Forecasting the Solar Drivers of Severe Space Weather from Active-Region Magnetograms

David A. Falconer (UAHuntsville/MSFC), Ronald L. Moore(MSFC), Abdulnasser F. Barghouty(MSFC), and Igor Khazanov(UAHutsville)

Large flares and fast CMEs are the drivers of the most severe space weather including Solar Energetic Particle Events (SEP Events). Large flares and their co-produced CMEs are powered by the explosive release of free magnetic energy stored in non-potential magnetic fields of sunspot active regions. The free energy is stored in and released from the low-beta regime of the active region's magnetic field above the photosphere, in the chromosphere and low corona. From our work over the past decade and from similar work of several other groups, it is now well established that (1) a proxy of the free magnetic energy stored above the photosphere can be measured from photospheric magnetograms, and (2) an active region's rate of production of major CME/flare eruptions in the coming day or so is strongly correlated with its present measured value of the free-energy proxy. These results have led us to use the large database of SOHO/MDI full-disk magnetograms spanning Solar Cycle 23 to obtain empirical forecasting curves that from an active region's present measured value of the free-energy proxy give the active region's expected rates of production of major flares, CMEs, fast CMEs, and SEP Events in the coming day or so (Falconer et al 2011, Space Weather, 9, S04003). We will present these forecasting curves and demonstrate the accuracy of their forecasts. In addition, we will show that the forecasts for major flares and fast CMEs can be made significantly more accurate by taking into account not only the value of the free energy proxy but also the active region's recent productivity of major flares; specifically, whether the active region has produced a major flare (GOES class M or X) during the past 24 hours before the time of the measured magnetogram.

By empirically determining the conversion of the value of free-energy proxy measured from a GONG or HMI magnetogram to that which would be measured from an MDI magnetogram, we have made GONG and HMI magnetograms useable with our MDI-based forecasting curves to forecast event rates.

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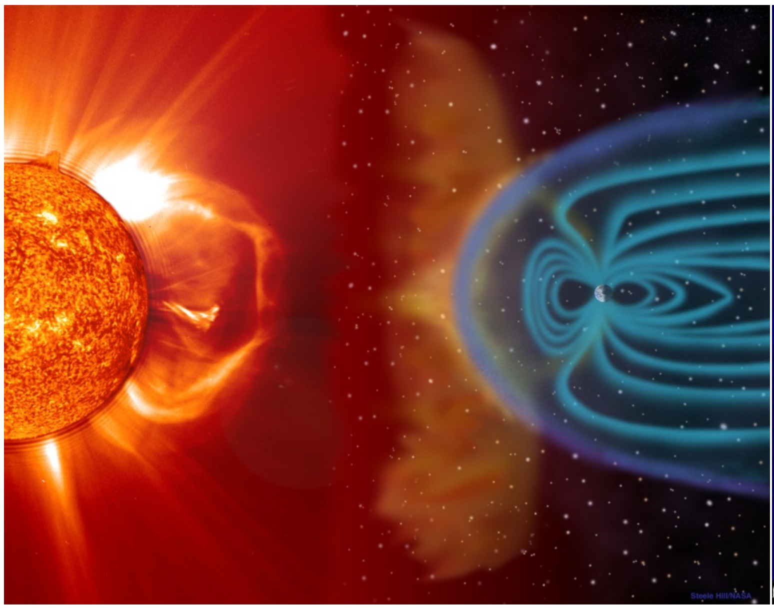
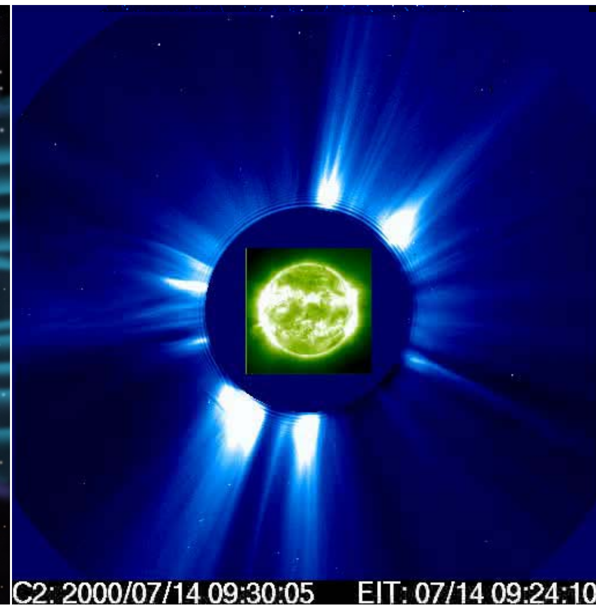
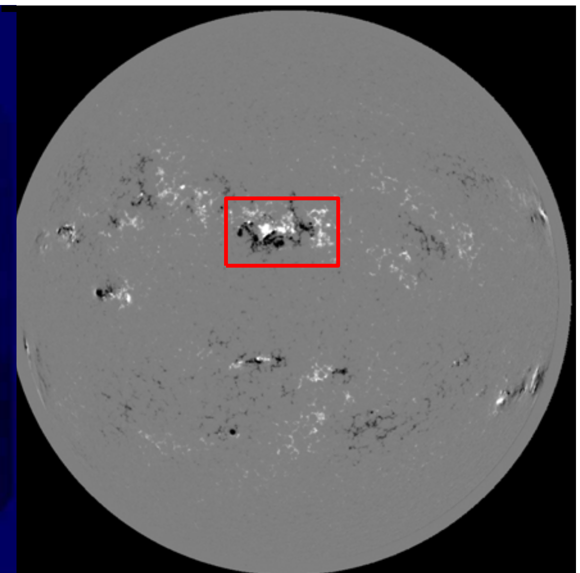




