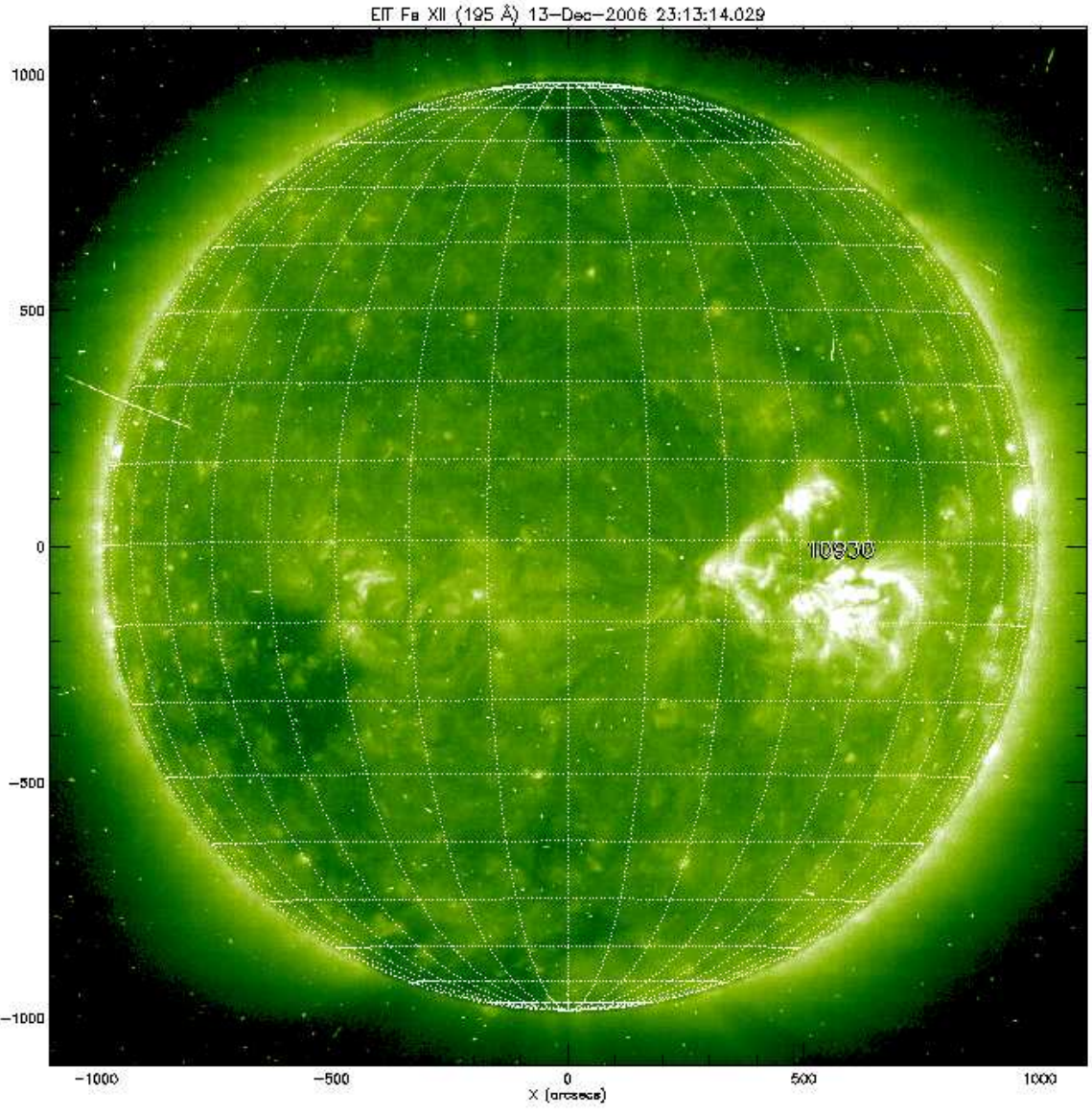
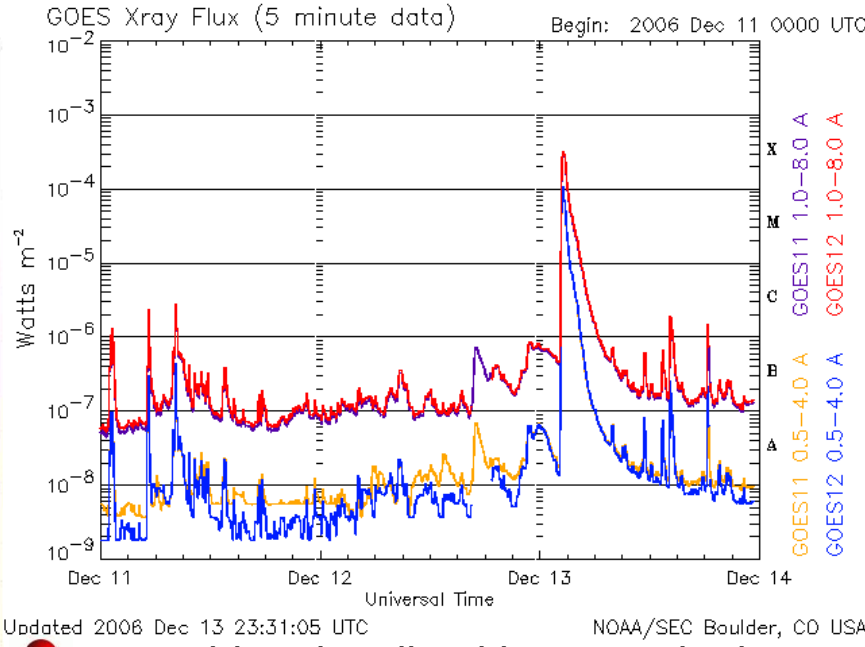
The Physics Behind Flare Prediction and Present Methods for Flare Forecasting

G. Barnes, K.D. Leka

NWRA

What is a Solar Flare?





- A sudden, localized increase in the (soft X-ray) emission from the Sun.
- Large flares are usually accompanied by a Coronal Mass Ejection (CME): rapid outflow of a bubble of plasma and magnetic field.
- Sometimes also accompanied by Solar Energetic Particle (SEP) event: sudden increase in high energy particles (e.g., MeV protons).

Definition of Flare Magnitude

Flare magnitude is typically defined by the peak emission in the 1.0-8.0 Å channel of a *GOES* satellite.

- A-flare: emission between $1.0 \times 10^{-8}\,\mathrm{W\,m^{-2}}$ and $9.9 \times 10^{-8}\,\mathrm{W\,m^{-2}}$.
- B-flare: emission between $1.0 \times 10^{-7}\,\mathrm{W\,m^{-2}}$ and $9.9 \times 10^{-7}\,\mathrm{W\,m^{-2}}$.
- C-flare: emission between $1.0 \times 10^{-6}\,\mathrm{W\,m^{-2}}$ and $9.9 \times 10^{-6}\,\mathrm{W\,m^{-2}}$.
- M-flare: emission between $1.0 \times 10^{-5}\,\mathrm{W\,m^{-2}}$ and $9.9 \times 10^{-5}\,\mathrm{W\,m^{-2}}$.
- X-flare: emission greater than $1.0 \times 10^{-4}\,\mathrm{W\,m^{-2}}$.

For example, an M3.2 flare has a peak emission of $3.2 \times 10^{-5}\,\mathrm{W\,m^{-2}}$.

The Space Weather Prediction Center typically produces forcasts for:

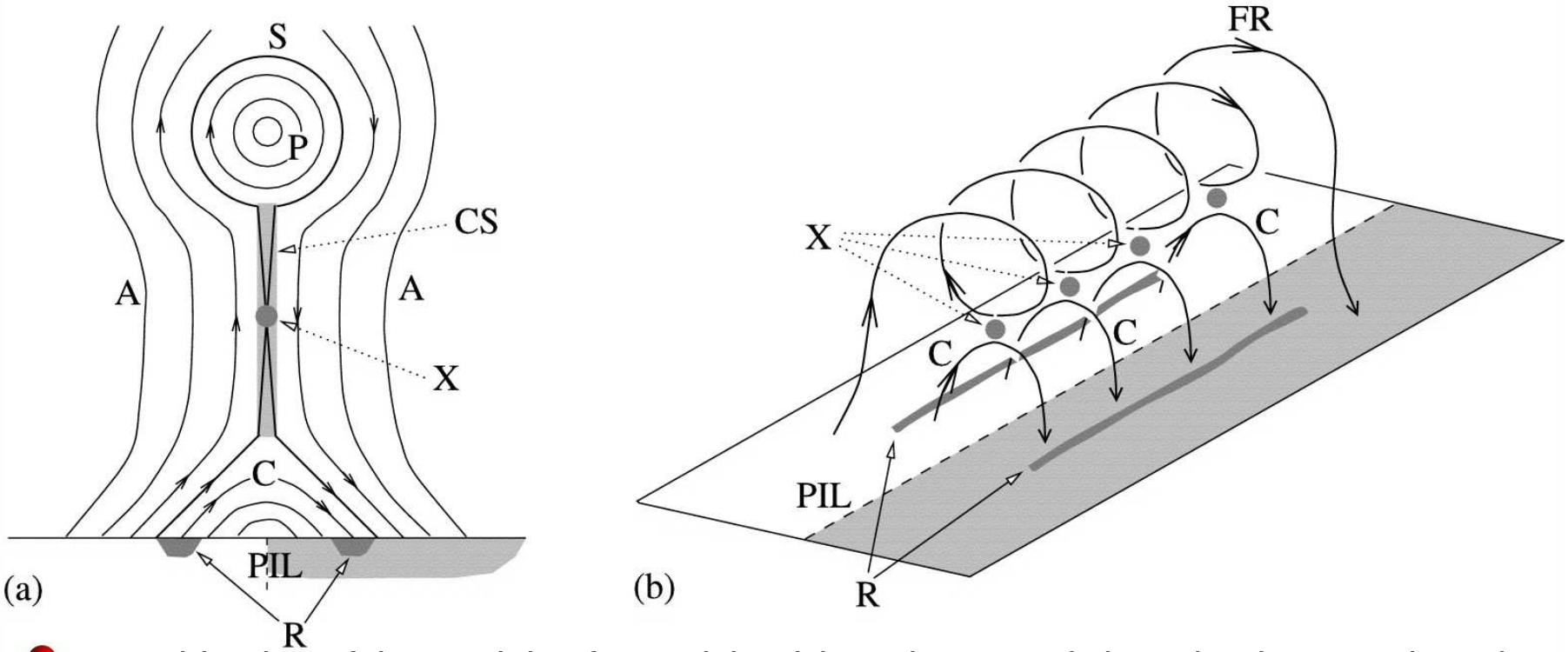
- C-class, M-class and X-class flares
- 24 hr validity with up to 48 hr latency

None of these definitions are based on anything directly related to the physics of flaring - see the discussion topic for this afternoon's working group session.

