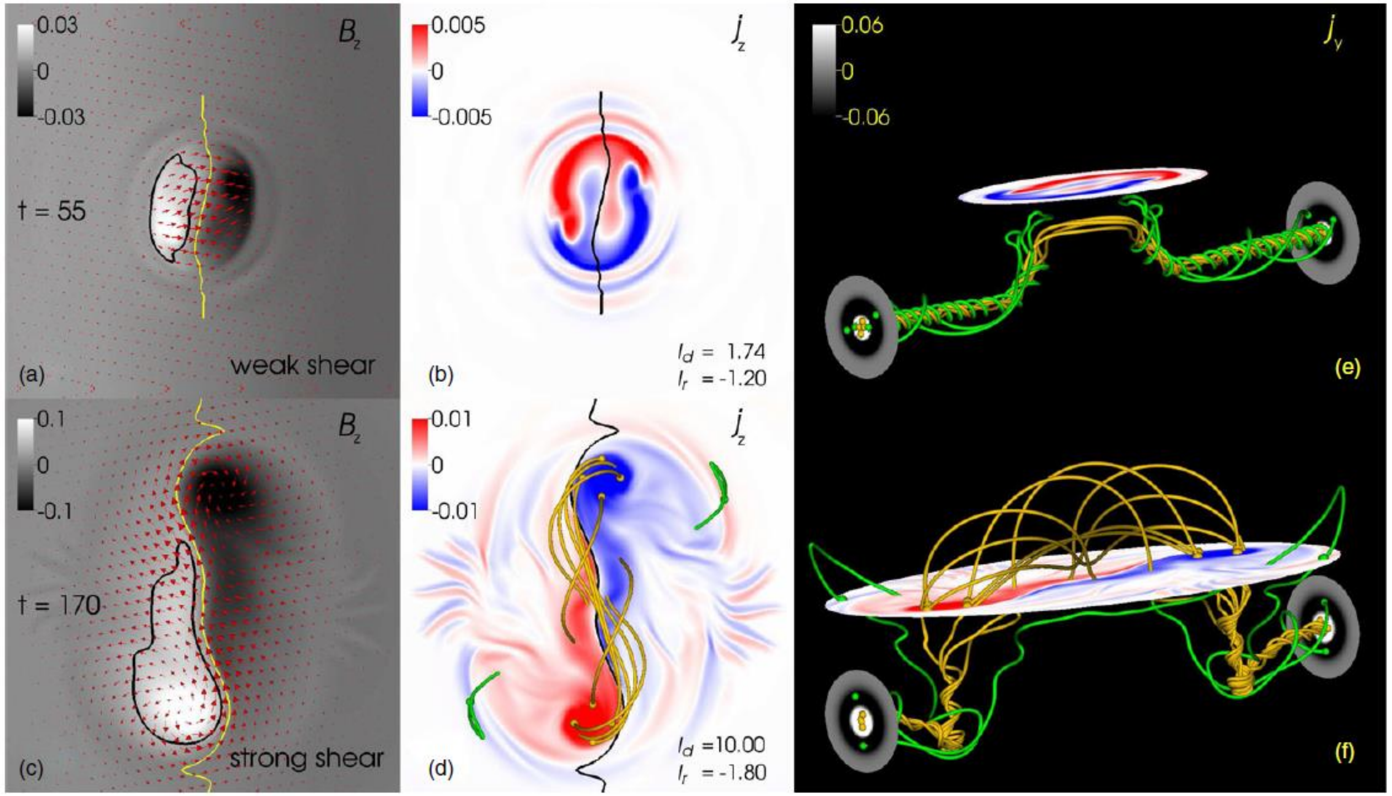
Photospheric motions: the net current produced by twist or shear should be neutralized (zero net current per polarity)
(*Melrose 1991, 1995*)

Observations show that currents are non-neutralized
(*Leka et al.1996, Semel & Skumanich 1998, Wheatland 2000, Falconer 2001*)

Non-neutralized currents

AR's are "born" with substantial net (non-neutralized) currents
(*Török+ 2014*)

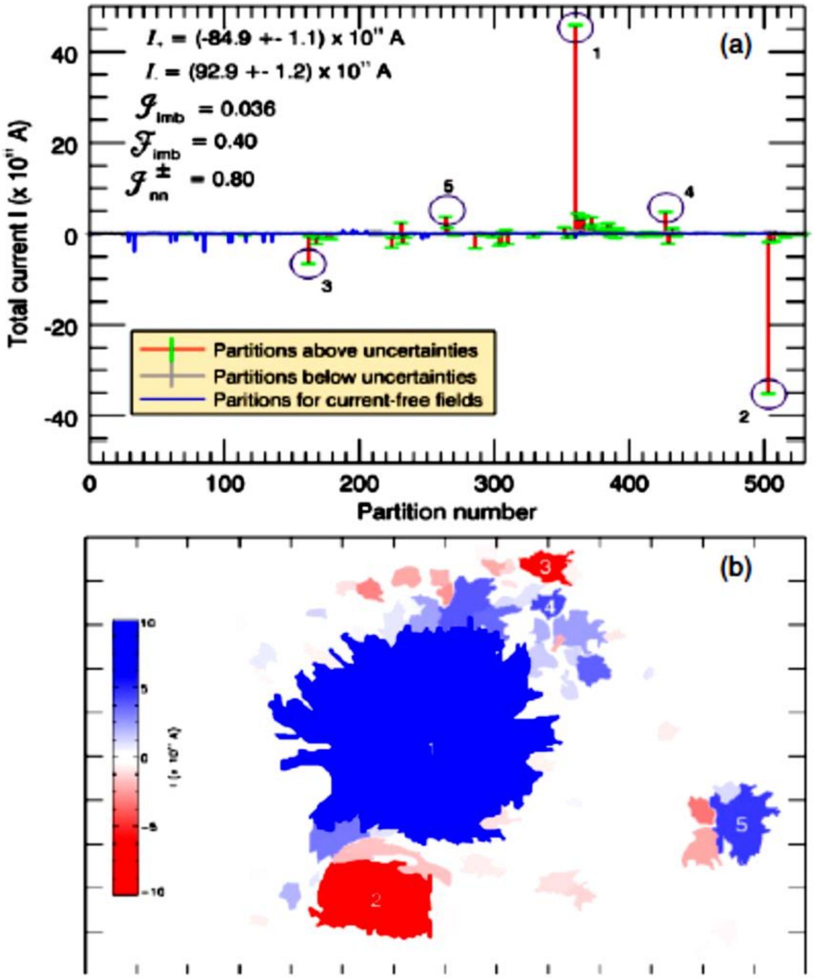
Photospheric motions can produce non-neutralized currents only in the presence of magnetic shear at PIL (*Dalmasse+ 2015*).



Török et al. 2014

Non-neutralized currents

Calculation based on observations



Georgoulis, Titov & Mikic, 2012

<u>Method:</u>

- Calculation of non-neutralized currents per partition
- Detailed error analysis and strict criteria
- Comparison between 2 AR (a flaring and a non-flaring one)

<u>Results:</u>

- Non neutralized partitions are adjacent to a PIL.
- AR are current balanced (*Iimb* < *Fimb*)
- The quiet AR exhibits 1 order of magnitude lower currents.

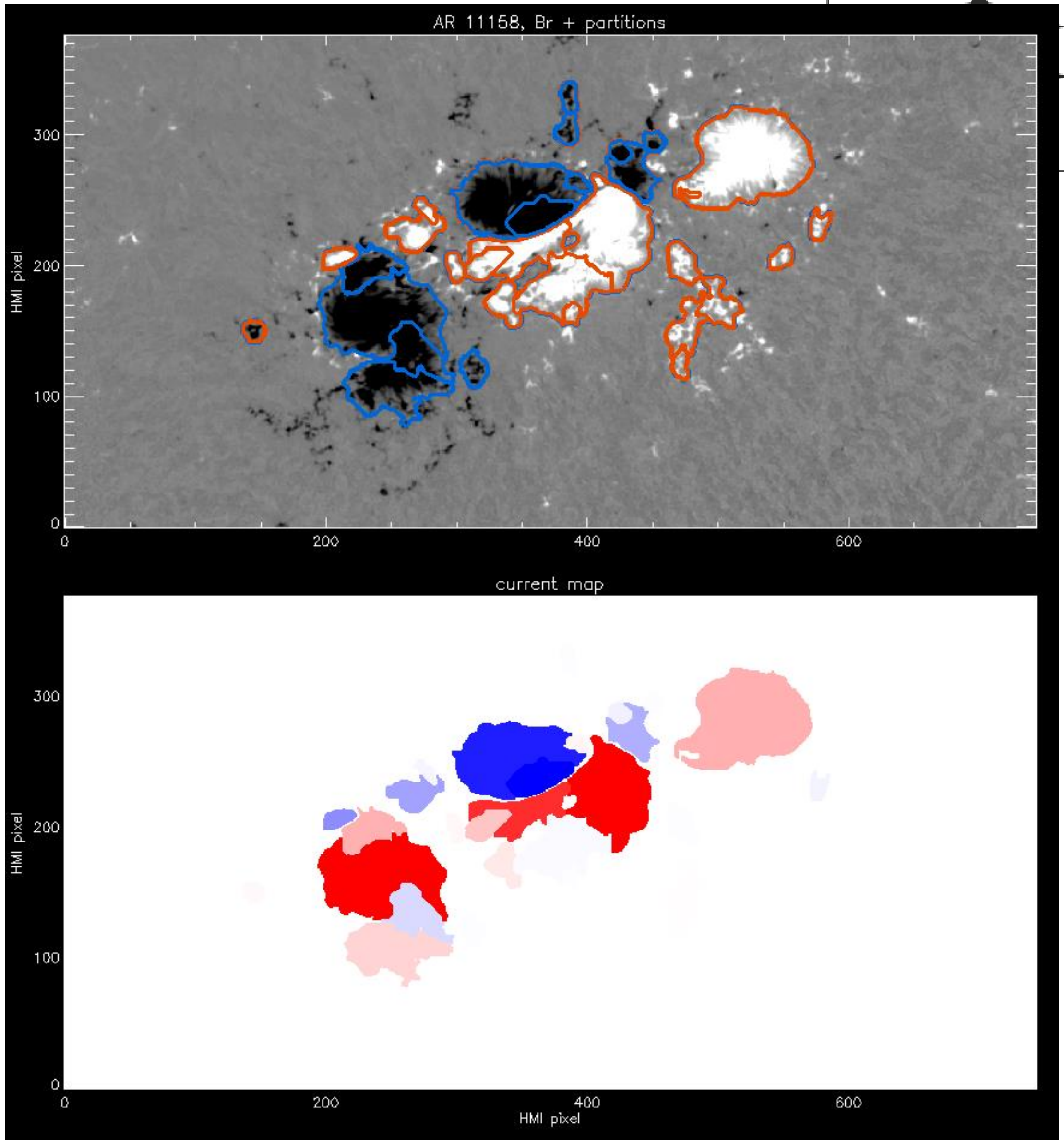
Analysis

- Input: photospheric vector magnetogram
- Flux partitioning of Bz (*Barnes+2005*)

Bz thres = 100 G, Min Flux = 5 10^{19} Mx, min size = 40 px

- Calculation of (vertical) current for each partition (Ampére's law) with corresponding errors.
- Potential field extrapolation (*Alissandrakis 1981*) and **re-calculate** the corresponding ***current for the potential field***.
- Characterize partition as non-neutralized only if

$$I > 5I_{pot} \quad \text{and} \quad I > 3\,\delta I$$



Analysis

Create predictors:

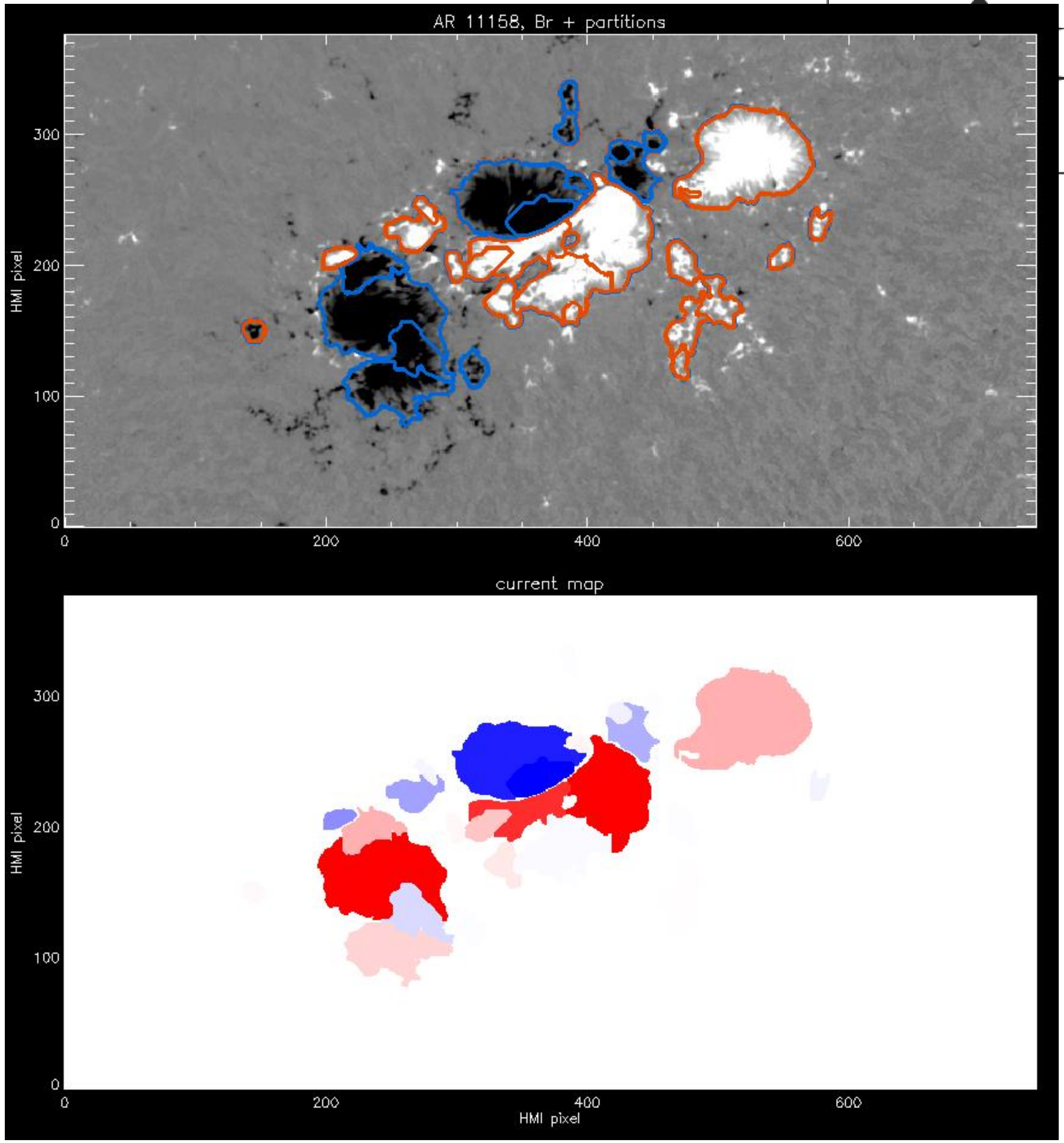
Total unsigned non-neutralized current

$$I_{NN,tot} = \sum_i \left| I_i^{NN} \right|$$

Maximum unsigned non-neutralized current

$$I_{NN,\max} = \max\left\{ \left| I_i^{NN} \right| \right\}$$

Test on a statistically significant sample



Data

***SHARP**: Space weather HMI Active Region Patches (Bobra+ 2014)*

USFLUX	Total unsigned flux	Mx	$\Phi = \sum \lvert B_z \rvert dA$	Integral	ERRVF
MEANGAM	Mean angle of field from radial	Degree	$\overline{\gamma} = \frac{1}{N} \sum \arctan(\frac{B_h}{B_z})$	Mean	ERRGAM
MEANGBT	Horizontal gradient of total field	$G\,Mm^{-1}$	$\overline{\lvert \nabla B_{tot} \rvert} = \frac{1}{N} \sum \sqrt{(\frac{\partial B}{\partial x})^2 + (\frac{\partial B}{\partial y})^2}$	Mean	ERRBT
MEANGBZ	Horizontal gradient of vertical field	$G\,Mm^{-1}$	$\overline{\lvert \nabla B_z \rvert} = \frac{1}{N} \sum \sqrt{(\frac{\partial B_z}{\partial x})^2 + (\frac{\partial B_z}{\partial y})^2}$	Mean	ERRBZ
MEANGBH	Horizontal gradient of horizontal field	$G\,Mm^{-1}$	$\overline{\lvert \nabla B_h \rvert} = \frac{1}{N} \sum \sqrt{(\frac{\partial B_h}{\partial x})^2 + (\frac{\partial B_h}{\partial y})^2}$	Mean	ERRBH
MEANJZD	Vertical current density	$mA\,m^{-2}$	$\overline{J_z} \propto \frac{1}{N} \sum (\frac{\partial B_y}{\partial x} - \frac{\partial B_x}{\partial y})$	Mean	ERRJZ
TOTUSJZ	Total unsigned vertical current	A	$J_{z_{total}} = \sum \lvert J_z \rvert dA$	Integral	ERRUSI
MEANALP	Characteristic twist parameter, α	$M\,m^{-1}$	$\alpha_{total} \propto \frac{\sum J_z B_z}{\sum B_z^2}$	Mean	ERRALP
MEANJZH	Current helicity (B_z contribution)	$G^2\,m^{-1}$	$\overline{H_c} \propto \frac{1}{N} \sum B_z J_z$	Mean	ERRMIH
TOTUSJH	Total unsigned current helicity	$G^2\,m^{-1}$	$H_{c_{total}} \propto \sum \lvert B_z J_z \rvert$	Sum	ERRTUI
ABSNJZH	Absolute value of the net current helicity	$G^2\,m^{-1}$	$H_{c_{abs}} \propto \lvert \sum B_z J_z \rvert$	Sum	ERRTAI
SAVNCPP	Sum of the modulus of the net	A	$J_{z_{sum}} \propto \lvert \sum^{B_z^+} J_z dA \rvert + \lvert \sum^{B_z^-} J_z dA \rvert$	Integral	ERRJHT

Data

AR time-series

NOAA	t_{start}	t_{end}	B	C	M	X	FI
11072	2010-05-20	2010-05-24	2	0	0	0	0.06
11158	2011-02-10	2011-02-15	1	25	4	1	100.67
11429	2012-03-04	2012-03-10	0	34	12	6	278.15
11515	2012-06-28	2012-07-07	2	39	14	0	53.97
11640	2013-01-01	2013-01-05	5	4	0	0	1.81
11663	2013-01-29	2013-02-03	2	2	0	0	0.55
11748	2013-05-15	2013-05-18	0	10	4	0	31.16
11863	2013-10-10	2013-10-13	0	0	0	0	0.0
11875	2013-10-18	2013-10-28	0	81	18	2	93.60
11882	2013-10-26	2013-10-30	0	7	10	0	49.10
11923	2013-12-12	2013-12-15	0	0	0	0	0.0

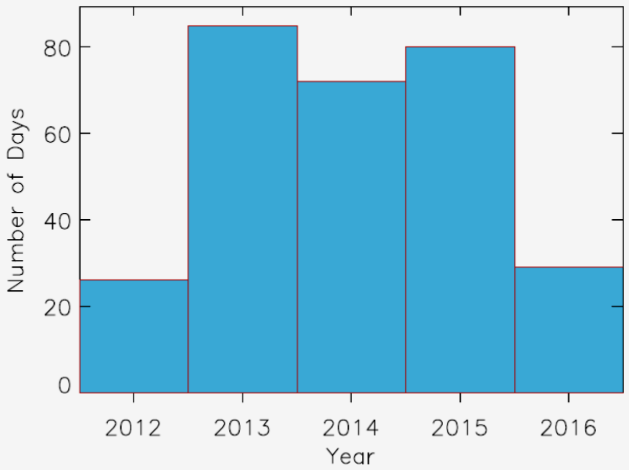
Flare association, i.e. number of C,M,X flares within 24 h from GOES catalogues (http://www.swpc.noaa.gov/)

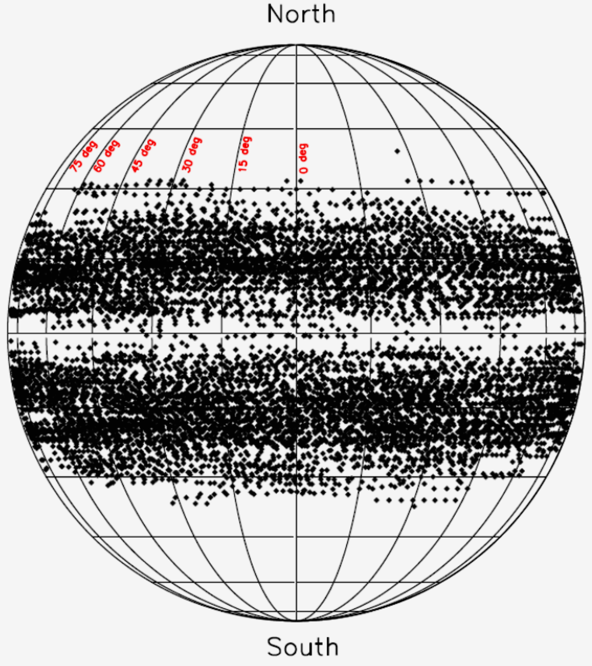
Representative sample of cycle 24 SHARP data