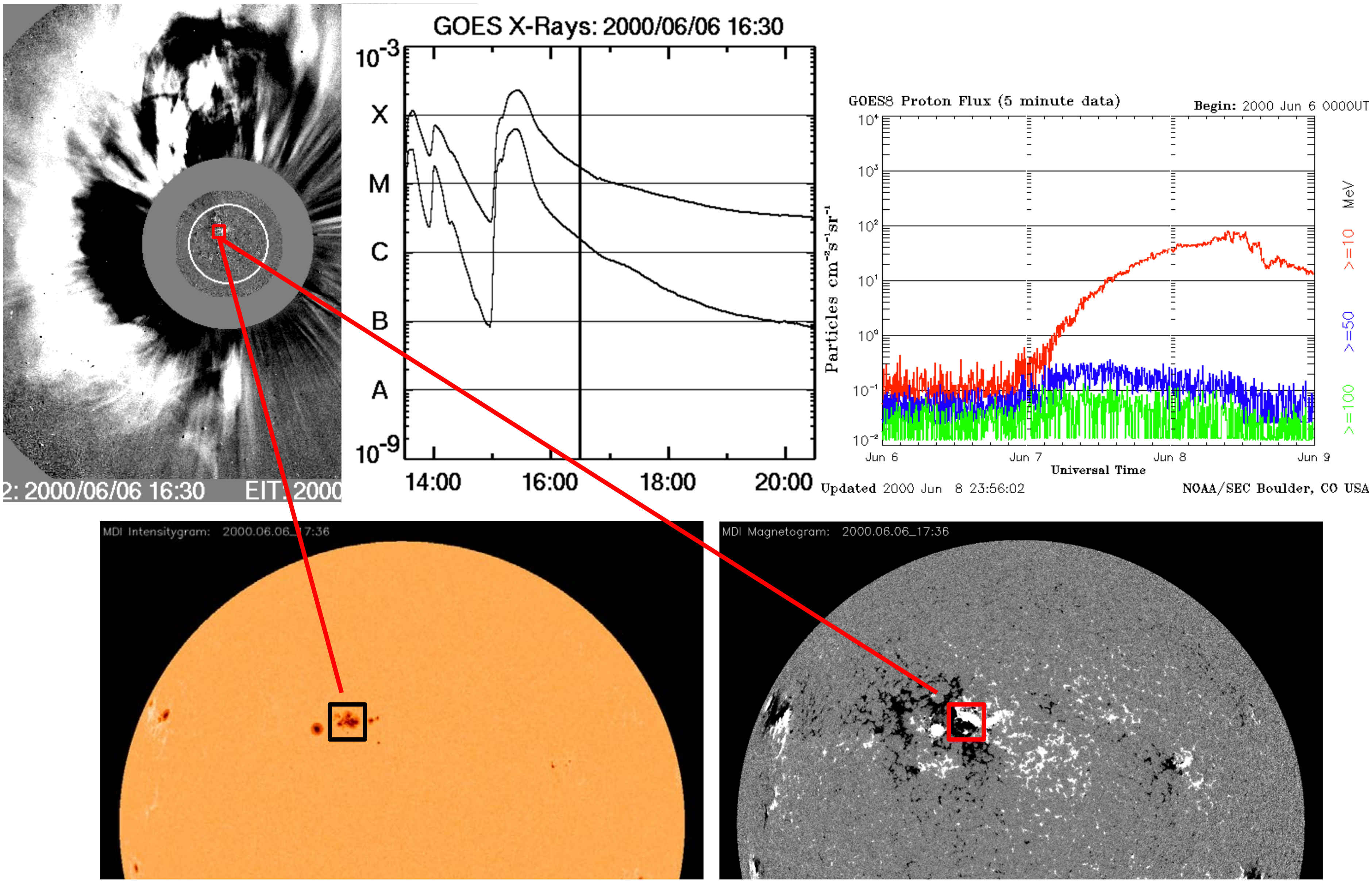


Forecasting X-class, M-class, CMEs, and SEP events from active region magnetograms.

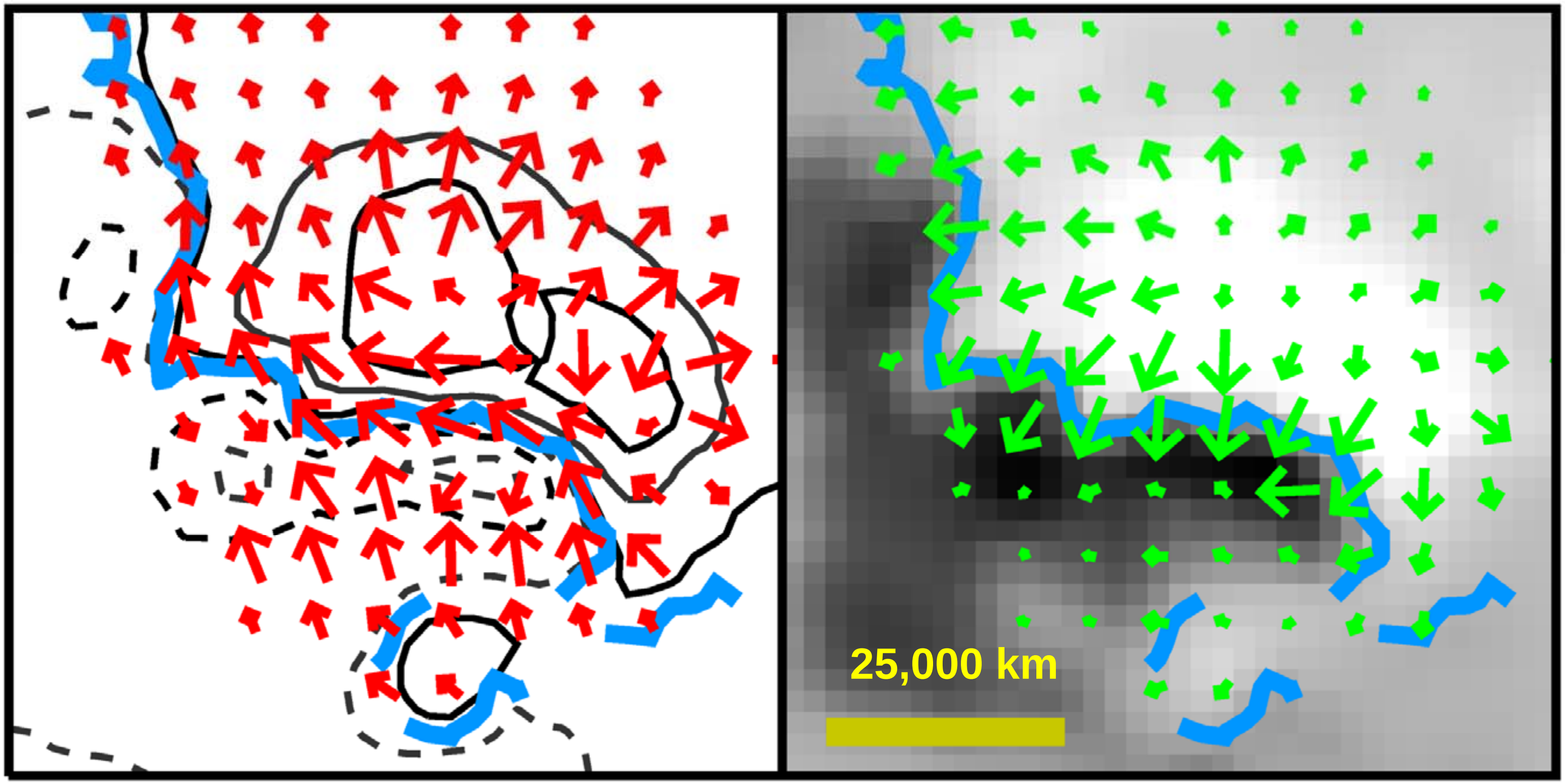
Forecasting Drivers of Space Weather

- Flares and CMEs are drivers of SEP events and other forms of sever space weather..
- Flares and CMEs are sudden explosions of energy stored in an active region's coronal magnetic field.
- A proxy of the active region's coronal free energy can be measured from photospheric magnetograms.
- We have found that CME/flare production rates are strongly correlated with the free-energy proxy.
- Other persistent factors are also important for determining an active regions expected event rates. All of these are reflected by the previous flare activity of the active region.