Overview of the Physics of Flaring

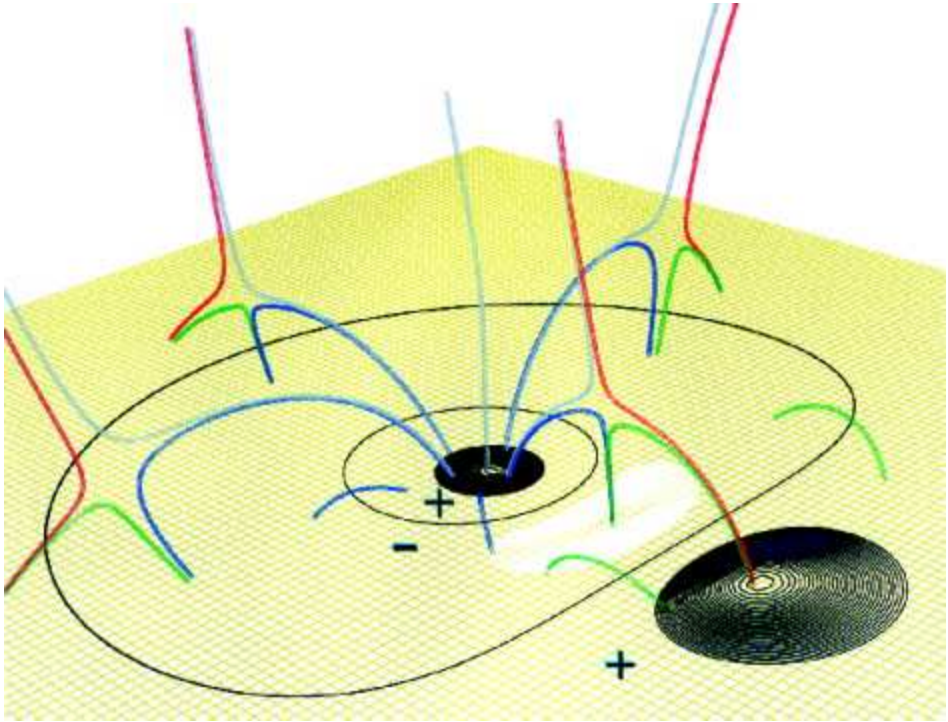
- The energy released by flares is stored in the coronal magnetic field.
  - The footpoints of magnetic field lines are frozen into the plasma at the photosphere (surface of the Sun).
  - Footpoint motion and/or the emergence of new magnetic flux introduce energy into the coronal magnetic field.
  - Most of the time, and in most places in the corona (solar atmosphere), reconnection is slow, so free magnetic energy can build up.
- Magnetic reconnection in the corona is needed to trigger the release of energy (flare).
  - Typically an instability triggers the onset of fast reconnection.
  - The reconnection happens on extremely small spatial scales compared to the scale on which energy is stored.
  - There are multiple (large-scale) models for flares.

CSHKP Flare Model

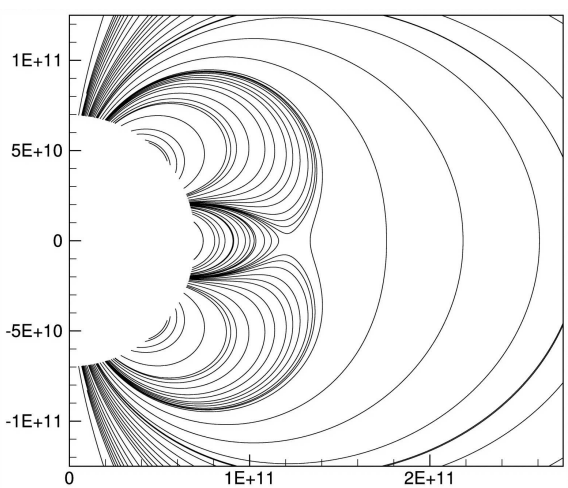


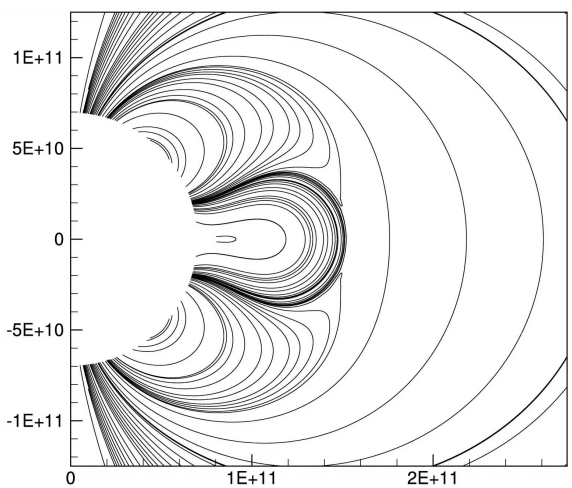
- Combination of the models of Carmichael (1964), Sturrock (1968), Hirayama (1974), and Kopp & Pneuman (1976). Also referred to as “tether-cutting” reconnection.
- Magnetic energy is stored when an arcade of field lines (A) overlying a photospheric polarity inversion line (PIL) is sheared by photospheric motion.
- The shear is released by reconnection at a coronal X-point (X) in a current sheet (CS).
- This creates low-lying closed field lines (C) and a disconnected plasmoid (P), whose ejection forms a coronal mass ejection (CME).
- From Longcope & Beveridge (2007).

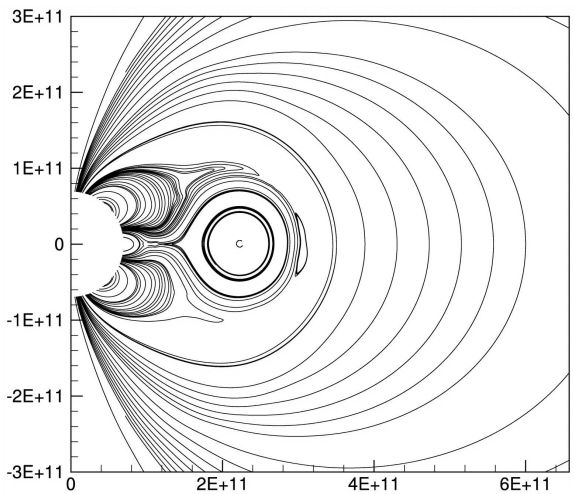
The Breakout CME Model



- Four distinct flux systems with (at least) one coronal magnetic null point.
- Again magnetic energy is stored when an arcade of field lines overlying a PIL is sheared.
- This time, the shear is released by reconnection above the arcade, removing overlying field holding down the arcade.
- Again, a bubble of plasma forms a CME.
- Reconnection may also occur under the plasmoid, but it is the reconnection above that initiates the event.
- From Antiochos (1998), MacNeice et al. (2004).







Overview of Making a Forecast

Four things are typically needed to make a meaningful forecast:

- A way to identify magnetic field concentrations: active regions.
- One or more parameters (descriptors) which characterize the properties of the active region.
- A technique for converting the values of the parameters to an actual forecast.
- A means of quantifying the result.

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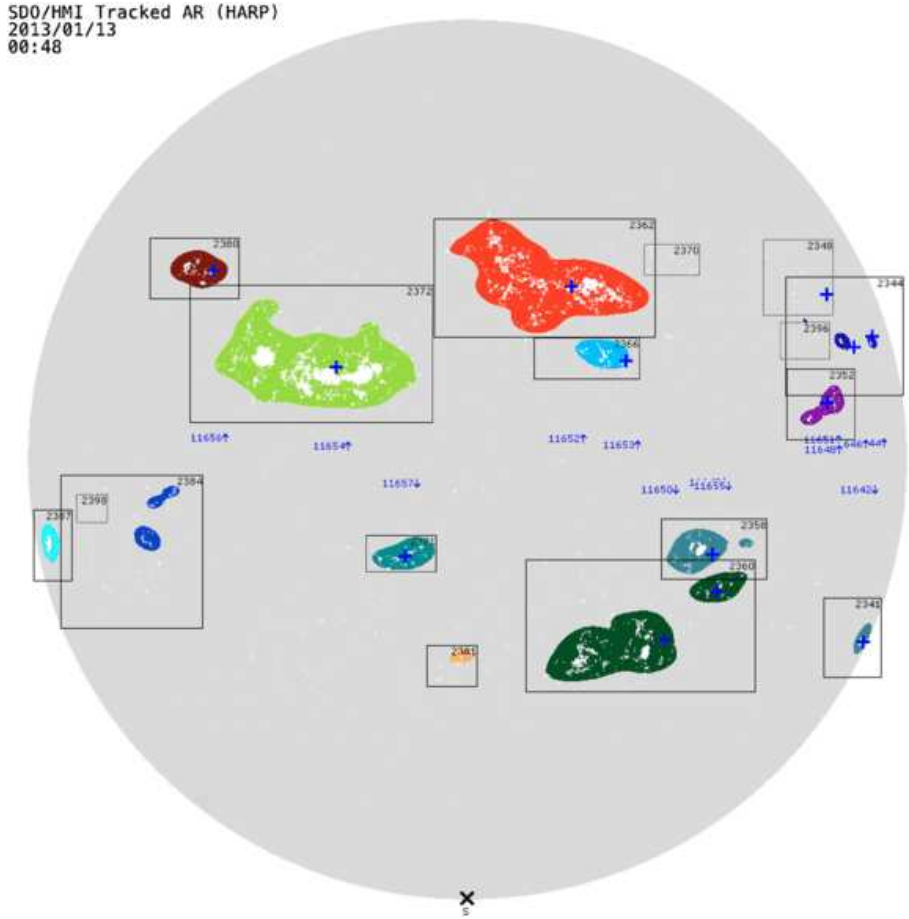

A comparison of HMI Active Region Patches (HARPs) with NOAA Active Regions. From Bobra et al. (2014).