336 random days from September 2012 to May 2016

All SHARP frames with a 6 h cadence

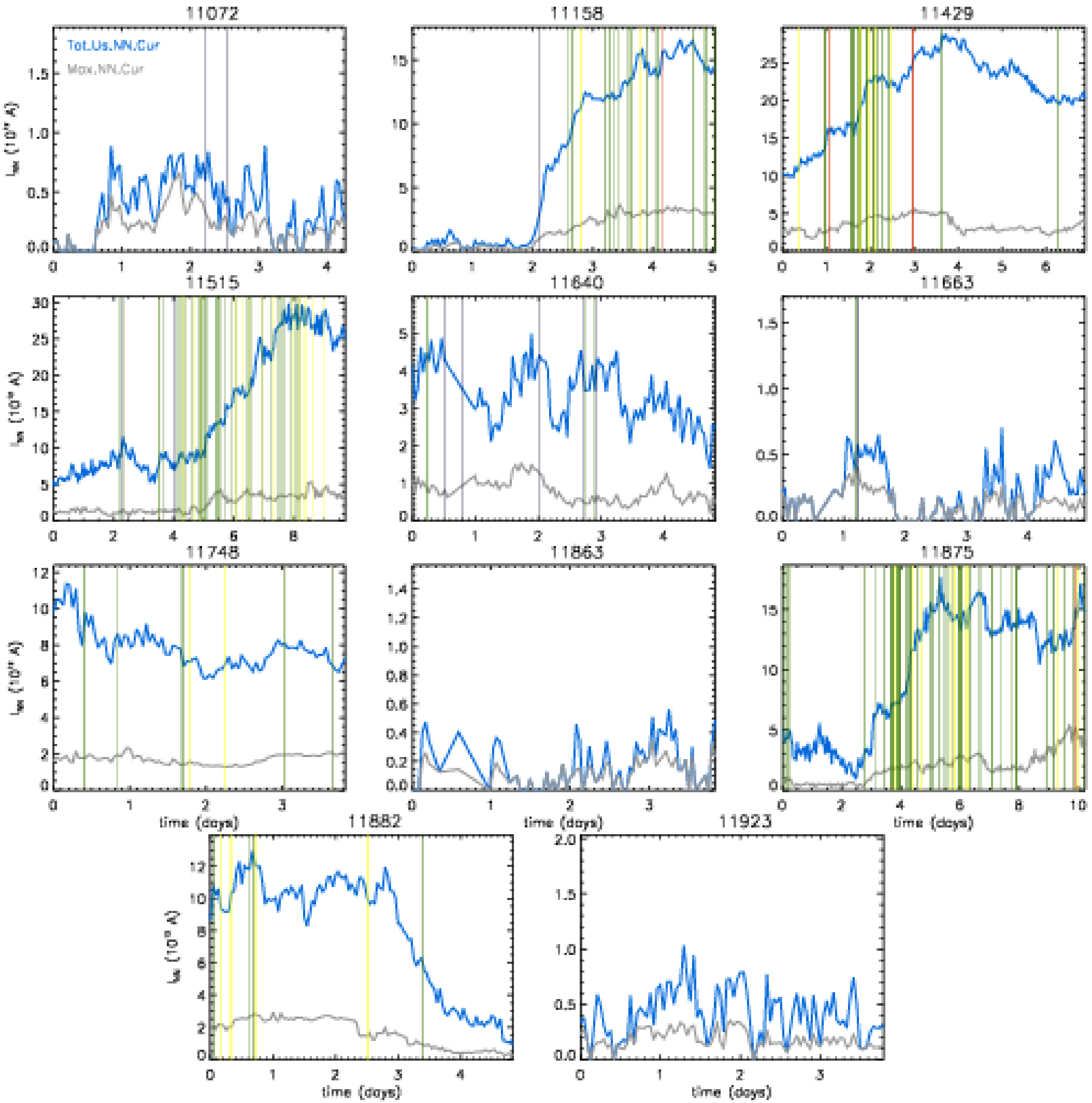
9454 points





From *Guerra+ in prep.*

Results: active regions time-series



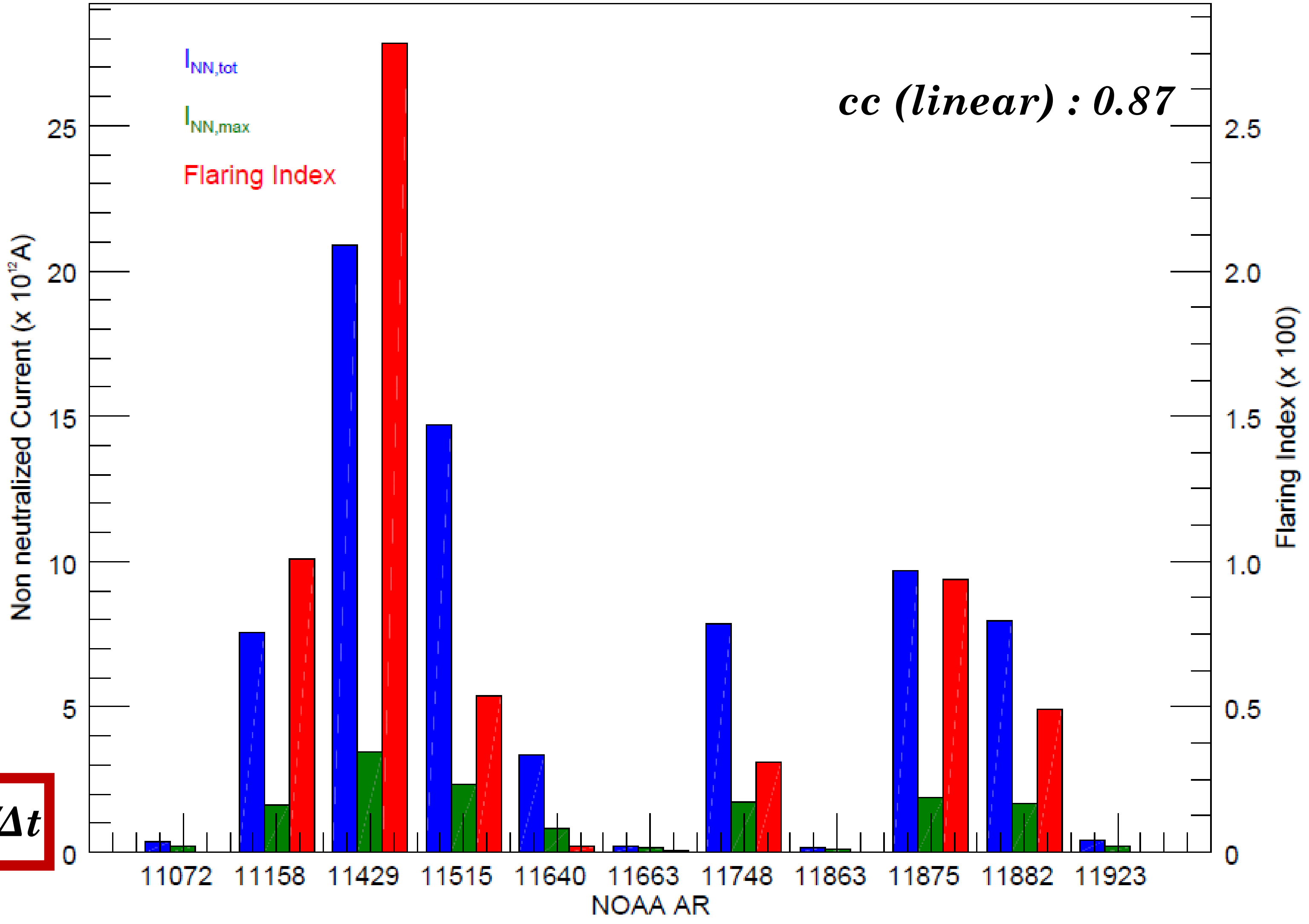
- More than an order of magnitude higher values of non-neutralized currents for flare productive active regions
- Evolution signifies eruptive phase
- Peaks of non-neutralized currents precede or coincide with repeated flaring activity

Results: non-neutralized currents and flaring index

AR time-series

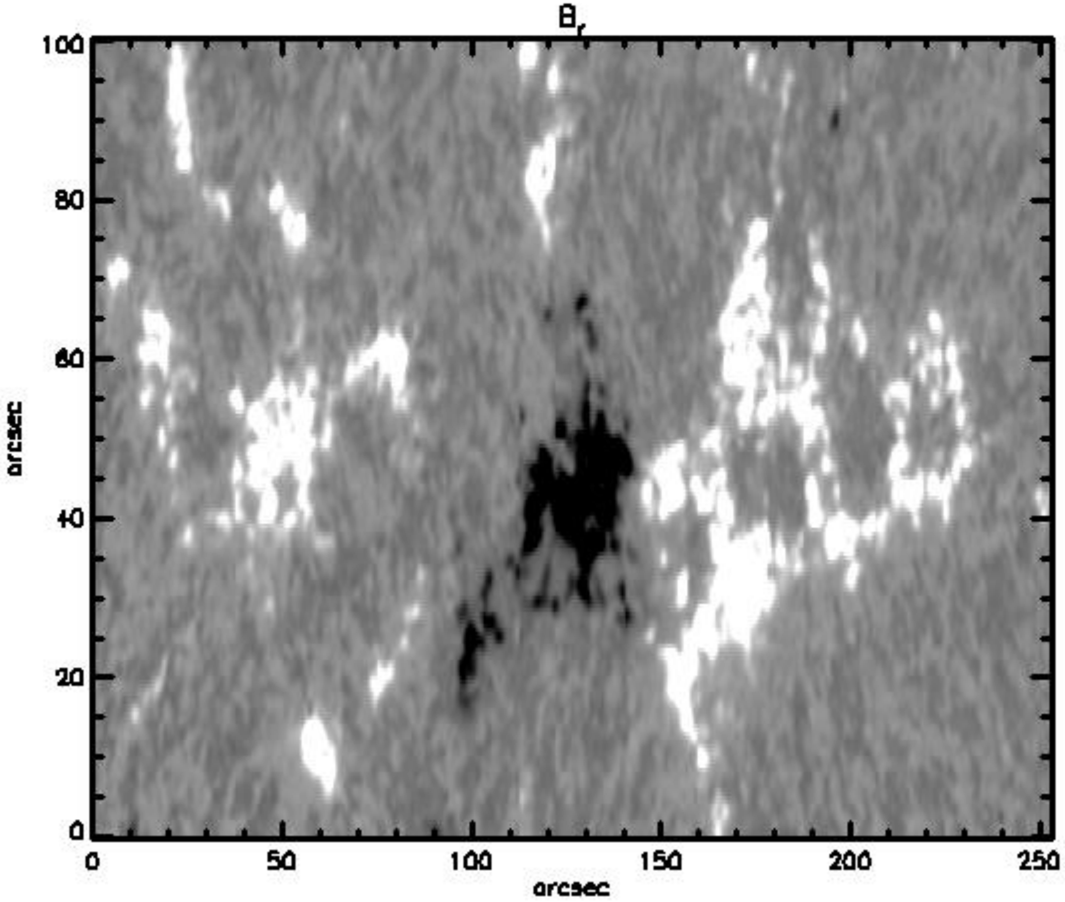
NOAA	t_{start}	t_{end}	B	C	M	X	FI
11072	2010-05-20	2010-05-24	2	0	0	0	0.06
11158	2011-02-10	2011-02-15	1	25	4	1	100.67
11429	2012-03-04	2012-03-10	0	34	12	6	278.15
11515	2012-06-28	2012-07-07	2	39	14	0	53.97
11640	2013-01-01	2013-01-05	5	4	0	0	1.81
11663	2013-01-29	2013-02-03	2	2	0	0	0.55
11748	2013-05-15	2013-05-18	0	10	4	0	31.16
11863	2013-10-10	2013-10-13	0	0	0	0	0.0
11875	2013-10-18	2013-10-28	0	81	18	2	93.60
11882	2013-10-26	2013-10-30	0	7	10	0	49.10
11923	2013-12-12	2013-12-15	0	0	0	0	0.0