Example: Halo CME, X-Flare, SEP Event and δ-Sunspot Source Region



MSFC Vector Magnetogram of δ-Sunspot Source Region of Example CME/Flare Eruption



An active-region field's horizontal shear is concentrated along neutral lines where the field's horizontal component is strong and the vertical component's horizontal gradient is steep.

Observed-field upward (downward) vert. comp. is shown by solid contours or light shading (dashed contours or dark shading); red arrows show observed hor. comp. ; green arrows show hor. comp. of pot. field computed from obs. vert. comp. ; strong-observed-field (>150G) intervals of neutral lines are blue.

Free-energy proxy from vertical-field component of vector magnetogram or from line-of-sight magnetogram:

- Active regions that have large magnetic shear along neutral lines (where the observed field is nearly perpendicular to the potential field, and thus has a large free energy content) also develop large transverse gradients along the neutral line.

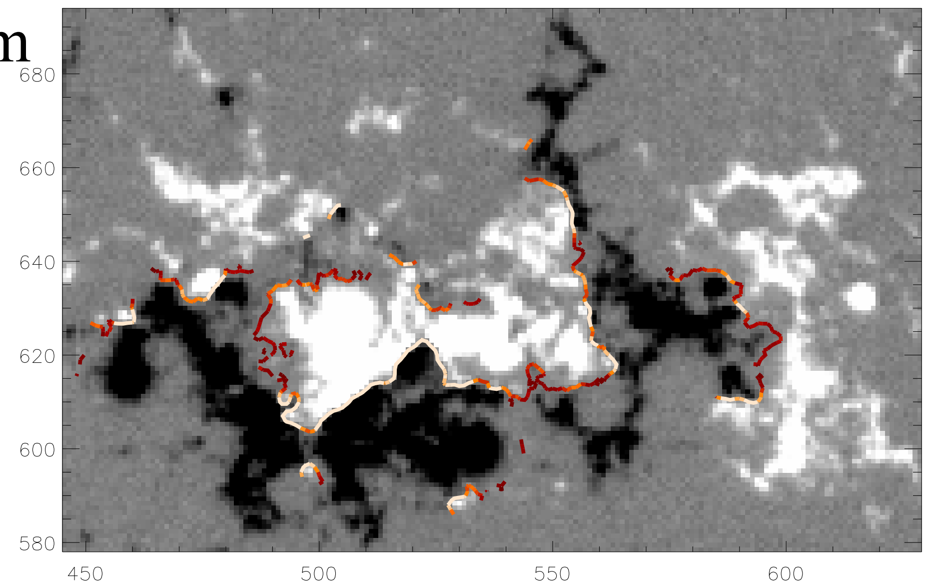
- Deprojected vector magnetogram version

$$\mathbf{WL_{SG}=\int(\nabla B_Z)dl}$$

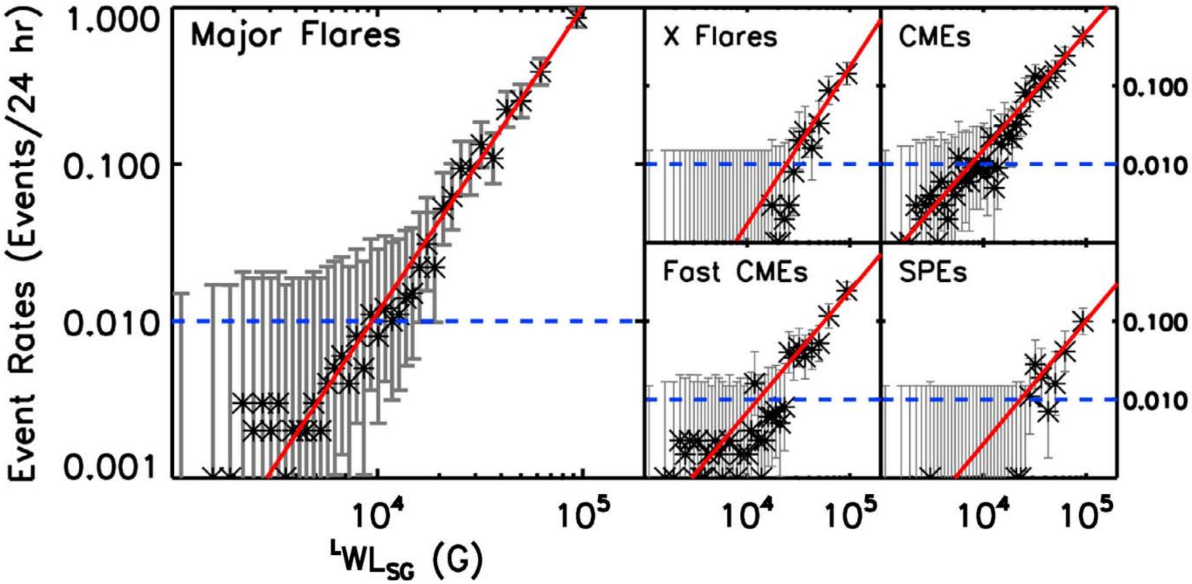
or line-of-sight approximation

$$\mathbf{{}^{L}WL_{SG}=\int(\nabla B_{LOS})dl}.$$

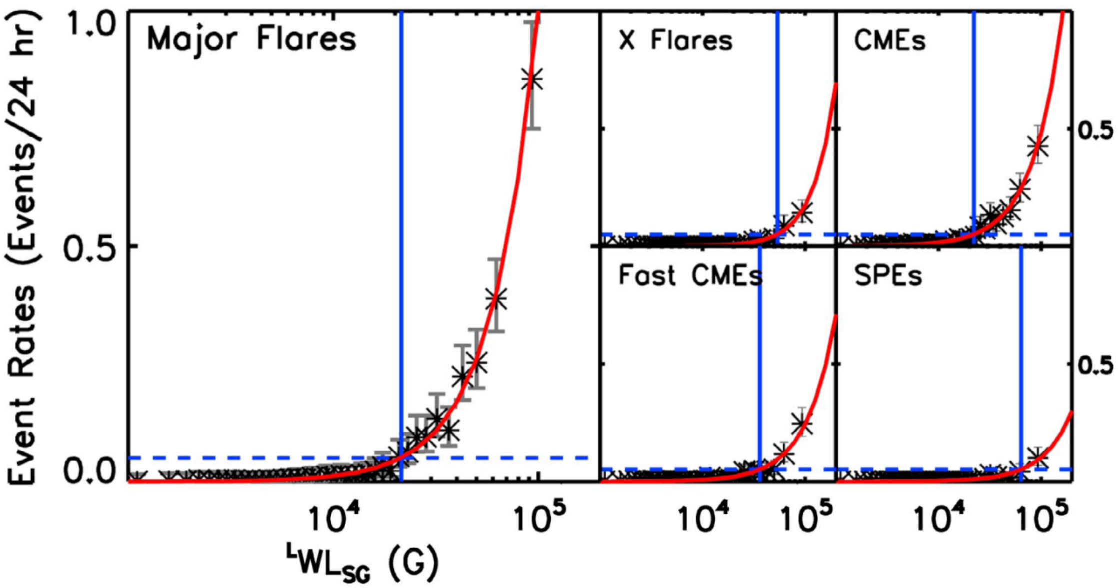
integration is along strong-field intervals of the AR neutral lines.