Overview of Making a Forecast

Four things are typically needed to make a meaningful forecast:

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- One or more parameters (descriptors) which characterize the properties of the active region.
  - White light images of the photosphere (McIntosh, SWPC, Colak, Qahwaji)
  - The photospheric magnetic field (Leka, Schrijver, Falconer, Moore, McAteer, Higgins, Liu, Wang)
  - Photospheric flows (Welsch)
  - Coronal connectivity/topology (Georgoulis, Rust, Barnes, Tarr)
  - Subsurface flows (Komm, Hill, Reinard, Braun)
  - Event statistics (Wheatland, Falconer, Moore)

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- One or more parameters (descriptors) which characterize the properties of the active region.
- A technique for converting the values of the parameters to an actual forecast.
  - Discriminant Analysis (Barnes, Leka)
  - Log-log correlation plots (Falconer, Moore)
  - Bayesian methods (Wheatland, Georgoulis)
  - Machine learning (Colak, Qahwaji)
  - Superposed Epoch Analysis (not really a prediction; Reinard, Mason, Hoeksema)

Overview of Making a Forecast

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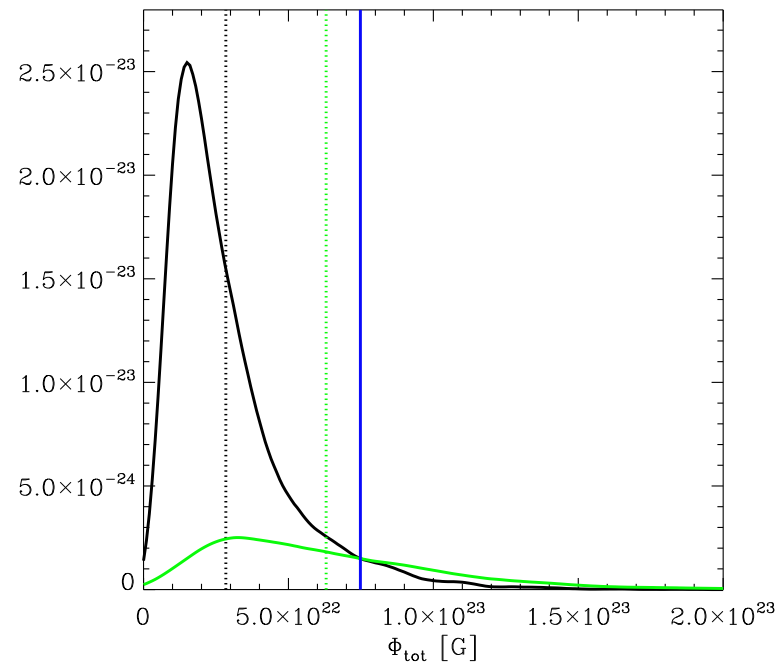
- A way to identify magnetic field concentrations: active regions.
- One or more parameters (descriptors) which characterize the properties of the active region.
- A statistical technique for converting the values of the parameters to an actual forecast.
- A means of quantifying the result.
  - Skill scores
  - Reliability plots

Moment Analysis and DA - K.D. Leka, G. Barnes

- Represent distributions of the observed field and its derivatives by the first four moments of the distribution. For example, for the field itself, consider not just the unsigned total flux, but also the moments of the field.
  - Can be sensitive to small areas of complexity within the field of view
- Use parametric and nonparametric Discriminant Analysis (DA) to make a prediction.
  - Given accurate representation of the probability density, will maximize the overall accuracy of predictions
  - Can consider multiple variables simultaneously
- See Leka & Barnes, 2007, ApJ, 656, 1173



Photospheric Magnetic Field Parameters

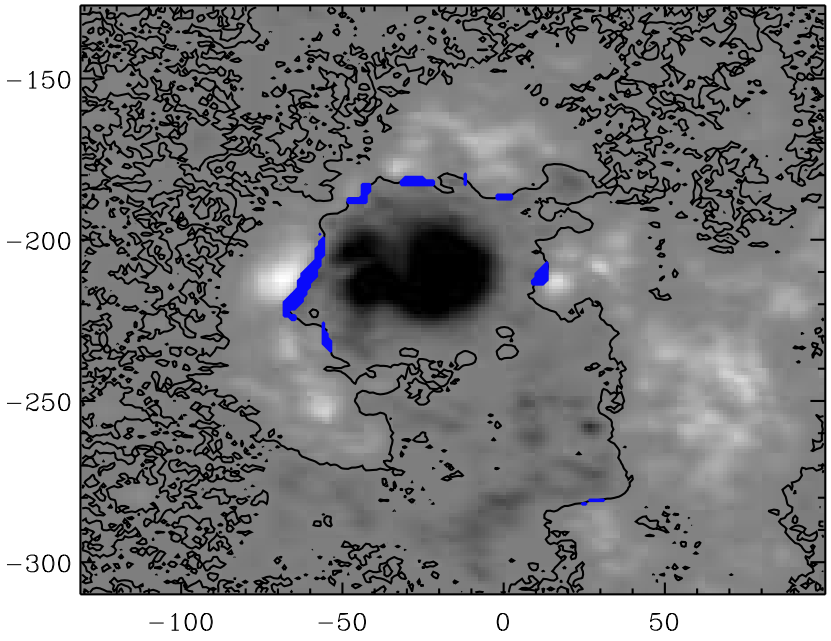
Description	Formula	Variable
Distribution of Magnetic Fields		
moments of vertical magnetic field	$B_z = \boldsymbol{B}\cdot\boldsymbol{e}_z$	$\mathcal{M}(B_z)$
total unsigned flux	$\Phi_{\rm tot} = \sum \lvert B_z\rvert\, dA$	$\Phi_{\rm tot}$
absolute value of the net flux	$\lvert\Phi_{\rm net}\rvert = \lvert\sum B_z\, dA\rvert$	$\lvert\Phi_{\rm net}\rvert$
moments of horizontal magnetic field	$B_h = \sqrt{B_x^2 + B_y^2}$	$\mathcal{M}(B_h)$
moments of inclination angle	$\gamma = \tan^{-1}(B_z/B_h)$	$\mathcal{M}(\gamma)$
Distribution of Horizontal Gradients of the Fields		
moments of total field gradients	$\lvert\boldsymbol{\nabla}_h B\rvert$	$\mathcal{M}(\lvert\boldsymbol{\nabla}_h B\rvert)$
moments of vertical field gradients	$\lvert\boldsymbol{\nabla}_h B_z\rvert$	$\mathcal{M}(\lvert\boldsymbol{\nabla}_h B_z\rvert)$
moments of horizontal field gradients	$\lvert\boldsymbol{\nabla}_h B_h\rvert$	$\mathcal{M}(\lvert\boldsymbol{\nabla}_h B_h\rvert)$
Distribution of Vertical Current Density		
moments of vertical current density	$J_z = C(\frac{\partial B_y}{\partial x} - \frac{\partial B_x}{\partial y})$	$\mathcal{M}(J_z)$
total unsigned vertical current	$I_{\rm tot} = \sum \lvert J_z\rvert\, dA$	$I_{\rm tot}$
absolute value of the net vertical current	$\lvert I_{\rm net}\rvert = \lvert\sum J_z\, dA\rvert$	$\lvert I_{\rm net}\rvert$
Distribution of Force-free Parameter		
moments of force-free parameter	$\alpha = CJ_z/B_z$	$\mathcal{M}(\alpha)$
best fit force-free parameter	$\boldsymbol{B} = \alpha_{\rm ff}\boldsymbol{\nabla}\times\boldsymbol{B}$	$\lvert\alpha_{\rm ff}\rvert$

Photospheric Magnetic Field Parameters

Description	Formula	Variable
Distribution of Current Helicity		
moments of current helicity	$h_c = CB_z(\partial B_y/\partial x - \partial B_x/\partial y)$	$\mathcal{M}(h_c)$
total unsigned current helicity	$H_c^{\rm tot} = \sum \lvert h_c \rvert \, dA$	$H_c^{\rm tot}$
absolute value of net current helicity	$\lvert H_c^{\rm net} \rvert = \lvert \sum h_c \, dA \rvert$	$\lvert H_c^{\rm net} \rvert$
Distribution of Shear Angles		
moments of 3-D shear angle	$\Psi = \cos^{-1}(\boldsymbol{B}^p \cdot \boldsymbol{B}^o / B^p B^o)$	$\mathcal{M}(\Psi)$
area with shear $> \Psi_0,\ \Psi_0 = 45°,\ 80°$	$A(\Psi > \Psi_0) = \sum_{\Psi > \Psi_0} dA$	$A(\Psi > \Psi_0)$
moments of neutral-line shear angle	$\Psi_{\rm NL} = \cos^{-1}(\frac{\boldsymbol{B}^p_{\rm NL} \cdot \boldsymbol{B}^o_{\rm NL}}{B^p_{\rm NL} B^o_{\rm NL}})$	$\mathcal{M}(\Psi_{\rm NL})$
length of neutral line with shear $> \Psi_0$	$L(\Psi_{\rm NL} > \Psi_0) = \sum_{\Psi_{\rm NL} > \Psi_0} dL$	$L(\Psi_{\rm NL} > \Psi_0)$
moments of horizontal shear angle	$\psi = \cos^{-1}(\boldsymbol{B}^p_h \cdot \boldsymbol{B}^o_h / B^p_h B^o_h)$	$\mathcal{M}(\psi)$
area with horizontal shear $> \psi_0$	$A(\psi > \psi_0) = \sum_{\psi > \psi_0} dA$	$A(\psi > \psi_0)$
Distribution of Excess Magnetic Energy		
moments of excess magnetic energy	$\rho_e = (\boldsymbol{B}^p - \boldsymbol{B}^o)^2 / 8\pi$	$\mathcal{M}(\rho_e)$
total excess magnetic energy	$E_e = \sum \rho_e \, dA$	E_e