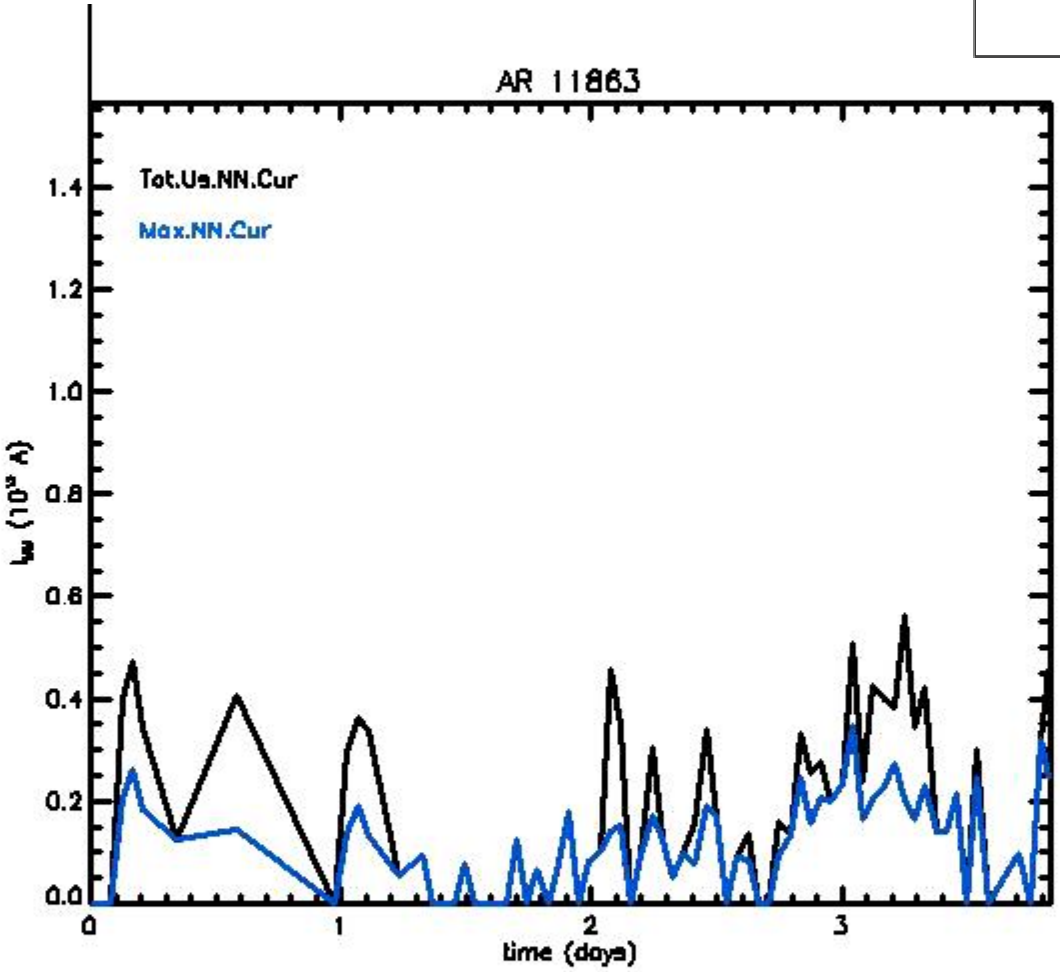
$$F.I. = (100\ N_X + 10\ N_M + N_C + 0.1\ N_B)/\Delta t$$