The Heart of the Forecasting Tool: The Forecast Curves



Only active regions that have a large free energy are likely to produce major events in the next 24 hours.



Most (~80%) active regions have a negligible (All Clear) chance of producing an event.

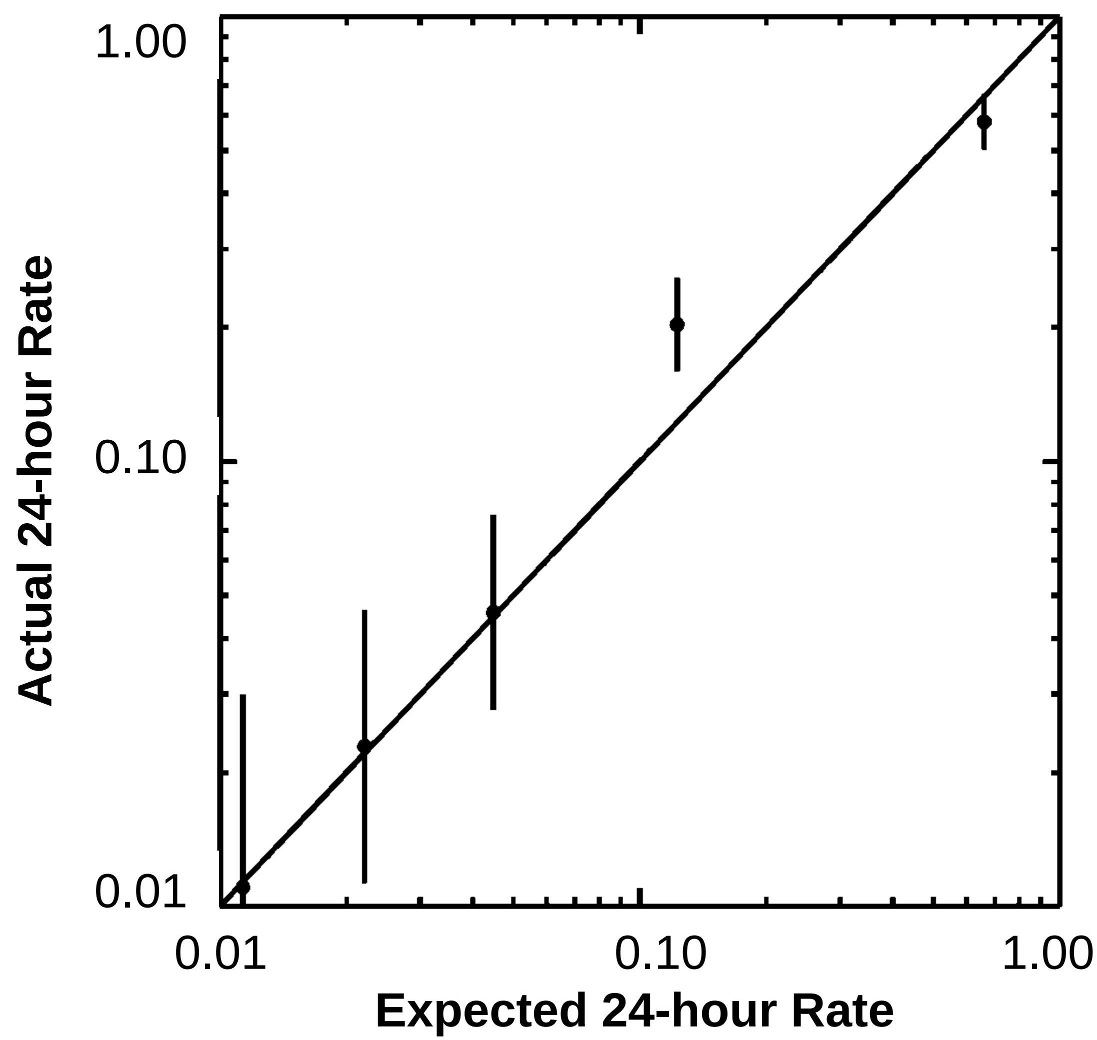
Verification of Accuracy of Forecast

Actual Performance versus Predicted Performance.

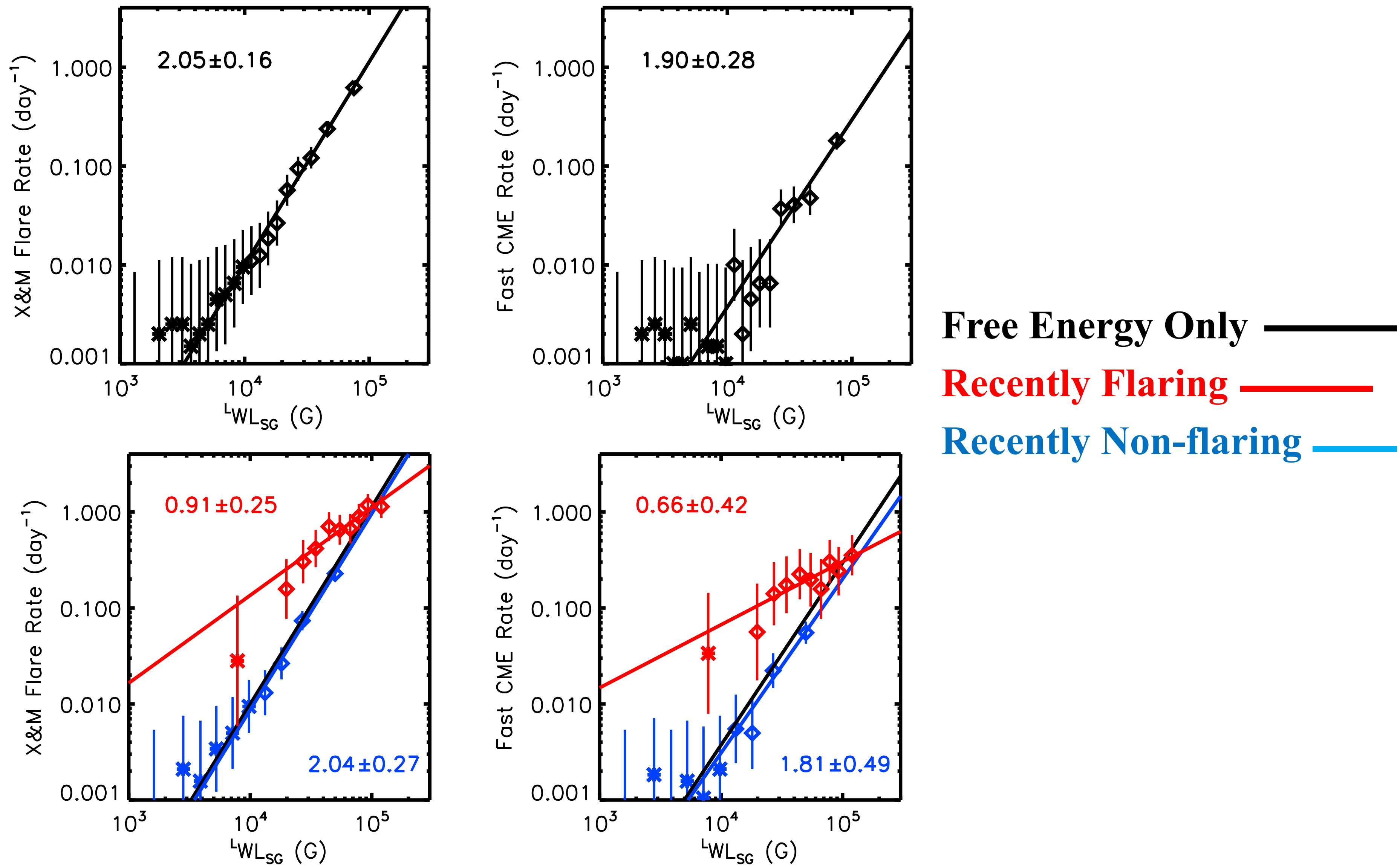
Predicted Performance from first 75% of sample.