Flux Close to High-gradient PIL - K. Schrijver

Proxy for the emergence of current-carrying flux

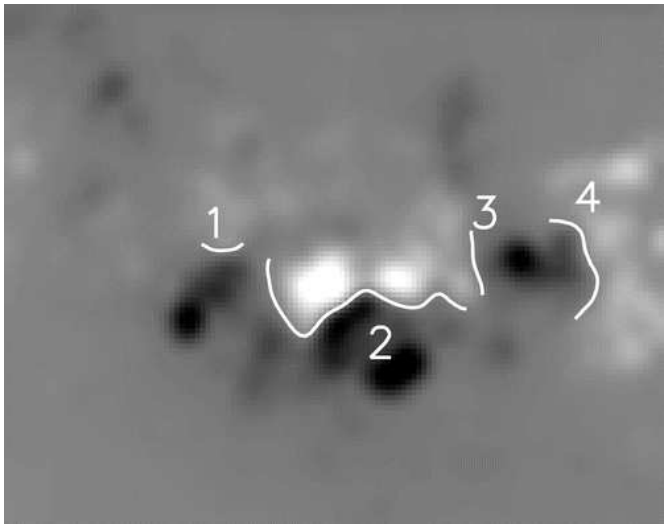


- Dilate bitmaps of the magnetograms where the positive or negative flux density exceeds a threshold
- Define high-gradient polarity-separation lines as areas where the bitmaps overlap
- Convolve the bitmap of high-gradient polarity-separation lines with a Gaussian to obtain a weighting map
- Obtain the parameter R by multiplying the weighting map by the unsigned line-of-sight field
- See Schrijver, ApJ, 2007, 655, L117

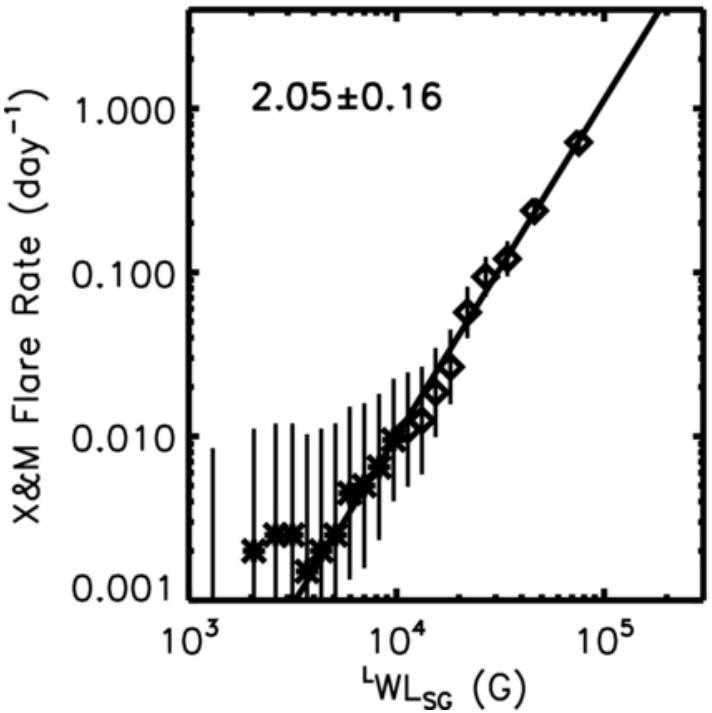
Total Nonpotentiality of Active Regions - D. Falconer

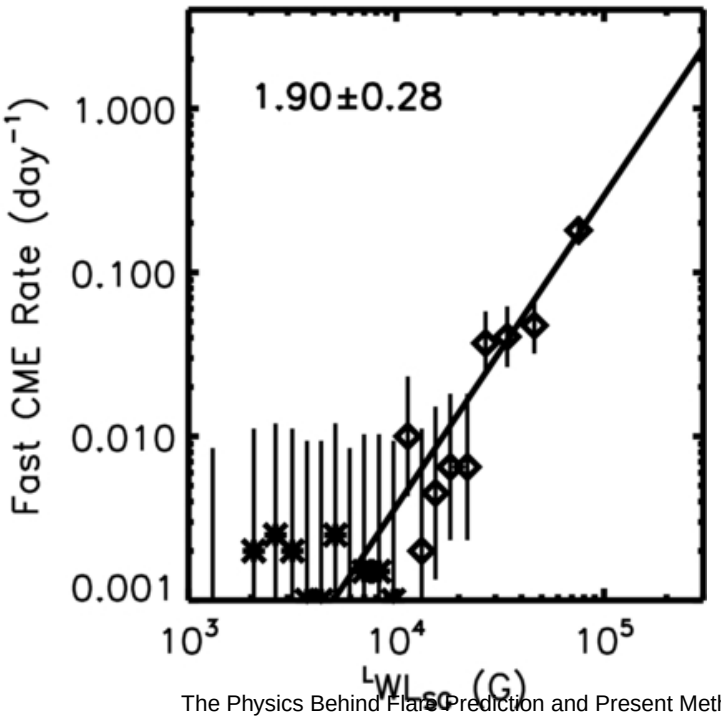
- Calculate a measure of the free magnetic energy based on the presence of strong gradient neutral lines

$$WL_{SG2} = \int_{NL} (\nabla B_{\mathrm{LOS}})^2 \, dl$$



- Use least squares power-law fit to predict rate of events
- See Falconer et al. (2011)