$I_{NN,tot} – I_{NN,max}$ *and Strong polarity inversion lines*

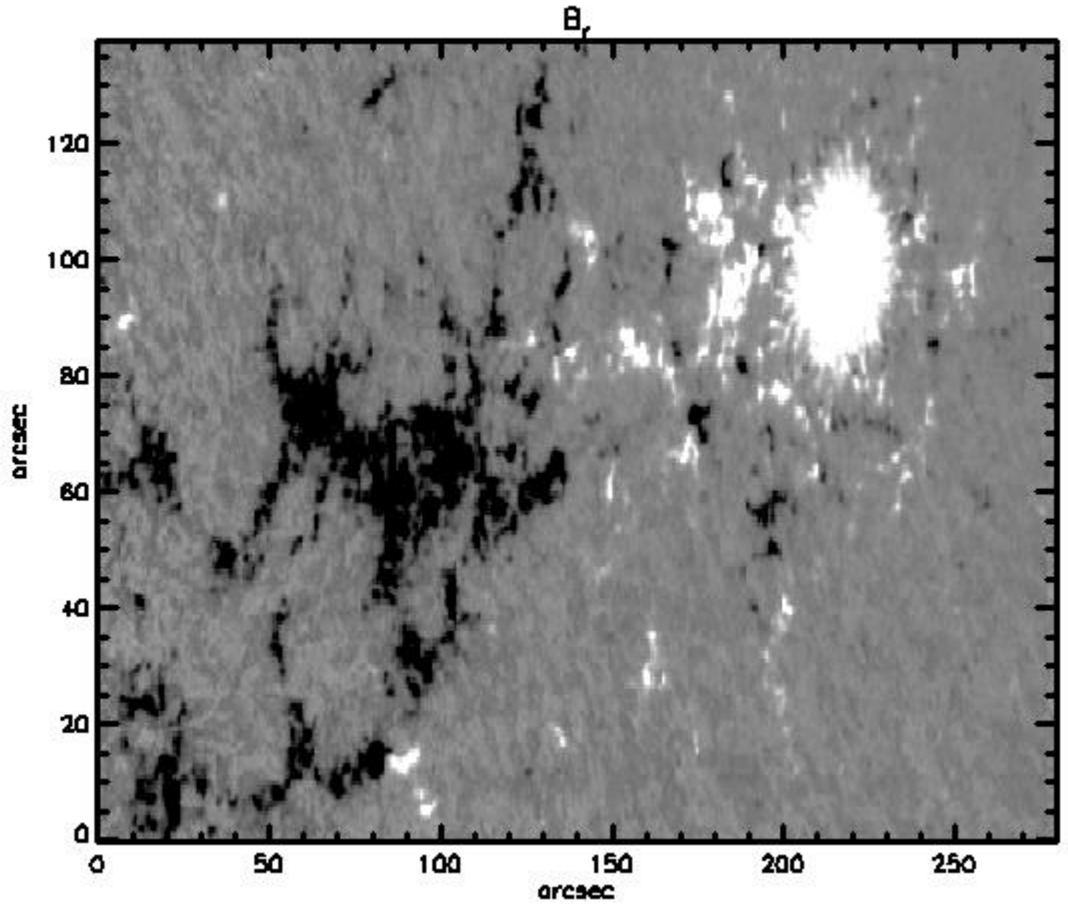
Example 1: A non-flaring AR

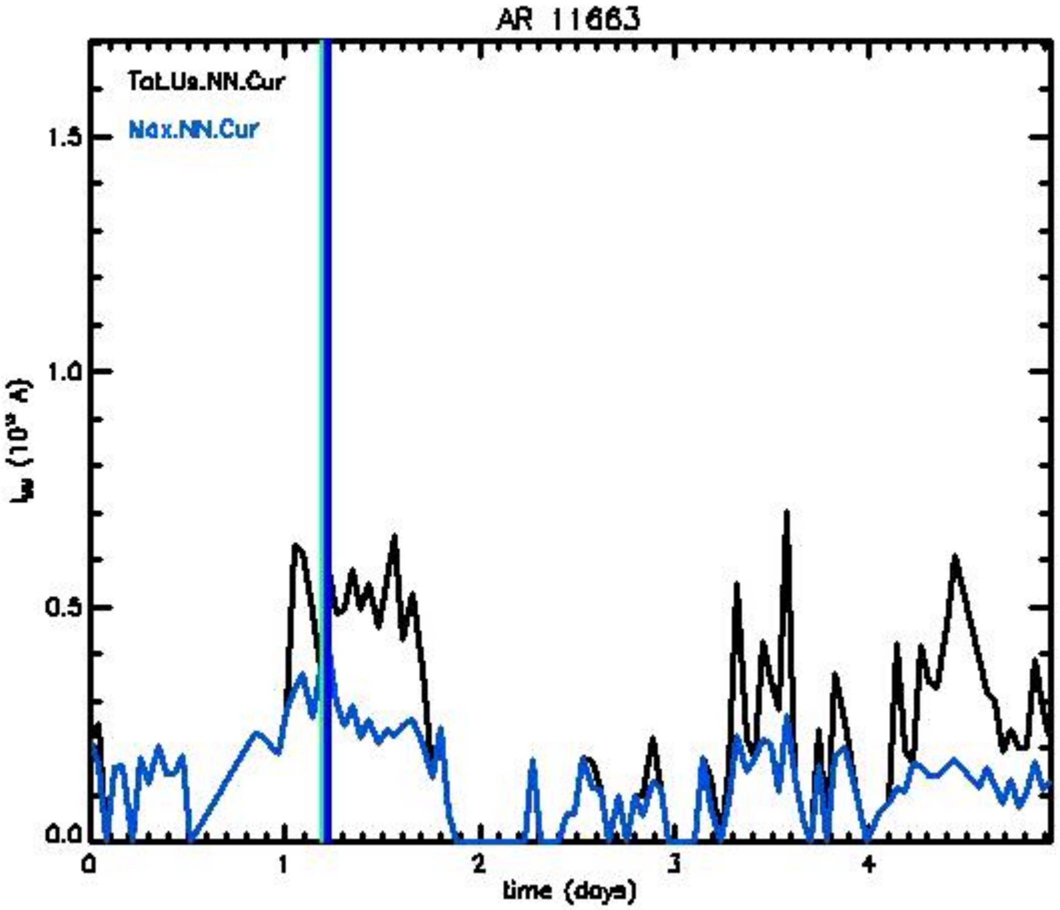




$I_{NN,tot} - I_{NN,max}$ *and Strong polarity inversion lines*

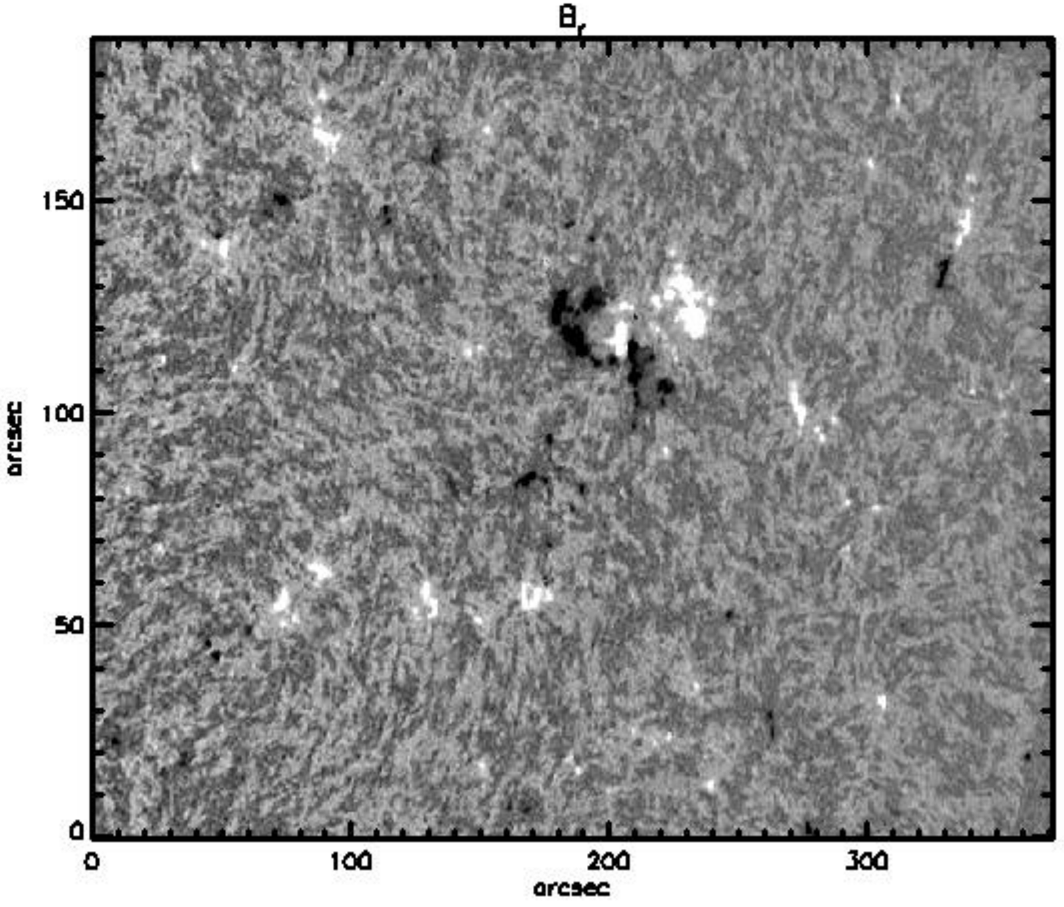
Example 2: A flaring AR

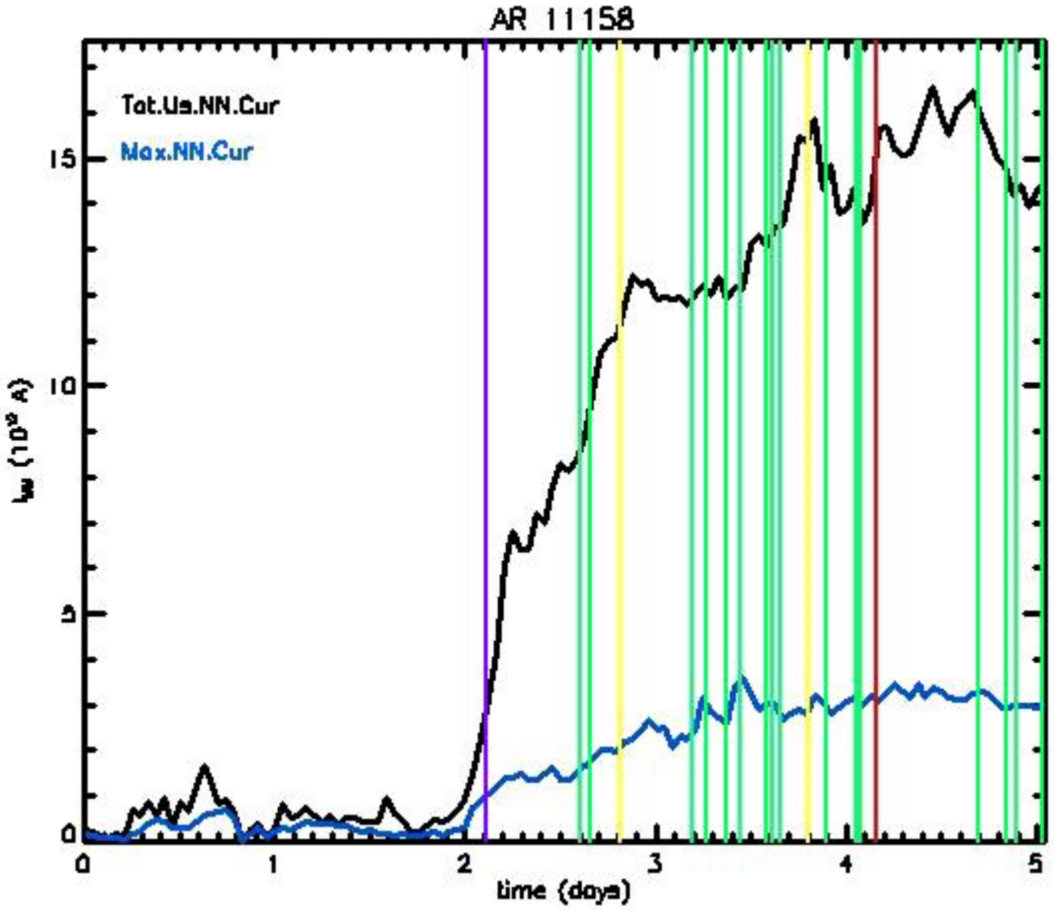




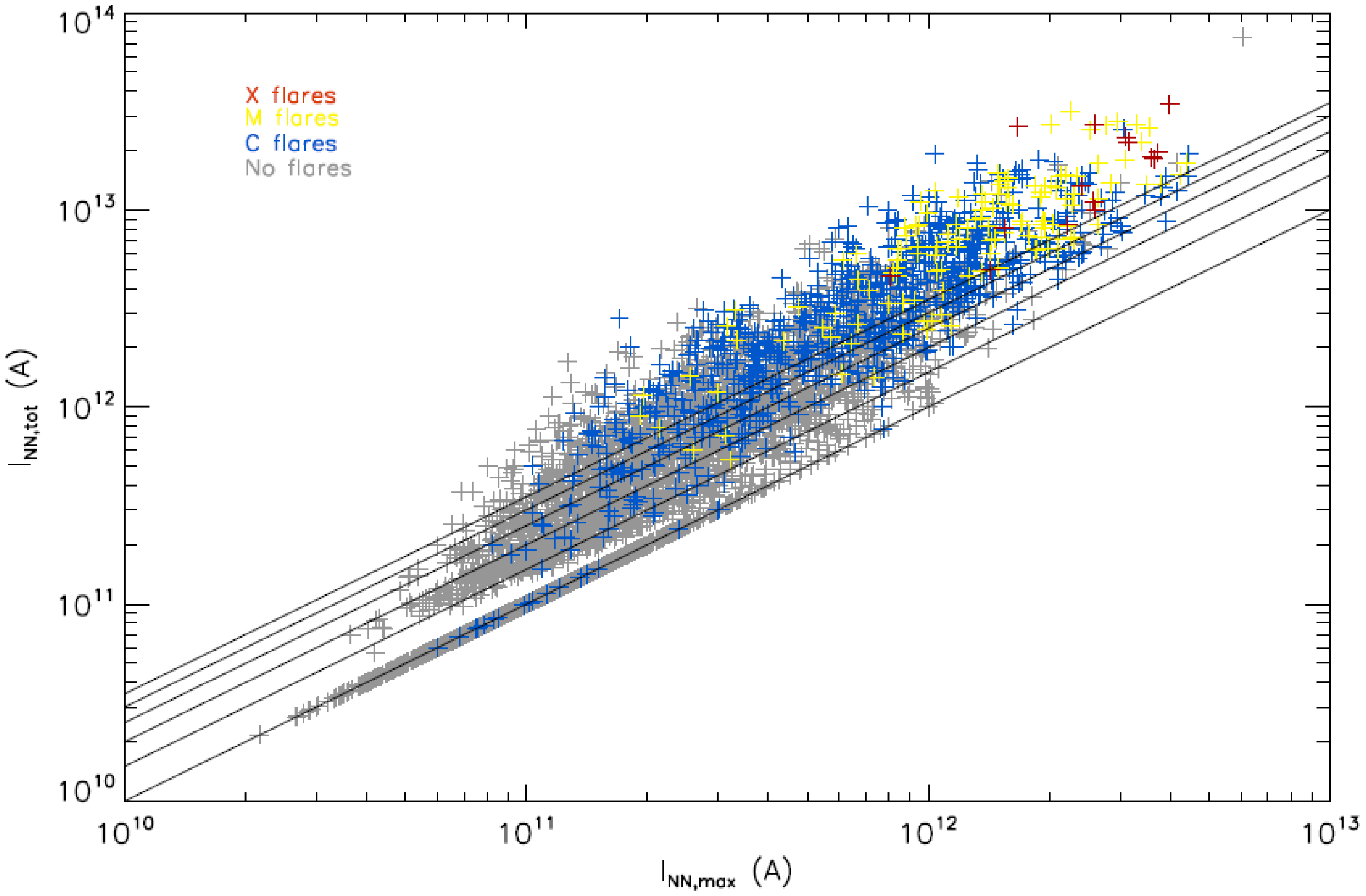
$I_{NN,tot} - I_{NN,max}$ *and Strong polarity inversion lines*