Actual Performance of last 25% of sample.

1-sigma error bars

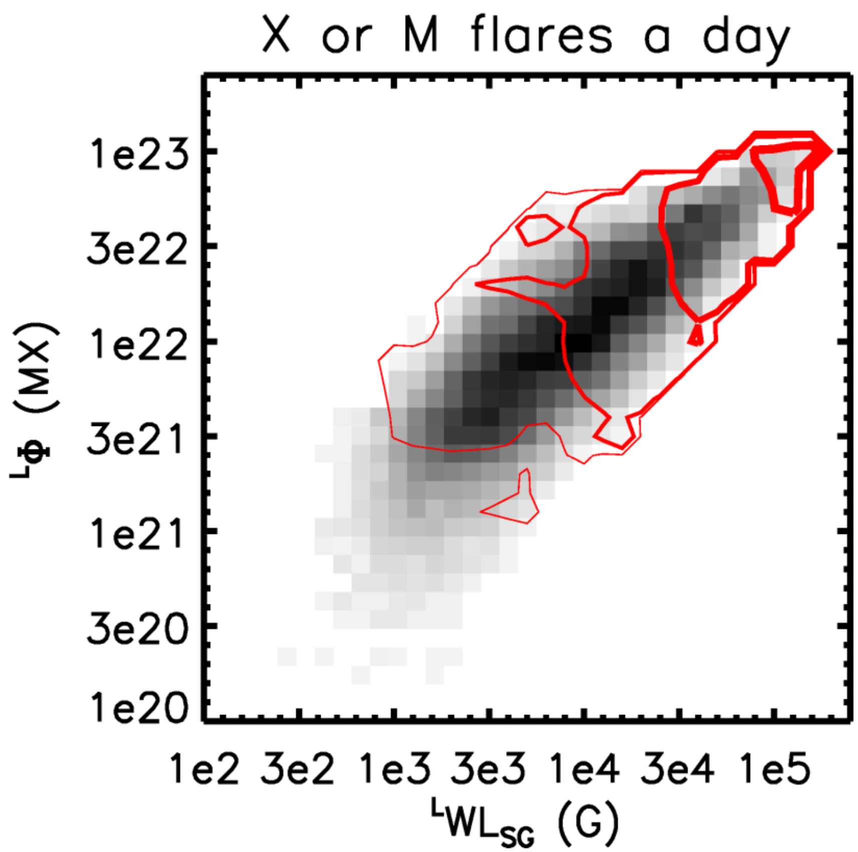


Incorporation of Previous Flaring Improves the Forecast



Flux Content is Not an Important Additional Determinant

Gray scale plot shows free energy/magnetic size distribution of 40,000 magnetograms of 1,300 active regions. Red contours are 0.001, 0.01, and 0.1, and 0.5 event/day levels.



Forecasting with HMI using MDI Forecast Curves

Comparison of HMI and MDI Magnetographs

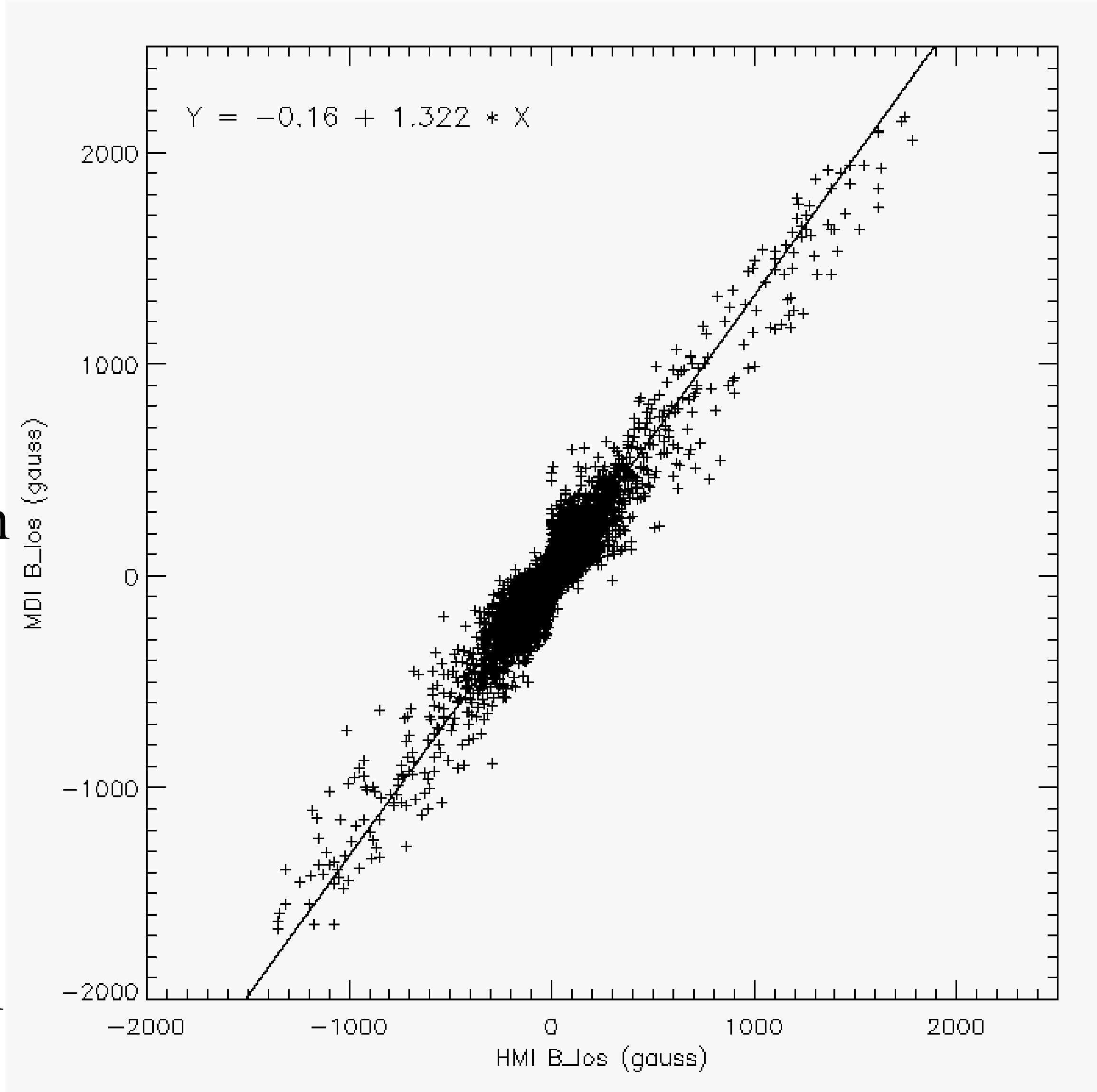
	MDI	HMI
pixels	2”	0.5”
Cadence	96 minutes	45 sec LOS, 90 sec Vector
Latency	Approximately a day	tens of minutes
Magnetograph Type	Line-of-sight	Vector
Operational	1996-Jan 2011 **Now Turned off**	May 2010 to present **Now Operating**