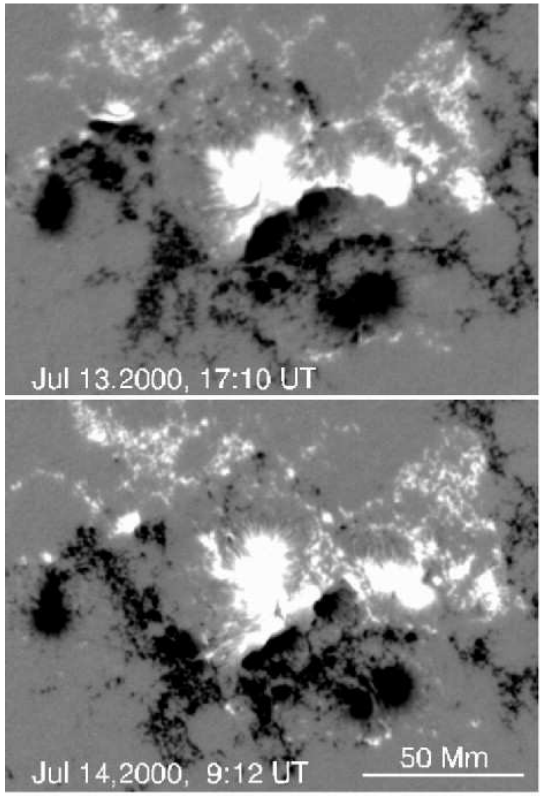


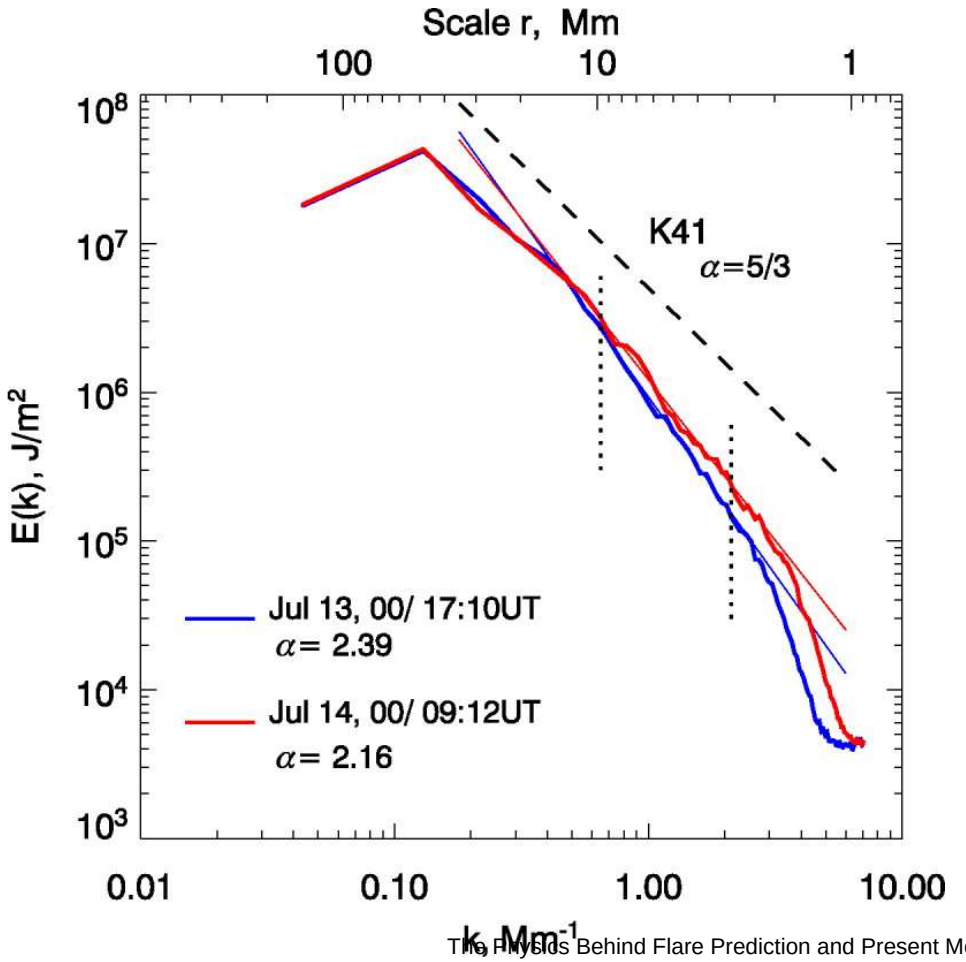


Active Region Complexity - R.T.J. McAteer, V. Abramenko

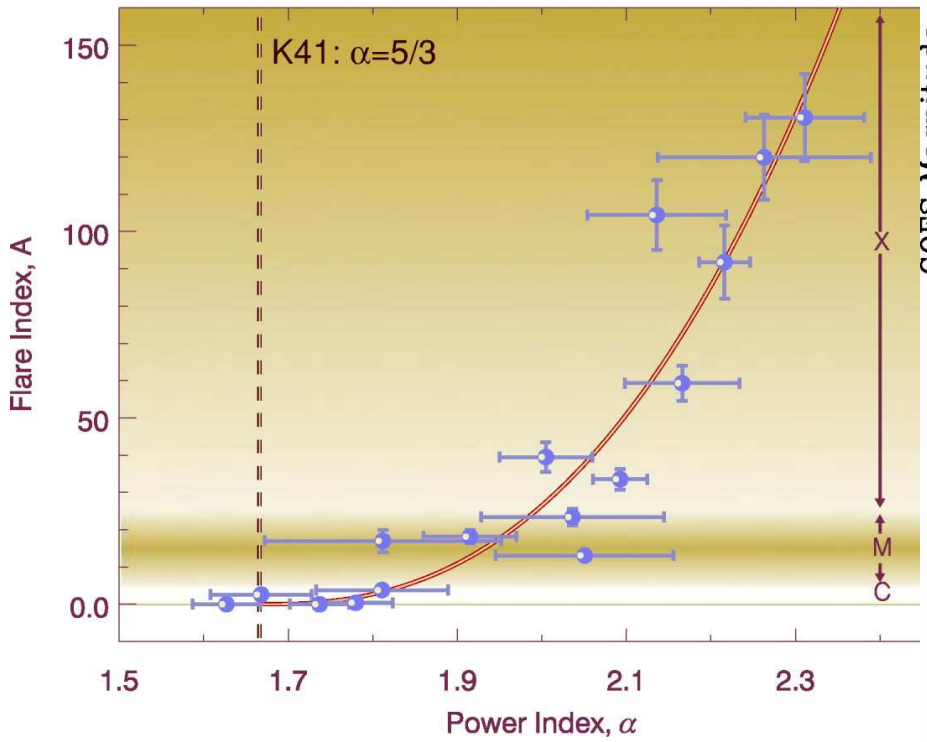
Measures of the “complexity” of an active region:

- Magnetic power spectrum
- Fractal dimension of active region
  - Can be extended to calculation of multifractals



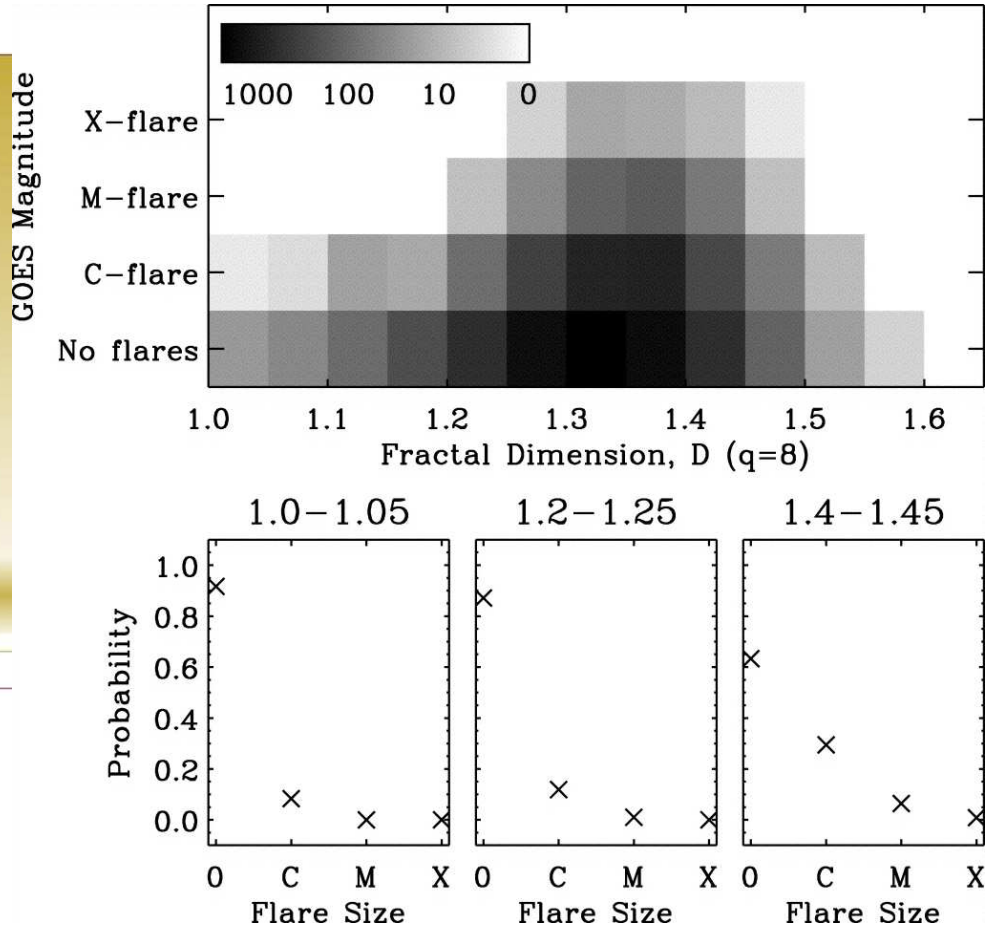


Active Region Complexity - R.T.J. McAteer, V. Abramenko



Results for the power law spectrum for 16 active regions.

- Higher power law index does correspond to an increased flare index.



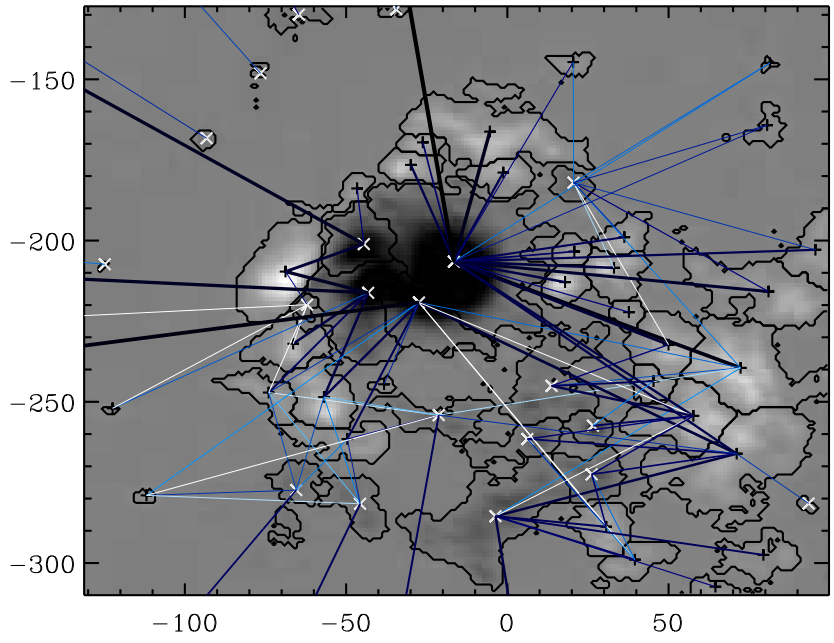
Results of a the fractal dimension for a large sample of active regions.

- Large flares are more strongly associated with higher fractal dimension, but many regions that did not produce a large flare also have high fractal dimension.

Magnetic Charge Topology - G. Barnes, K.D. Leka

Apply a Magnetic Charge Topology (MCT) model to extrapolate the coronal magnetic field

- Partition the photospheric field into magnetic field concentrations
- Represent each partition by a single point source, located at the flux-weighted center of the partition, with magnitude equal to the flux in the partition.
- Calculate the location of magnetic null points, places where the magnetic field vanishes.
- Calculate the magnetic connectivity by tracing field lines



- Consider moments and totals of parameters derived from the properties of the extrapolated coronal magnetic field
- Use parametric and nonparametric Discriminant Analysis (DA) to make a prediction
- See Barnes & Leka, 2006, ApJ, 646, 1303

The Effective Connected Magnetic Field - M. Georgoulis

- Partition the photospheric magnetic field into flux concentrations.
- Determine a connectivity matrix, ψ_{ij}, using simulated annealing to minimize

$$F = \sum_{i=1}^{N_+} \sum_{j=1}^{N_-} \left(\frac{|\boldsymbol{x}_i - \boldsymbol{x}_j|}{|\boldsymbol{x}_i| + |\boldsymbol{x}_j|} + \frac{|\Phi'_i + \Phi'_j|}{|\Phi'_i| + |\Phi'_j|} \right)$$