Example 3: A very productive and (in)famous AR, NOAA AR 11158





$I_{NN,tot}$ – $I_{NN,max}$ and Strong polarity inversion lines



M-class flares occurred for

$$I_{NN,tot} > 1.5 \cdot I_{NN,max}$$

X-class flare occurred for

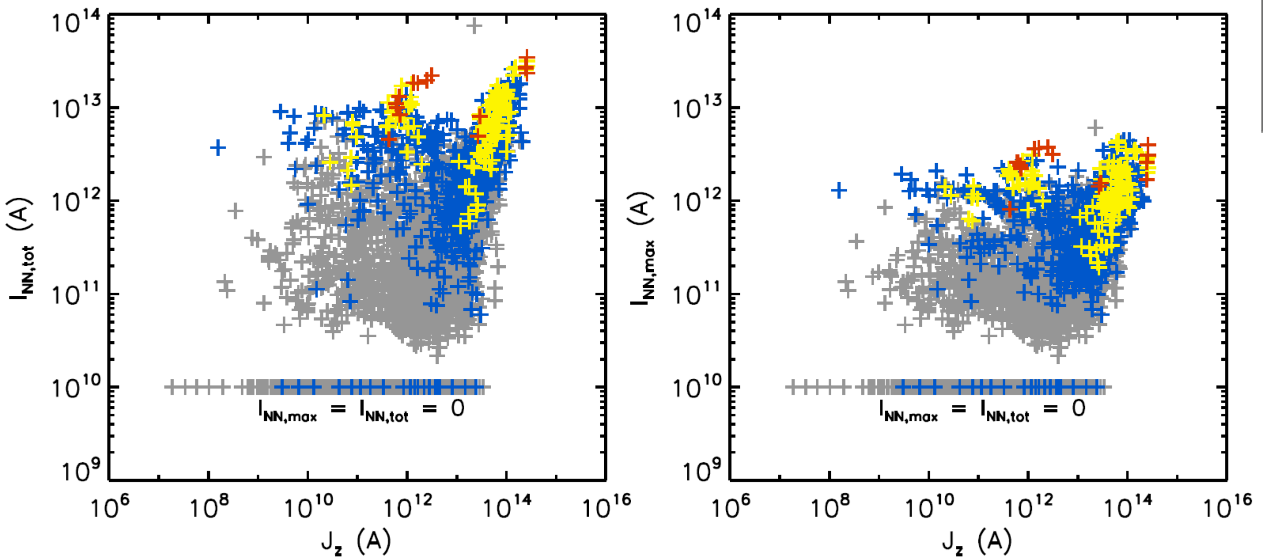
$$I_{NN,tot} > 3.5 \cdot I_{NN,max}$$

Exclusive relation between non-neutralized currents and strong-fragmented MPIL

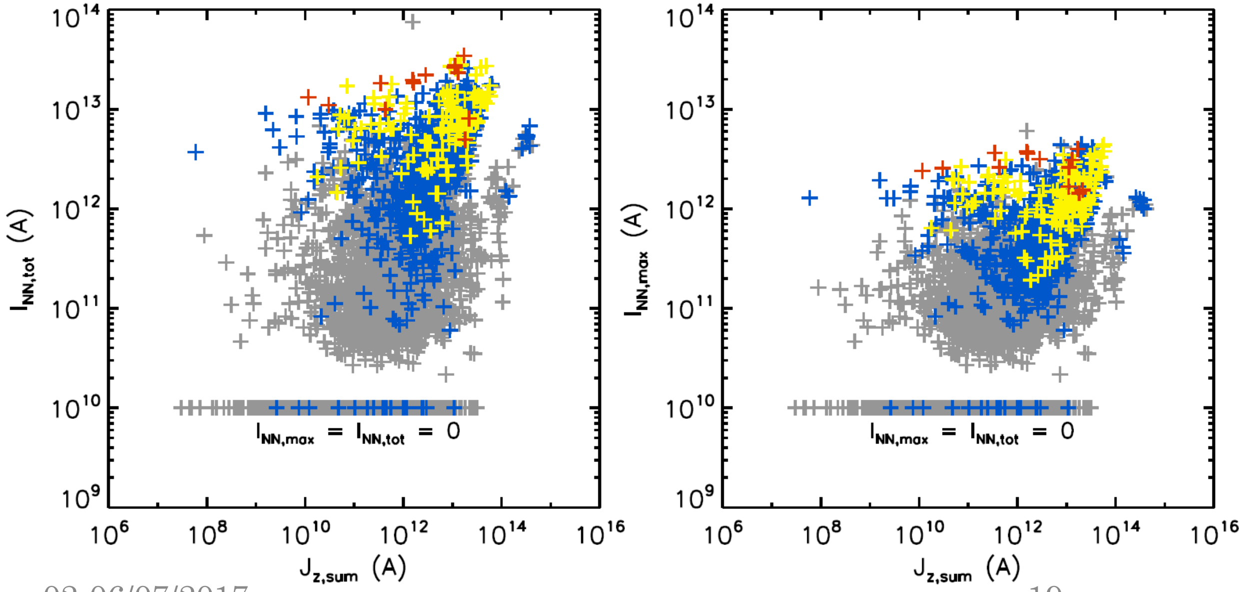
Correlations with current-related parameters

Non - trivial relationship between non-neutralized currents and current-related parameters

Total unsigned vertical current density



Total vertical current per polarity



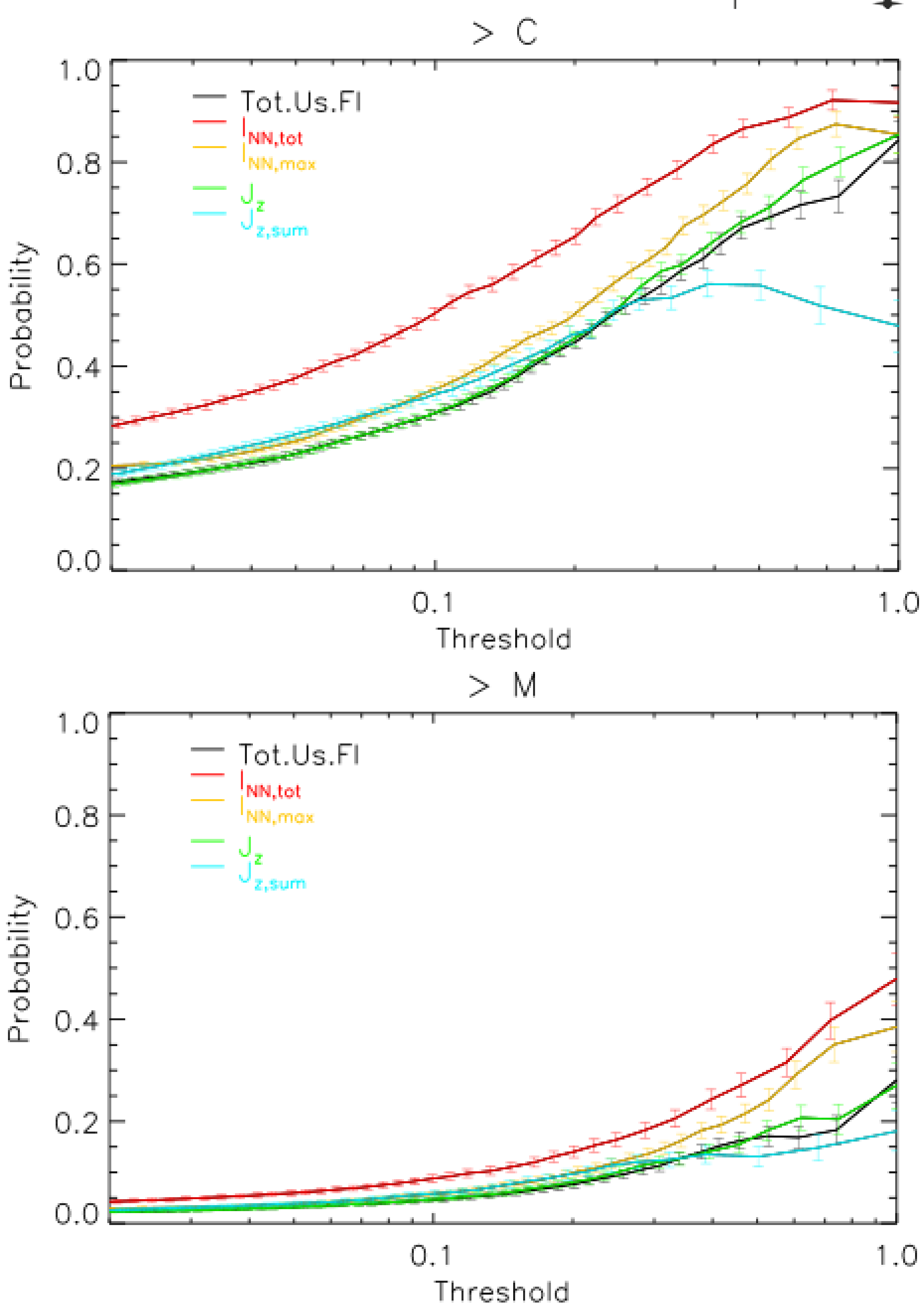
Non-neutralized currents as flare predictors

Bayesian inference of the flaring probability:

$$p = \frac{F+1}{N+2} \qquad \delta p = \sqrt{\frac{p(1-p)}{N+3}}$$

For a given threshold of a **predictor** R:

F: Flaring AR with $R > Rthres$
N: total number of AR with $R > Rthres$



Correlation with CME properties – Preliminary results

Event Type	Start Time (UT)	Associated Instrument	Peak Time	End Time	Class	Source Location	Active Region Number	Directly Linked Event(s)
Solar Flare	2012-09-27 23:36	GOES15: SEM/XRS 1.0-8.0	2012-09-27T23:57Z	2012-09-28T00:34Z	C3.7	N09W26	11577	2012-09-28T02:25:00-CME-001 2012-09-28T02:47:00-SEP-001 STEREO A: IMPACT 13-100 MeV 2012-09-28T03:00:00-SEP-001 GOES13: SEM/EPS >10 MeV 2012-09-28T05:21:00-SEP-001 STEREO B: IMPACT 13-100 MeV
Solar Flare	2012-10-20							
Solar Flare	2012-10-22							
Solar Flare	2012-10-23							
Solar Flare	2012-11-08							
Solar Flare	2012-11-13							
Solar Flare	2012-11-20							
Solar Flare	2012-11-21							
Solar Flare	2013-03-15							
Solar Flare	2013-04-11							
Solar Flare	2013-05-03							
Solar Flare	2013-05-13							
Solar Flare	2013-05-13							

First C2 Appearance Date	Time [UT]	Central PA [deg]	Angular Width [deg]	Linear Speed [km/s]	2nd-order Speed at final height [km/s]	2nd-order Speed at 20 Rs [km/s]	Accel [m/s²]	Mass [gram]	Kinetic Energy [erg]	MPA [deg]	Movies, plots, & links	Remarks
2014/02/01	00:12:05	135	33	141	129	0	-2.4[*1]	3.4e+14	3.3e+28	136	C2 C3 195 PHTX DST Java Movie	Only C2
2014/02/01	03:48:05	71	37	301	337	473	6.4[*1]	5.9e+14	2.7e+29	77	C2 C3 195 PHTX DST Java Movie	Poor Event
2014/02/01	04:00:05	80	218	203	249	311	2.9[*1]	2.0e+15[*2]	4.1e+29[*2]	112	C2 C3 195 PHTX DST Java Movie	Partial Halo
2014/02/01	11:12:05	93	152	297	348	388	3.8[*1]	1.9e+15[*2]	8.5e+29[*2]	90	C2 C3 195 PHTX DST Java Movie	Partial Halo
2014/02/01	20:36:06	84	80	310	414	497	8.6[*1]	1.2e+14	5.9e+28	47	C2 C3 195 PHTX DST Java Movie	Poor Event
2014/02/02	02:24:05	180	19	278	282	290	0.4[*1]	----	----	188	C2 C3 195 PHTX DST Java Movie	Poor Event
2014/02/02	02:24:05	57	25	438	508	964	32.8[*1]	5.9e+13	5.6e+28	48	C2 C3 195 PHTX DST Java Movie	Poor Event; Only C2
2014/02/02	03:24:05	101	16	505	393	0	-59.9[*1]	----	----	101	C2 C3 195 PHTX DST Java Movie	Poor Event; Only C2
2014/02/02	06:48:36	94	132	230	235	242	0.3[*1]	2.2e+15[*2]	5.8e+29[*2]	84	C2 C3 195 PHTX DST Java Movie	Partial Halo
2014/02/02	08:48:06	261	258	591	552	571	-2.9	1.1e+16[*2]	1.9e+31[*2]	235	C2 C3 195 PHTX DST Java Movie	Partial Halo
2014/02/02	17:24:05	208	143	463	569	512	5.2	2.2e+15[*2]	2.4e+30[*2]	224	C2 C3 195 PHTX DST Java Movie	Partial Halo
2014/02/02	23:48:05	120	30	199	181	0	-6.4[*1]	8.6e+13	1.7e+28	123	C2 C3 195 PHTX DST Java Movie	Poor Event; Only C2
2014/02/03	08:00:05	185	67	210	209	207	-0.1[*1]	1.0e+15	2.3e+29	184	C2 C3 195 PHTX DST Java Movie	
2014/02/03	08:24:05	93	113	431	255	0	-16.0[*1]	1.1e+15	1.0e+30	114	C2 C3 195 PHTX DST Java Movie	
2014/02/03	11:24:06	91	81	213	255	392	5.0[*1]	9.3e+14	2.1e+29	90	C2 C3 195 PHTX DST Java Movie	Poor Event
2014/02/03	17:00:05	192	78	287	222	85	-4.6[*1]	1.3e+15	5.4e+29	193	C2 C3 195 PHTX DST Java Movie	
2014/02/03	20:24:05	59	33	273	430	994	39.8[*1]	2.7e+14	9.9e+28	55	C2 C3 195 PHTX DST Java Movie	Poor Event; Only C2
2014/02/03	21:24:05	186	60	223	140	0	-13.0[*1]	5.7e+14	1.4e+29	192	C2 C3 195 PHTX DST Java Movie	
2014/02/04	01:25:46	233	181	528	457	501	-4.4[*1]	6.9e+15[*2]	9.6e+30[*2]	208	C2 C3 195 PHTX DST Java Movie	Partial Halo
2014/02/04	08:48:05	126	89	261	213	0	-9.0[*1]	5.5e+14	1.9e+29	123	C2 C3 195 PHTX DST Java Movie	Only C2
2014/02/04	12:24:05	57	29	151	94	0	-11.3[*1]	1.2e+14	1.3e+28	58	C2 C3 195 PHTX DST Java Movie	Poor Event; Only C2
2014/02/04	16:36:06	250	189	368	339	323	-2.2[*1]	1.7e+15[*2]	1.2e+30[*2]	212	C2 C3 195 PHTX DST Java Movie	Partial Halo
2014/02/04	17:48:06	304	51	194	225	301	2.6[*1]	4.7e+14	8.9e+28	310	C2 C3 195 PHTX DST Java Movie	\; Poor Event
2014/02/04	19:48:05	219	127	294	306	317	0.8	1.6e+14[*2]	6.7e+28[*2]	218	C2 C3 195 PHTX DST Java Movie	Partial Halo