Calibration of HMI B_{LOS} to MDI

Empirical conversion of HMI magnetic field strength to MDI magnetic field strength

Hoeksema and the HMI team has done this work.

Early HMI Magnetic Field Observations Hoeksema et al



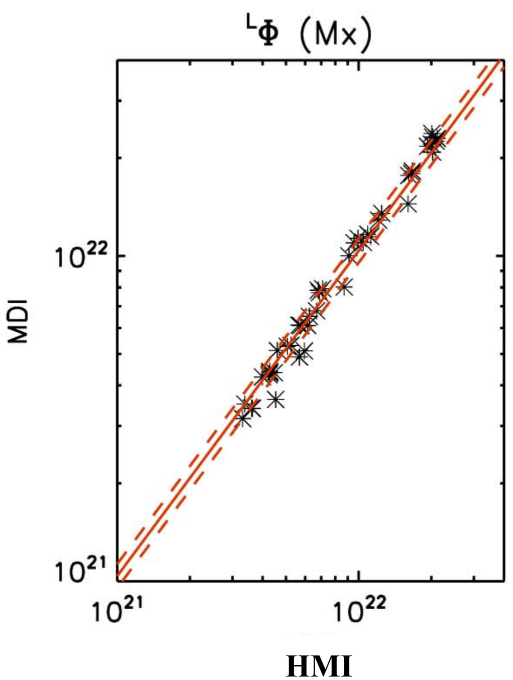
Scaling the HMI Value of $^{L}WL_{SG}$ to MDI

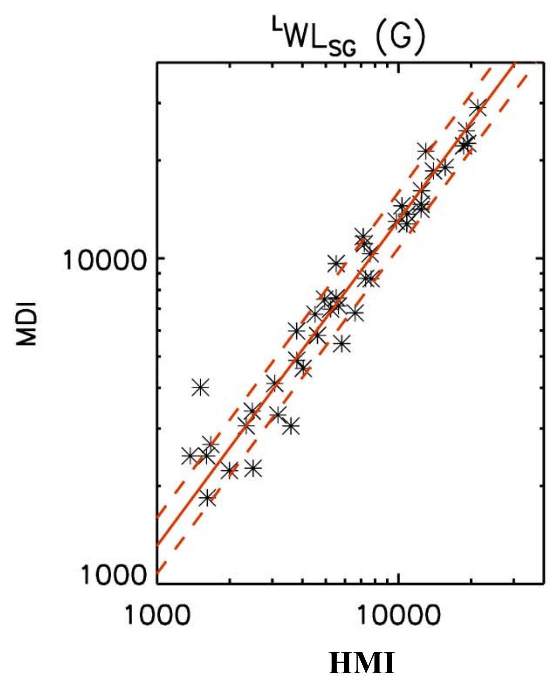
For MDI resolution

- $^{L}WL_{SG}(MDI) = 1.31 * {}^{L}WL_{SG}(HMI)$
- Multiplicative uncertainty is 1.22

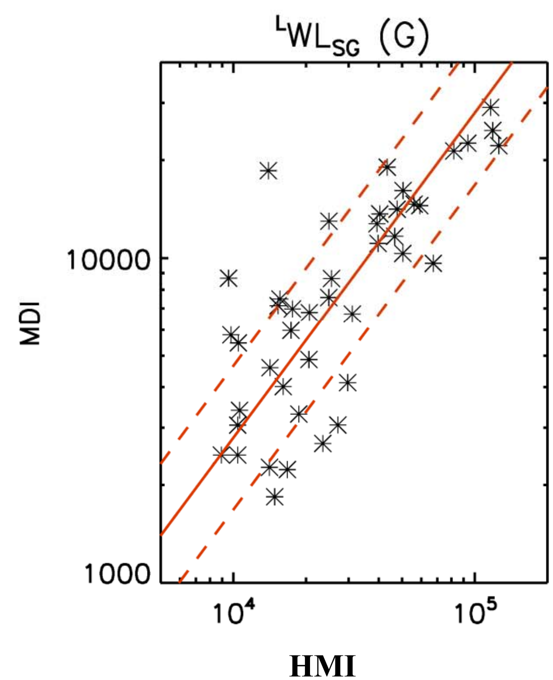
1σ Multiplicative uncertainty in forecast event rate due to for different instruments and spatial resolutions			
Event Type	MDI	**HMI-MDI-res**	HMI-full res
X and M Flares	1.07	**1.48**	2.71
X Flares	1.29	**1.60**	2.86
CMEs	1.10	**1.36**	2.16
Fast CMEs	1.17	**1.41**	2.24
SPEs	1.32	**1.51**	2.33