- Define the effective connected magnetic field as

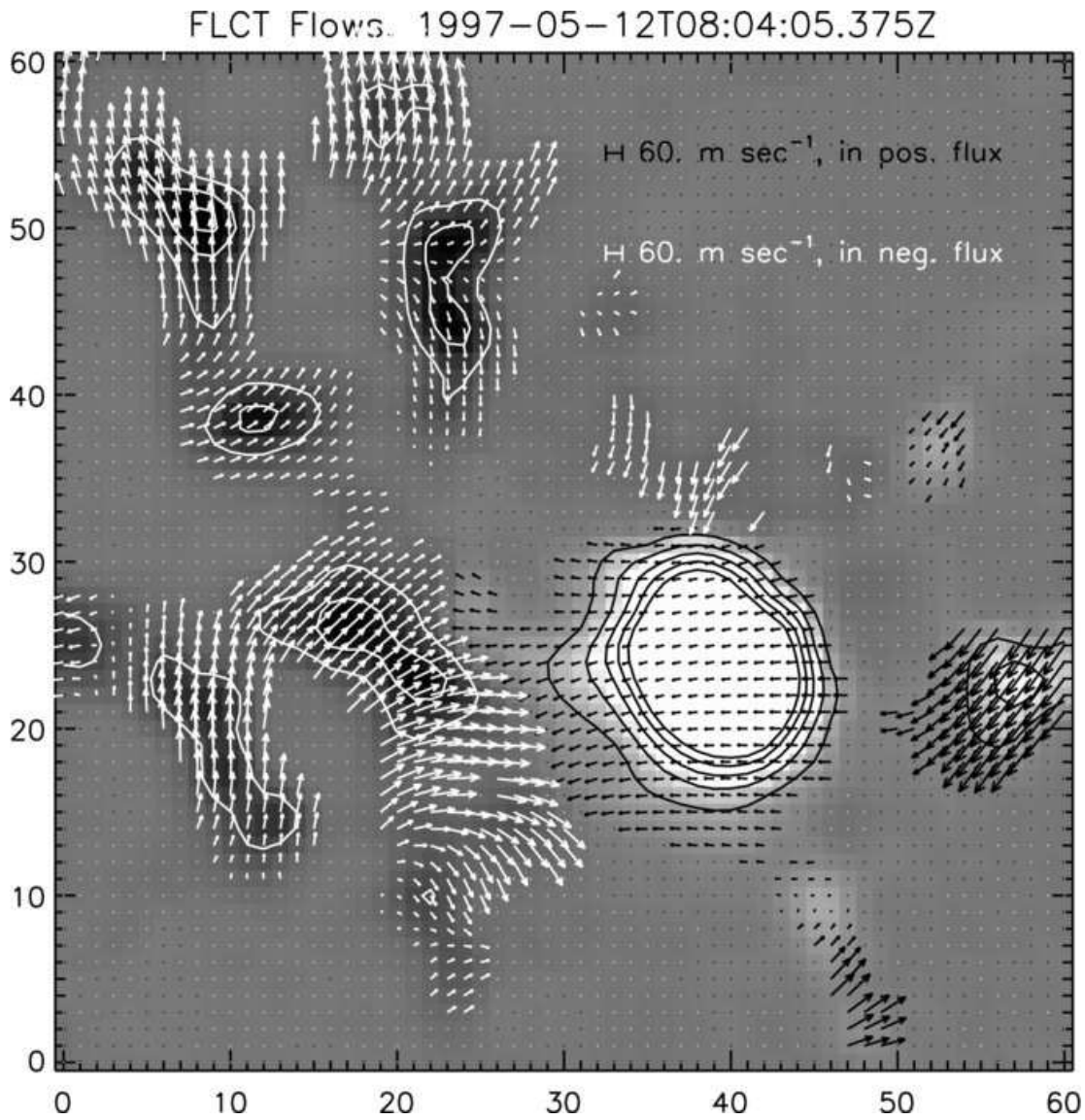
$$B_{\rm eff} = \frac{1}{2} \sum_{i \neq j} \frac{\psi_{ij}}{|\boldsymbol{x}_i - \boldsymbol{x}_j|^2}$$

- Construct the probability of an event from Bayes's Theorem:

$$P_{\rm flare} = \frac{N_{\rm flare} + 1}{N_{\rm total} + 2}$$

  where $N_{\rm flare}$ is the number of event-producing ARs with $B_{\rm eff}$ greater than a threshold, and $N_{\rm total}$ is the total number of ARs with $B_{\rm eff}$ greater than a threshold.
- See Georgoulis & Rust, ApJ, 2007, 661, L109

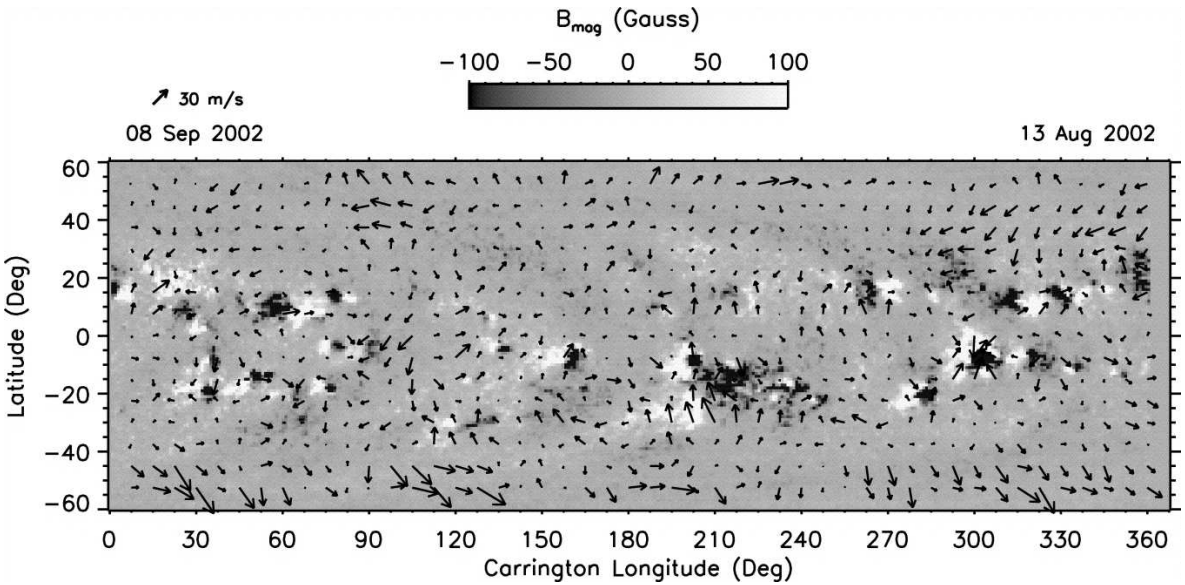
Photospheric Flows - B. Welsch, G. Fisher

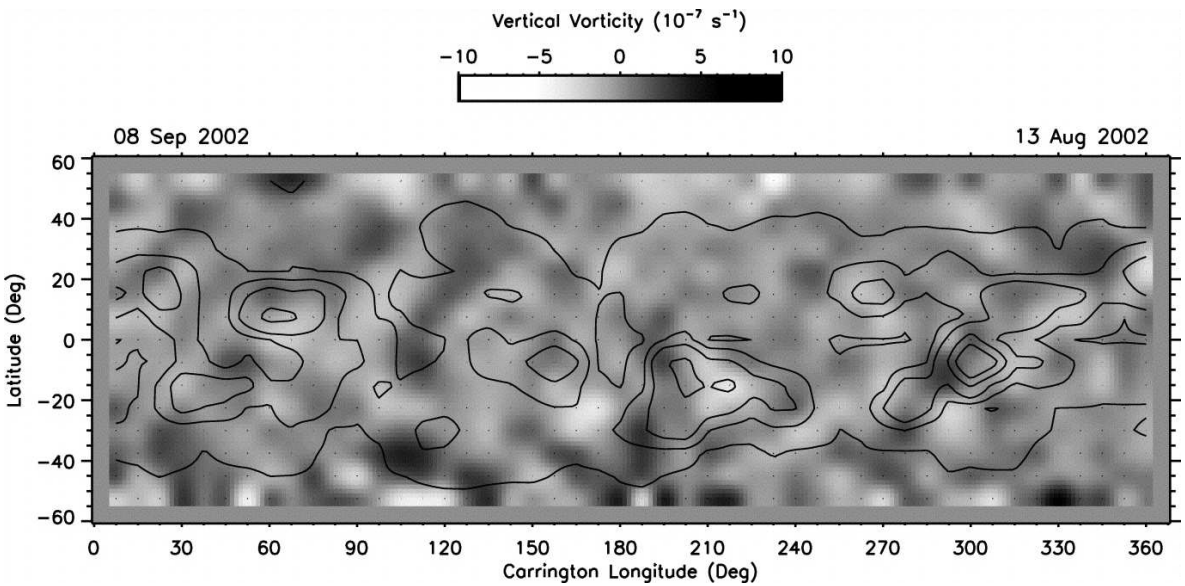


- Determine photospheric flows from local correlation tracking.
- Compute energy flux, helicity flux into the corona.
- Also use moment analysis on the flow, vorticity, converging flows, diverging flows, etc.
- From Welsch et al. (2009).

Helioseismic Parameters - R. Komm, A. Reinard

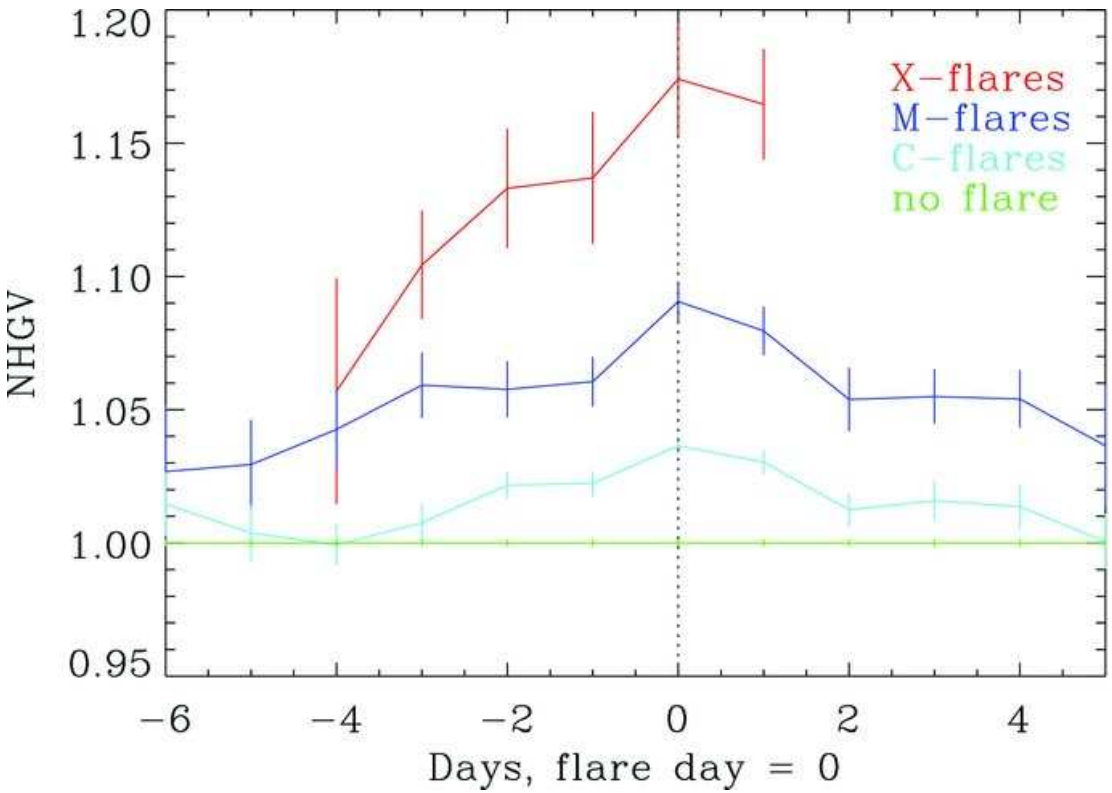
- Use ring diagrams to invert for subsurface flows.
- Compute the vorticity ($\boldsymbol{\omega} = \boldsymbol{\nabla} \times \boldsymbol{v}$), kinetic helicity density ($h = \boldsymbol{\omega} \cdot \boldsymbol{v}$) of the flow at a variety of depths (~ 1 to 15 Mm).
- Combine helicity density at all depths into Normalized Helicity Gradient Variance (NHGV), which measures the change in helicity with depth.