Gopalswamy+ 2009

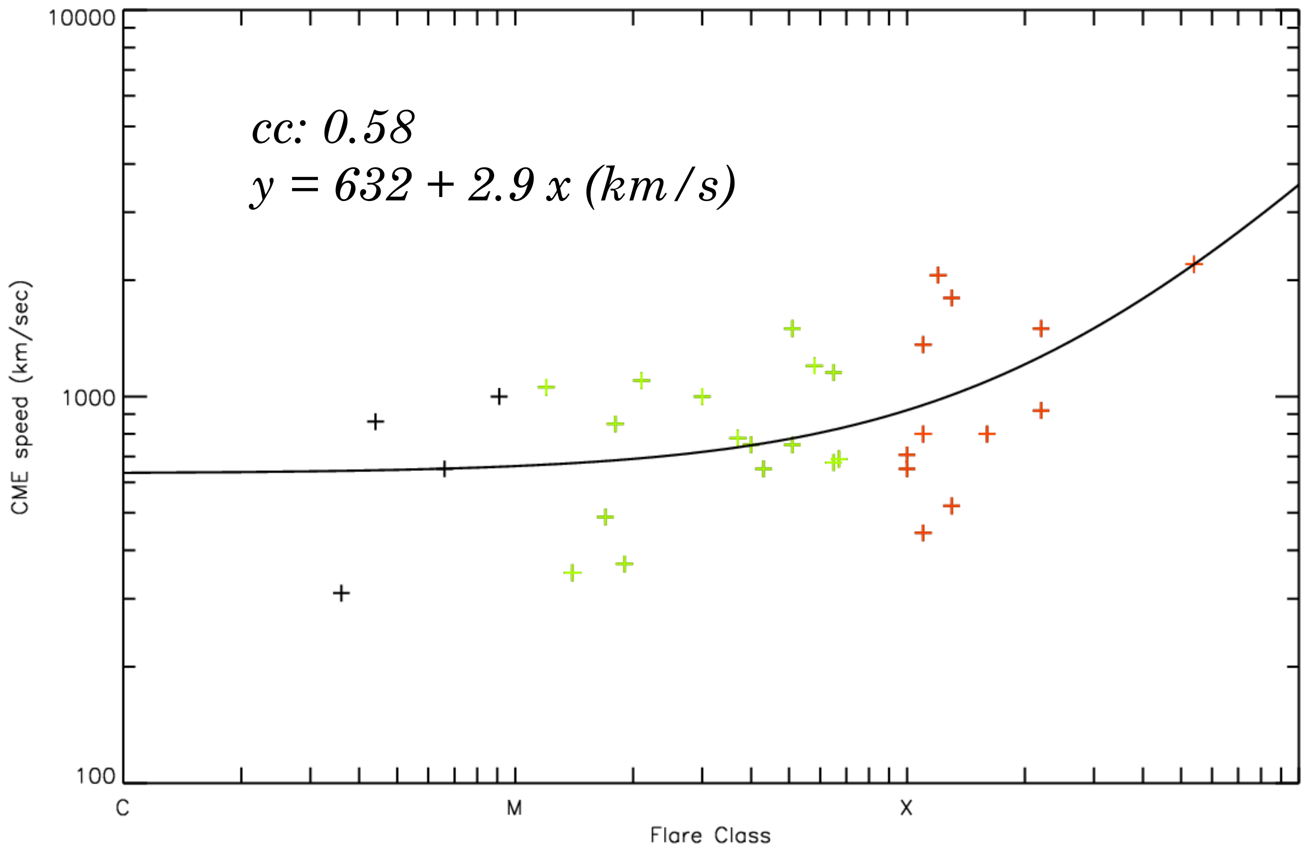
DONKI data base

LASCO CME database

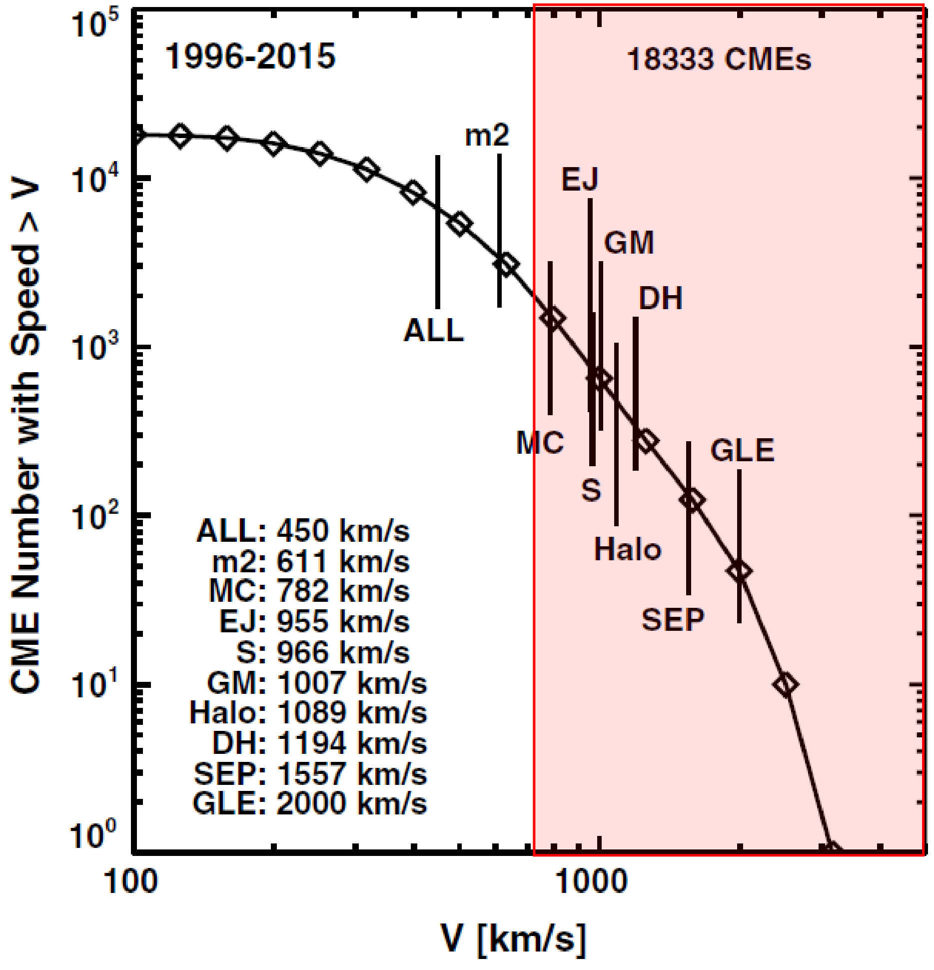
- NOAA AR
- Events registered on both lists
- Clear source association
- HARP data that contain only one AR
- Avoid highly deformed regions

Correlation with CME properties – Preliminary results

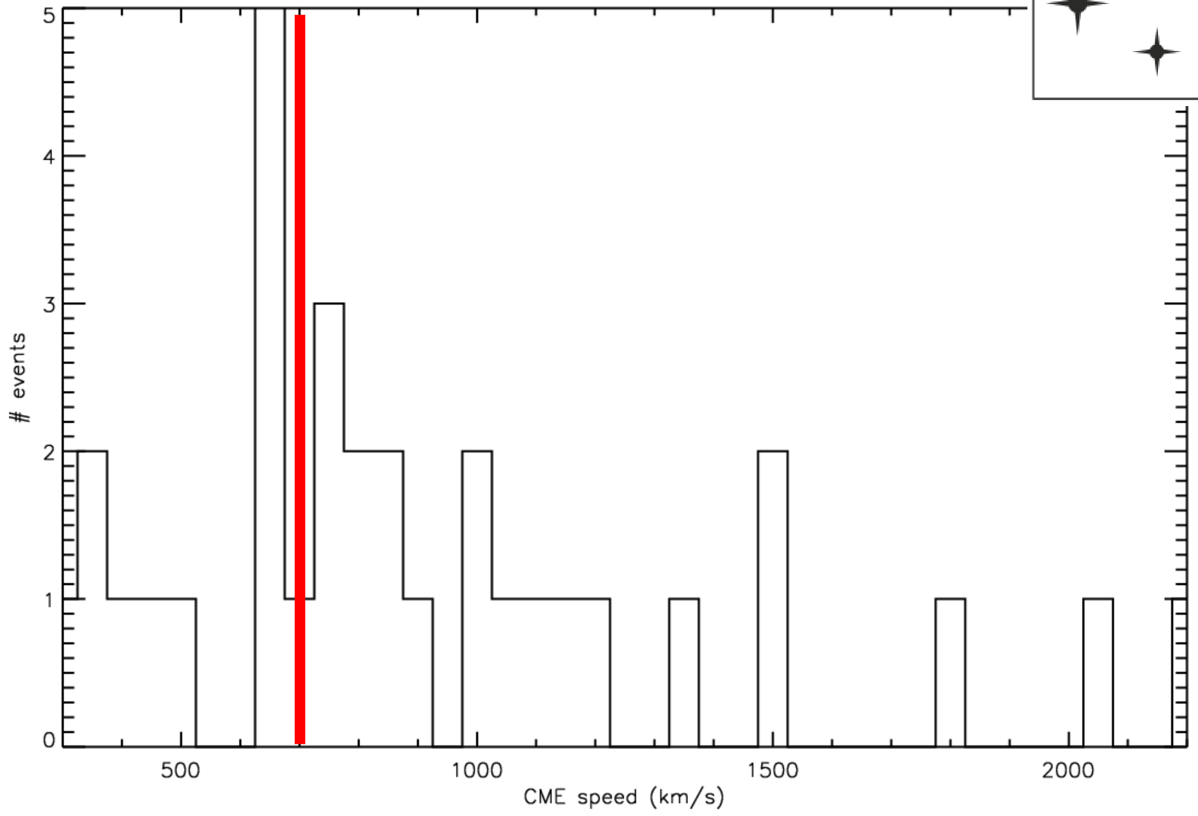
FLARE TIME START	CLASS	NOAA AR	speed
2013-04-11T06:55:00.000	M6.5	11719	675.00
2013-11-08T04:20:00.000	X1.1	11890	444.00
2013-11-10T05:08:00.000	X1.1	11890	800.00
2014-01-07T18:02:00.000	X1.2	11944	2061.0
2014-02-11T03:22:00.000	M1.7	11974	488.0
2014-03-29T17:36:00.000	X1.0	12017	707.00
2014-04-25T00:17:00.000	X1.3	12035	521.0
2015-06-18T16:33:00.000	M3.0	12371	1000.0
2015-06-22T17:39:00.000	M6.5	12371	1155.0
2015-11-04T13:30:00.000	M3.7	12443	780.0
2015-12-28T11:20:00.000	M1.8	12473	850.0
2015-03-09T23:29:00.000	M5.8	12297	1200.0
2015-03-11T16:11:00.000	X2.2	12297	1500.0
2014-10-24T07:37:00.000	M4.0	12192	750.0
2014-11-07T16:53:00.000	X1.6	12205	800.0
2011-02-15T01:44:00.000	X2.2	11158	920.0
2012-03-05T03:30:00.000	X1.1	11429	1363.0
2012-03-07T00:02:00.000	X5.4	11429	2200.0
2012-03-07T01:05:00.000	X1.3	11429	1800.0
2013-10-28T01:41:00.000	X1.0	11875	650.0
2013-10-22T21:15:00.000	M4.3	11875	650.0
2013-10-28T04:32:00.000	M5.1	11875	750.0
2015-03-10T03:19:00.000	M5.1	12297	1500.0
2015-03-15T01:15:00.000	C9.1	12297	1000.0
2015-08-21T09:34:00.000	M1.4	12403	350.0
2015-08-22T06:39:00.000	M1.2	12403	1057.0
2015-09-20T17:32:00.000	M2.1	12415	1100.0
2015-10-22T02:13:00.000	C4.4	12434	861.0
2015-11-04T03:20:00.000	M1.9	12445	369.0
2015-12-01T07:59:00.000	C3.6	12458	310.0
2015-12-16T08:34:00.000	C6.6	12468	650.0
2016-04-18T00:14:00.000	M6.7	12529	689.0