HMI Smoothed to MDI Resolution





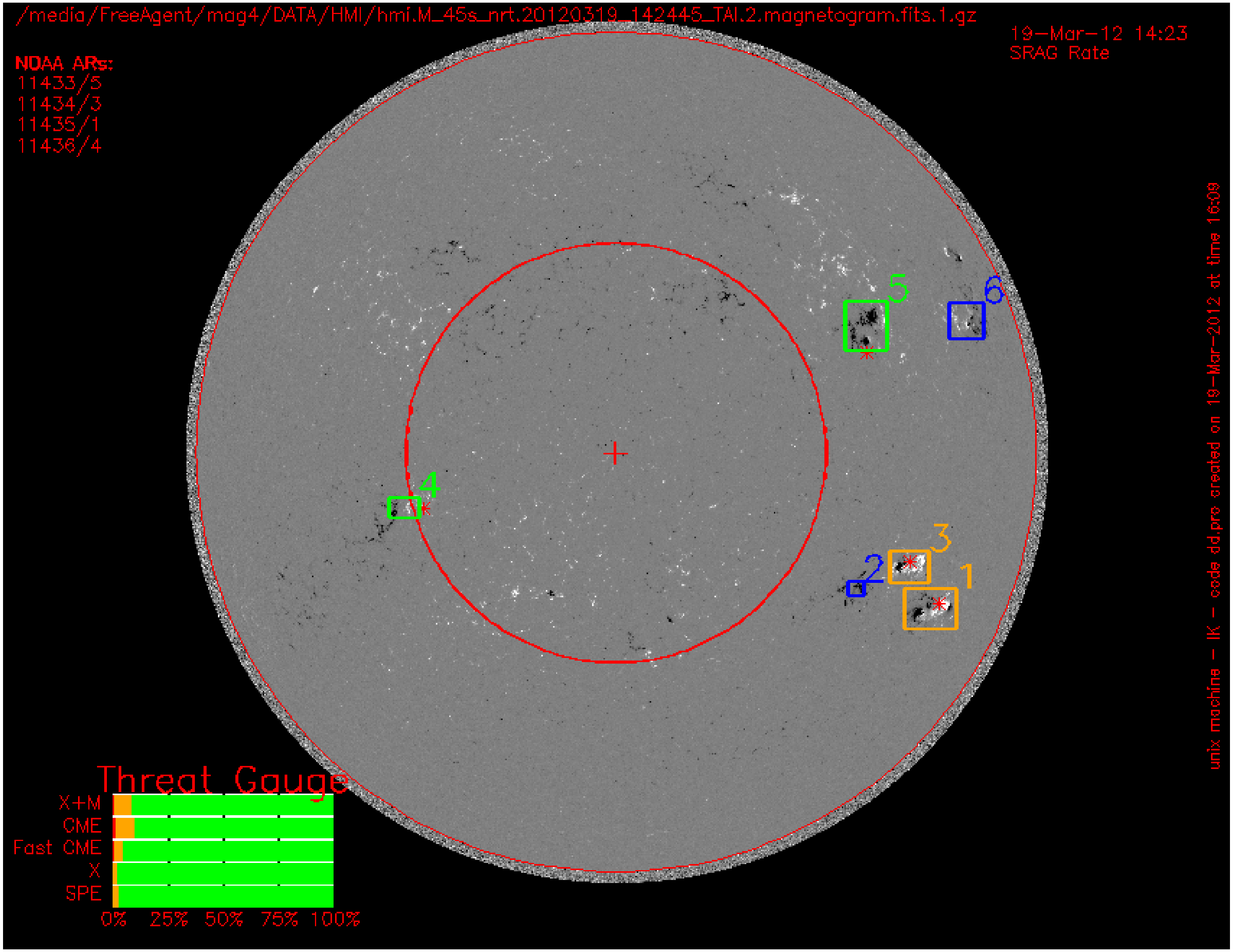
Unsmoothed



Forecasting with GONG using MDI forecast Curves

- For each GONG Telescope have to determine scaling and 1σ noise level of the active-region magnetograms to convert GONG measured $^{L}WL_{SG}$ to MDI $^{L}WL_{SG}$, similar as shown for HMI.
- This allows using the 6 ground-based GONG telescopes to be used as a backup for HMI.
- Due to variable seeing need to determine useful way to determine which observations are of acceptable quality (seeing) and which are unacceptable to improve conversion factors and better estimate conversion uncertainties.