Helioseismic Predictions - A. Reinard

- Results for Superposed Epoch Analysis Based on NHGV.
- See Reinard et al. (2010).



Event Statistics - M. Wheatland

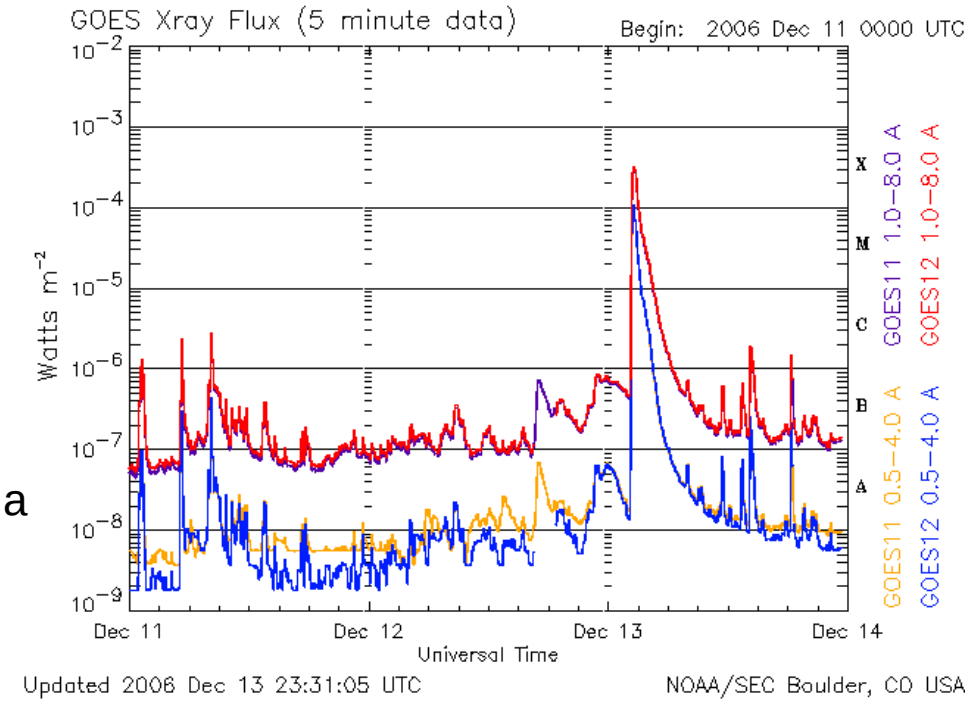
Use only event statistics to make a prediction

- Completely different data source
- Flares obey a power-law frequency-size distribution

$$N(S) = \lambda_1(\gamma - 1)S_1^{\gamma-1}S^{-\gamma}$$

- Occurrence in time may be modelled as a Poisson process

$$P(\tau) = \lambda \exp(-\lambda\tau)$$



- Use distribution of small events to estimate the parameters and make predictions about the large(r) events
- See Wheatland, 2004, ApJ, 609, 1134

Quantifying Forecast Performance: Contingency Tables

Definitions

- A: Hits
- B: False Alarms
- C: Missed Events
- D: Correct Nulls
- N=A+B+C+D: sample size

	observed	
predicted	event	no event
event	A	B
no event	C	D

Simple Quality Measures

- Accuracy (Hit Rate): (A+D)/N
- Critical Success Index: A/(A+B+C)
- Probability of Detection: A/(A+C)
- False Alarm Rate: B/(A+B)

- For rare events (A+C$<<$N), high accuracy is easy: always predict that no event will happen.
- This is the situation for large solar flares, certainly X-class, and generally M-class also.
- If someone tells your his/her method is successful 90% of the time, your first question should be: what was the event rate?
- A measure of performance that takes into account the event rate is important!

General Skill Scores

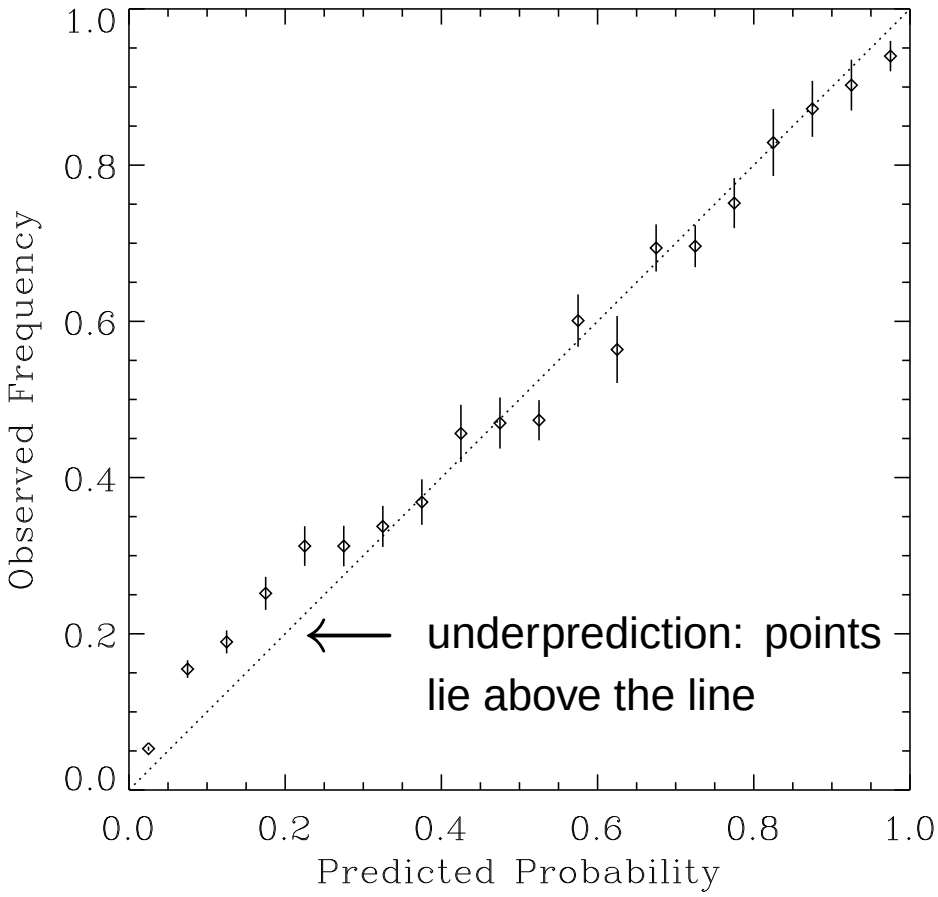
- Skill: relative performance with respect to a reference forecast
- Skill score calculation:
  - Let M be an accuracy metric of the forecast system under study
  - Let M_{ref} be accuracy of the reference forecasts
  - Let M_{perfect} be the accuracy of perfect forecasts
  - Then the skill score, SS, is:

$$SS = \frac{M - M_{\mathrm{ref}}}{M_{\mathrm{perfect}} - M_{\mathrm{ref}}}$$

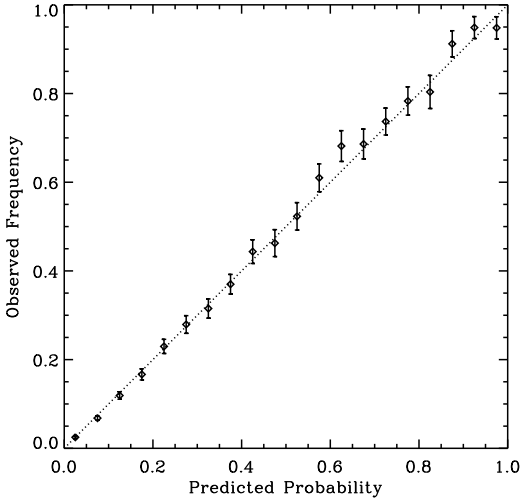
- If the forecasts are perfect, $SS = 1$
- If the forecasts are no better than the reference, $SS = 0$
- If the forecasts are worse than the reference, $SS < 0$
- For “RMS” forecasts, $M_{\mathrm{perfect}} = 0$; $SS = 1 - M/M_{\mathrm{ref}}$
- For “Proportion Correct”, however, $M_{\mathrm{perfect}} = 1$; $SS = (M - M_{\mathrm{ref}})/(1 - M_{\mathrm{ref}})$