Correlation with CME properties – Preliminary results



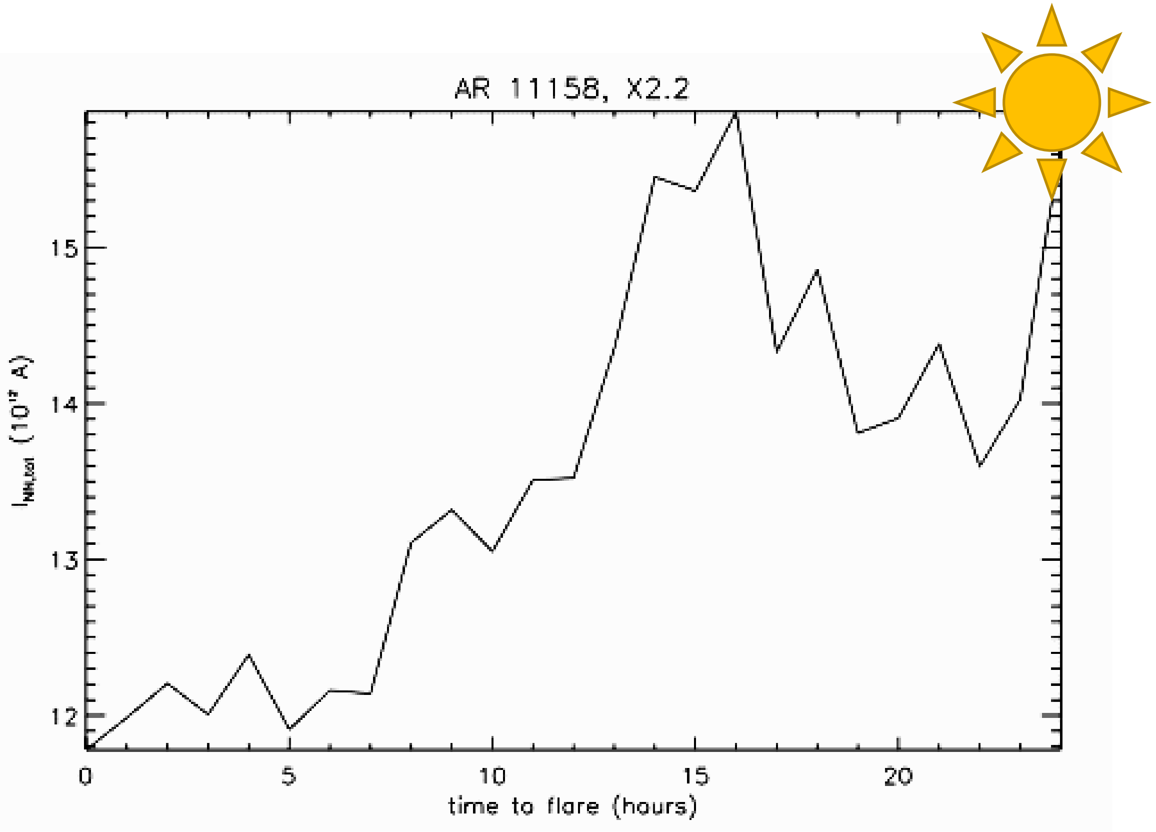
Gopalswamy 2016



Linear speed threshold at 700 km/s
more "interesting" events

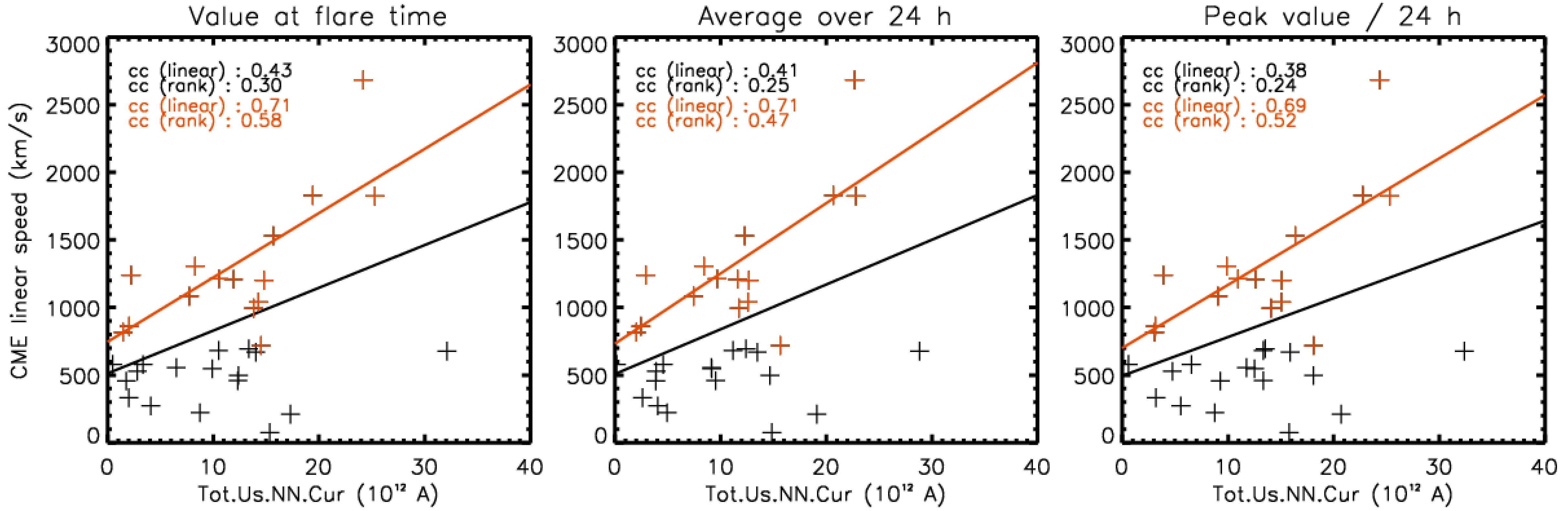
Impulsive CME's (Sheeley et al. 1999)

Correlation with CME properties – Preliminary results

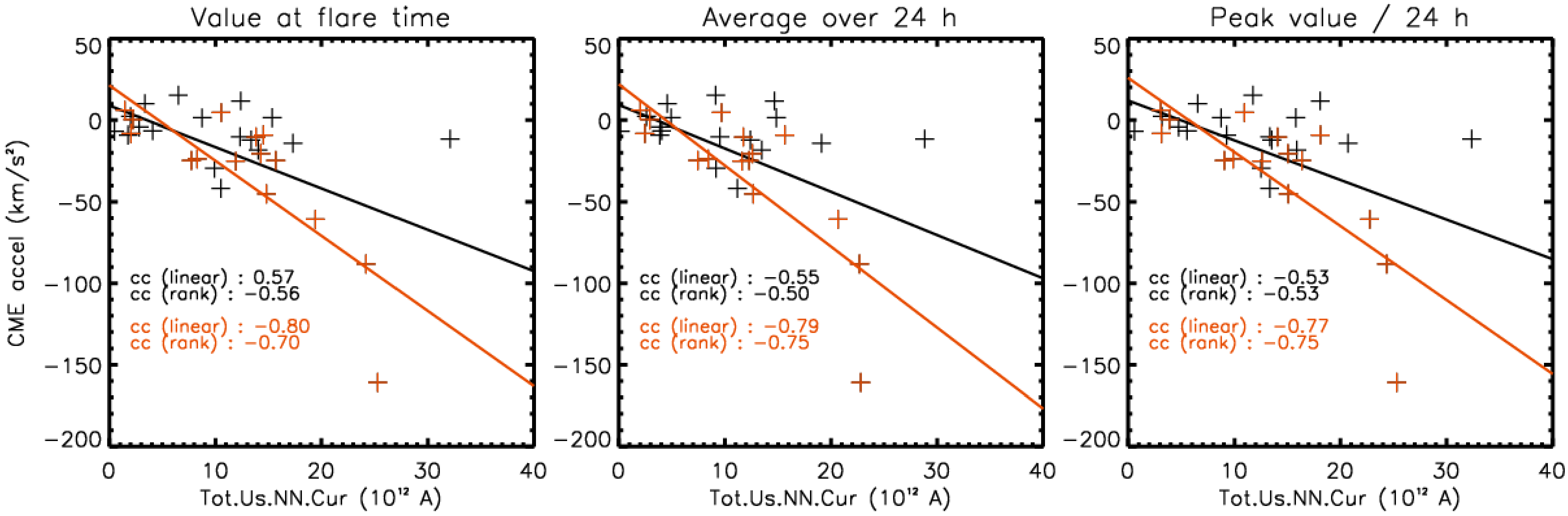


- $I_{NN,tot}$ at flare onset time
- $I_{NN,tot}$ peak during preceding 24 h
- $I_{NN,tot}$ average during preceding 24 h

Correlation with CME properties – Preliminary results



Correlation with CME properties – Preliminary results



Conclusions – future work/in progress

- Exclusive relation between non-neutralized currents and MPIL formation

  $\boldsymbol{I_{NN,tot}} = \boldsymbol{0}$ for *AR* without strong ***PILs***

- Very good correlation between non-neutralized currents and flaring index
- $\boldsymbol{I_{NN,tot}}$ and $I_{NN,max}$ produce better flaring probabilities than the total flux.
- $I_{NN,tot}$ produces better flaring probabilities than other current-related predictors
- Good correlation with CME properties (speed, acceleration, kinetic energy)

Future

- Ongoing work, involve more predictors!
- Future work: explore evolution of non-neutralized currents, develop more predictors

Kontogiannis, Georgoulis, Park & Guerra 2017 SoPh submitted

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Flare Likelihood And Region Eruption foreCASTing

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A Horizon2020 PROTEC (Protection of our Assets in Space) Research and Innovation Action