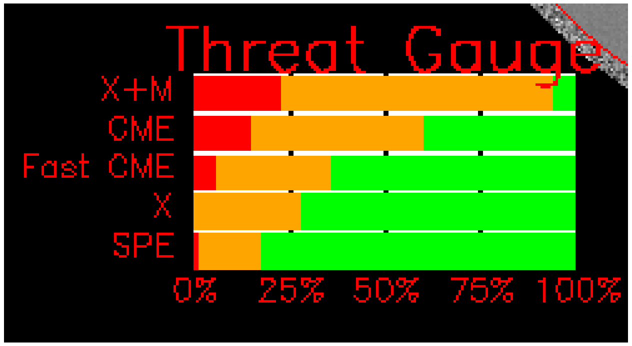
Today Forecast

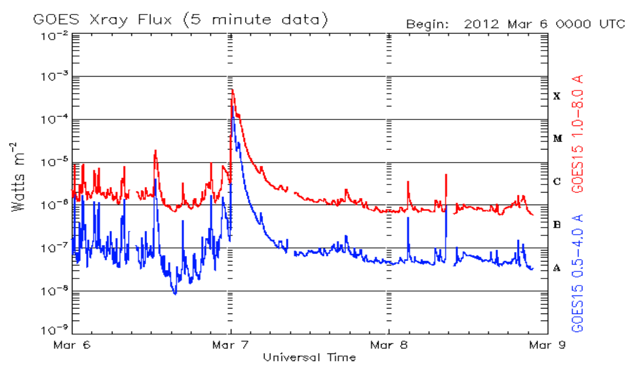


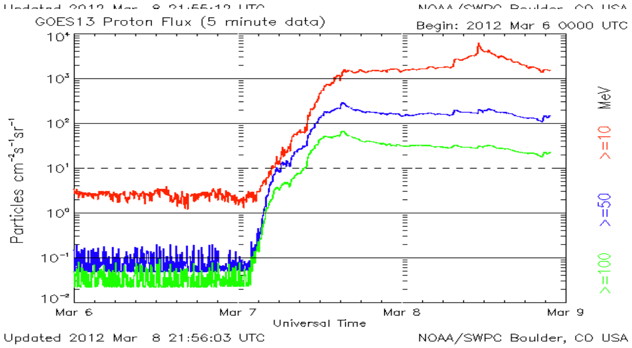
SRAG MAG4 Forecast Tool

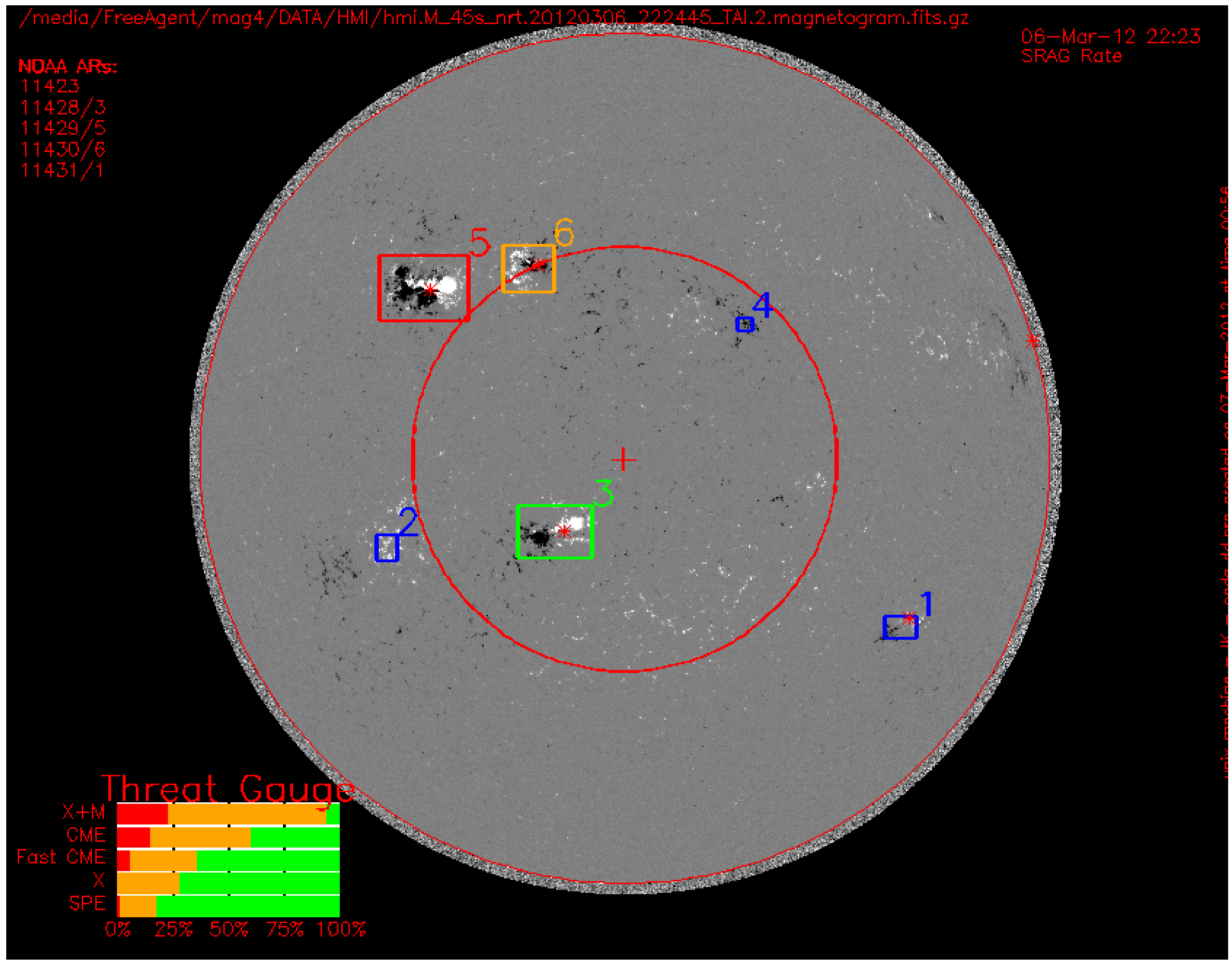
Example Display (March 6, 2012)

- Active region in upper-left corner produced the March 7 Solar Energetic particle event and geo-effective CME



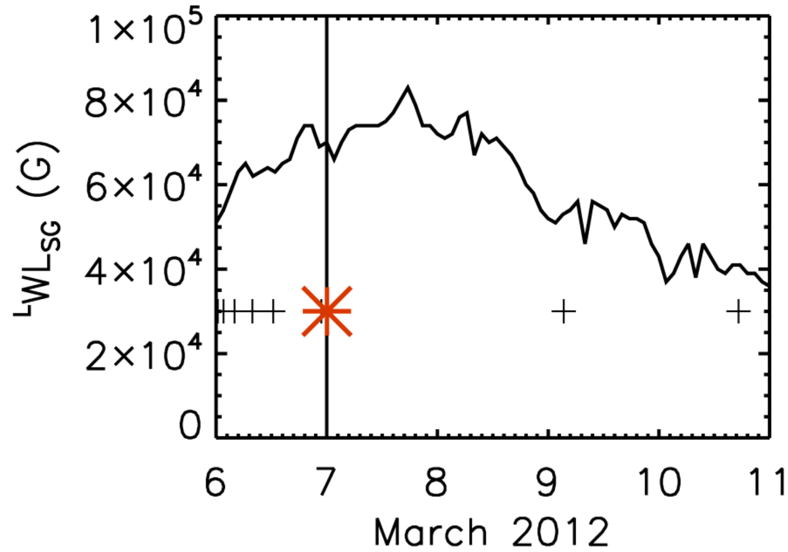




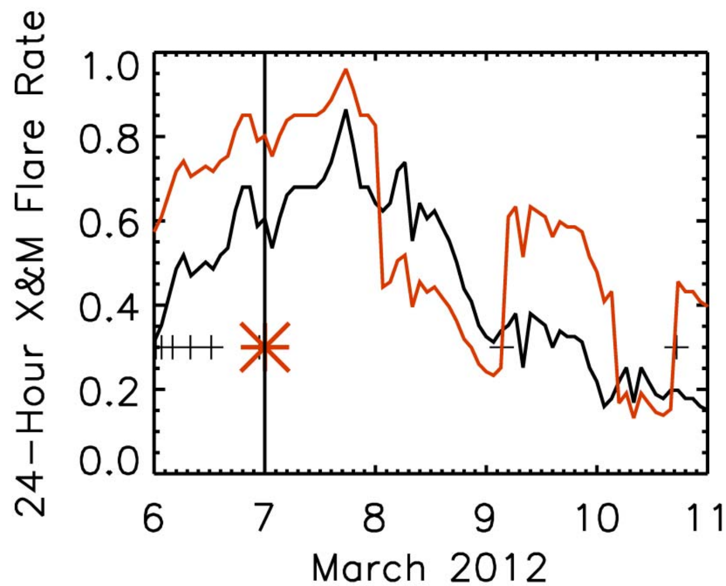


Forecast of March 7 X-Flare/SEP Eruption

- **Top panel:** Free Energy proxy level and evolution.



- **Lower Panel:** Forecast M&X flare rate
  - Forecast using free-energy proxy only
  - Forecast using Free-energy proxy and previous Flare History



- **Flare Symbol**
  - \+ M-class Flares
  - * X-class Flares & SEP

Future Work:

- Incorporate prior flaring into MAG4 Forecasting Tool.
- Find Optimal Forward and Backward Windows.
- Transition to deprojected HMI vector magnetograms
- Improve forecasts from GONG by taking seeing into account
- Find the main physical causes that are the source of Prior-Flaring/Free-Energy Proxy Forecast being superior to Free-Energy Proxy Forecast only.
- Find short term additional indicators that improve short term forecasting (hours not day).
- Improve SEP Event forecasts.
  - Longitudinal dependencies
  - Prior Flares and fast CMEs

Backup
SRAG MAG4 Tool Forecast Before X5 Flare

2012/03/06 22:23

#	AR#	WL!DSG!N (kG)	Lng (deg)	Lat	M&X	CME	FCME	X	SPE	Dist (deg)
					24 Hour Event Rate					
3	11428	8	-21	-17	0.010	0.020	0.007	0.002	0.003	27
5	**11429**	**69**	**-41**	**17**	**0.800**	**0.400**	**0.200**	**0.100**	**0.090**	**44!**
6	11430	14	-25	20	0.040	0.040	0.020	0.006	0.007	32!
Disk Forecast Rates					0.900	0.500	0.200	0.100	0.100	
Multiplicative Uncertainties					2.7x	2.1x	2.3x	3.0x	2.5x	
Disk All-Clear Forecast Probabilities					40.00%	60.00%	80.00%	90.00%	91.00%	
Uncertainties					40.00%	20.00%	10.00%	10.00%	8.00%	