Reliability Plots

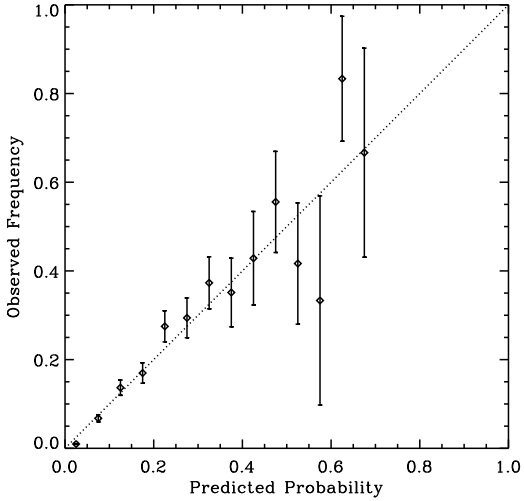
- Select predicted probability intervals and determine the frequency of observed events within each interval
- Plot the observed frequency versus the predicted probability
  - Error bars are estimated based on the number of points in each bin
- Predictions with perfect reliability lie along the line with observed frequency equal to predicted probability
  - Points lying above the line indicate underprediction
  - Points lying below the line indicate overprediction
- Perfect reliability is not enough to guarantee perfect forecasts



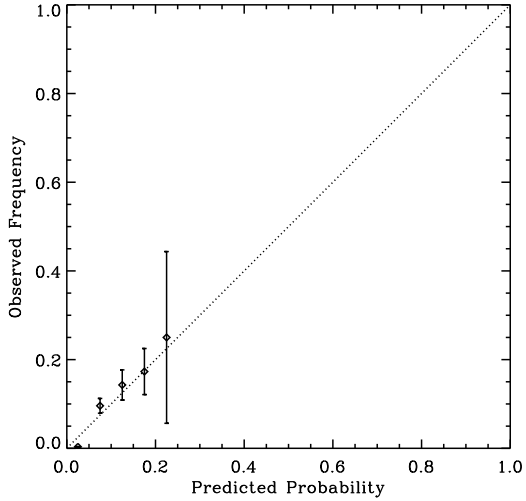
Sample Results



C1.0, 24 hr



M1.0, 12 hr



M5.0, 12 hr

	observed	
predicted	event	no event
event	1128	453
no event	1481	9903

Heidke SS: 0.46

Brier SS: 0.33

	observed	
predicted	event	no event
event	9	7
no event	391	12558

Heidke SS: 0.04

Brier SS: 0.15

	observed	
predicted	event	no event
event	0	0
no event	93	12872

Heidke SS: 0.00

Brier SS: 0.06

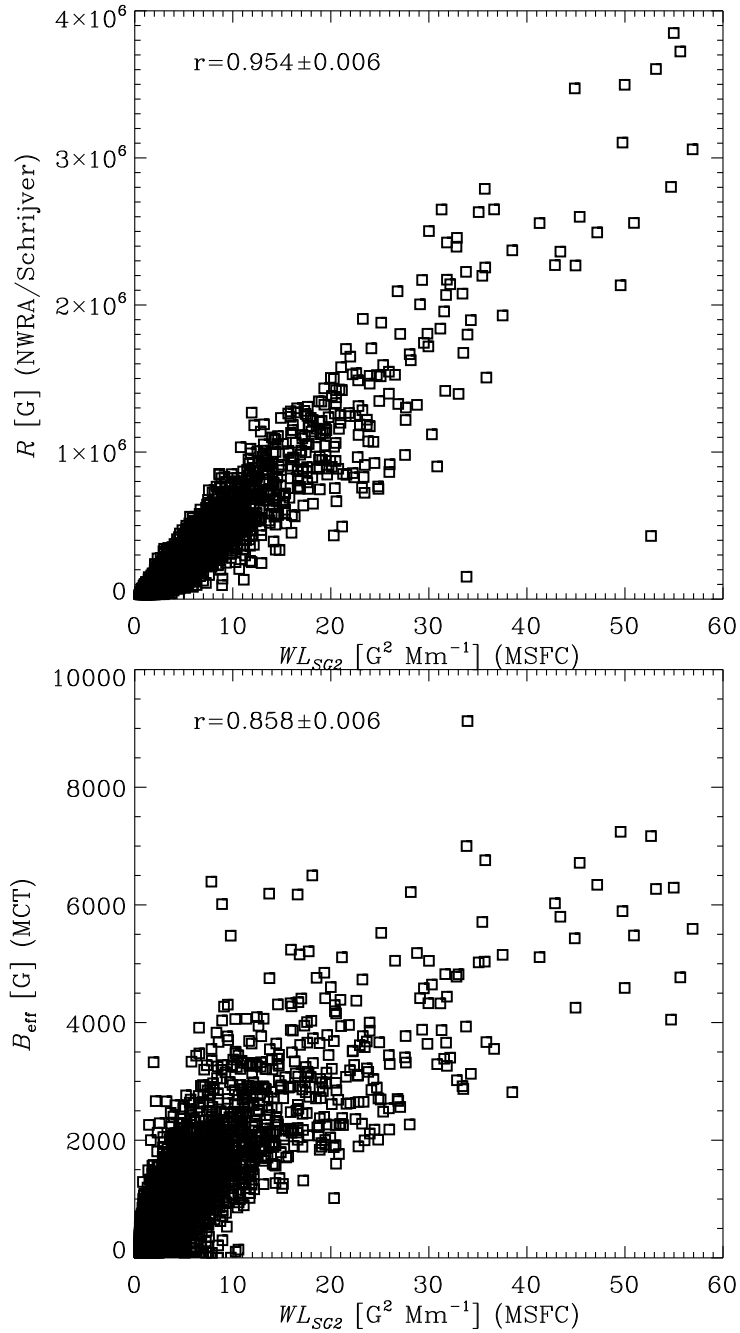
Skill of forecasts typically decreases with increasing event size. This is true for most methods.

Correlations

Parameters proposed by different researchers are often strongly correlated. For example, the parameter R proposed by Schrijver and the parameter WL_{SG2} proposed by Falconer are both measures of the strong gradient polarity inversion lines. The methods by which they are calculated are quite different, but the linear correlation coefficient between the two is $r = 0.95$.

Even less obviously related parameters are also correlated. For example, the linear correlation coefficients between the same WL_{SG2} parameter and a measure of the coronal connectivity, B_{eff} is $r = 0.86$.

There is limited independent information available.

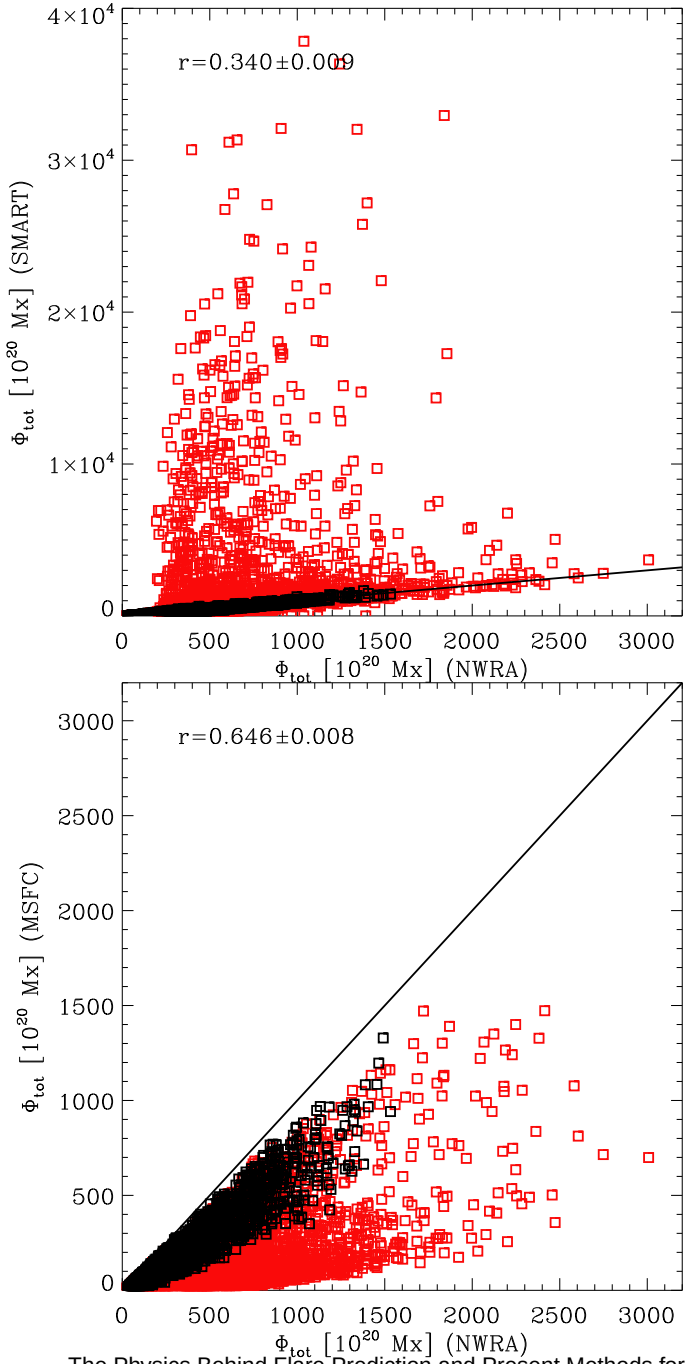


Implementation Matters

Multiple research compute the "same" parameter, but the results can be quite different, even for as simple a parameter as the total unsigned magnetic flux, $\Phi = \int |B_n|\, dA$.

Some of this is a result of how projection effects are handled: black points are close to disk center, red points are mostly not. However, these is still significant scatter between methods even close to disk center.

How a parameter is computed can be as significant as which parameter is computed.



Summary of Photospheric Predictions

- Many, many parameters and parameter combinations have been tried.
- Particularly when only the line of sight magnetic field is available, many of them are correlated to some degree: limited independent information.
- None works substantially better than all the others, and none are close to being perfect forecasts.
  - To make a meaningful comparison of two methods, it is essential to use the same definition of event on the same time interval.
- Many of these are “physics inspired” or estimate a physical quantity (e.g., free energy), but none are based on an actual physical model of a flare.
  - My personal interpretation is that they are basically all addressing the question of how much energy is available to be released and not what triggers the fast reconnection needed to release the energy.