Forecasting of Solar Flares From Vector Magnetogram Data

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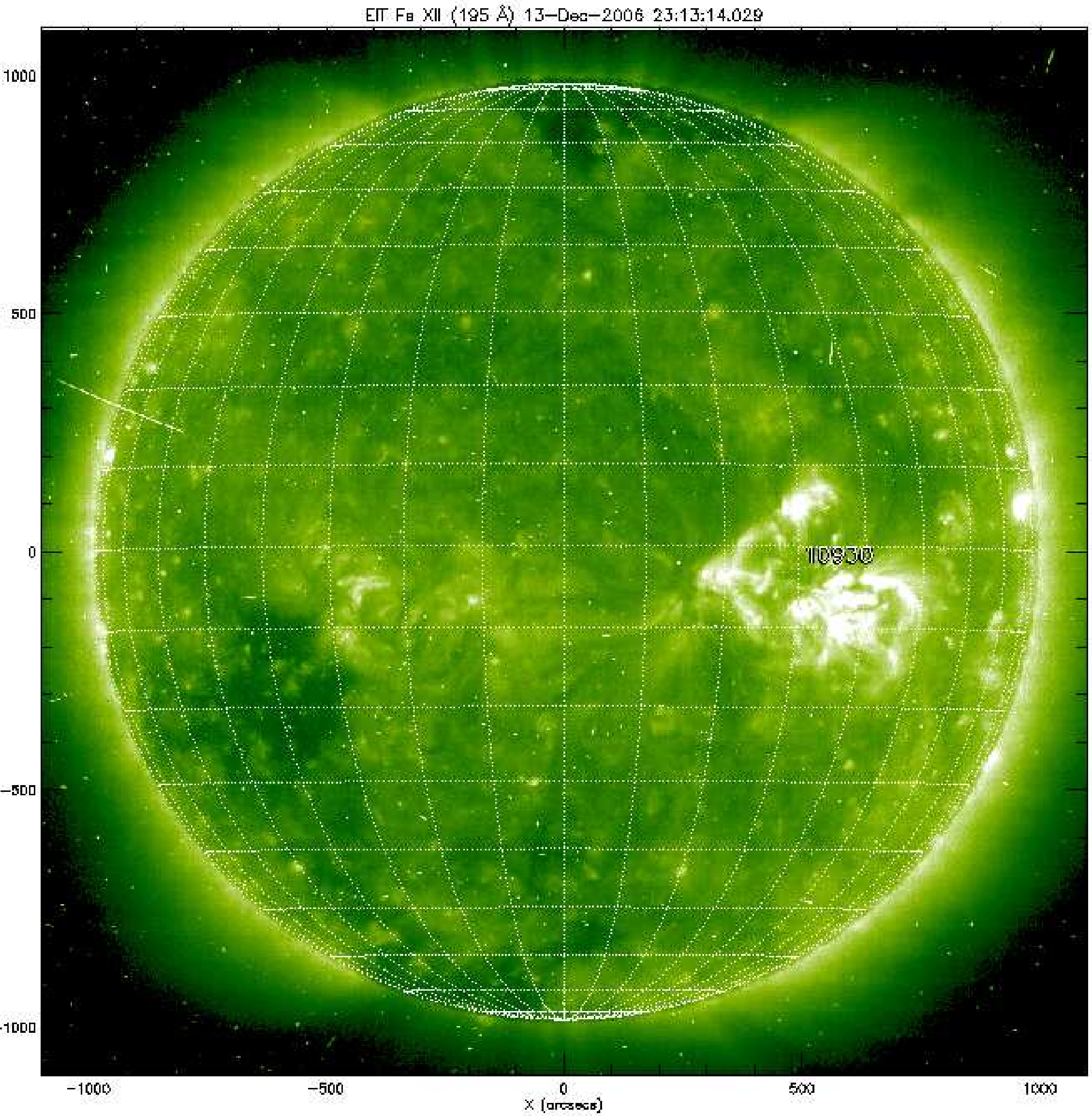
in collaboration with K.D. Leka,

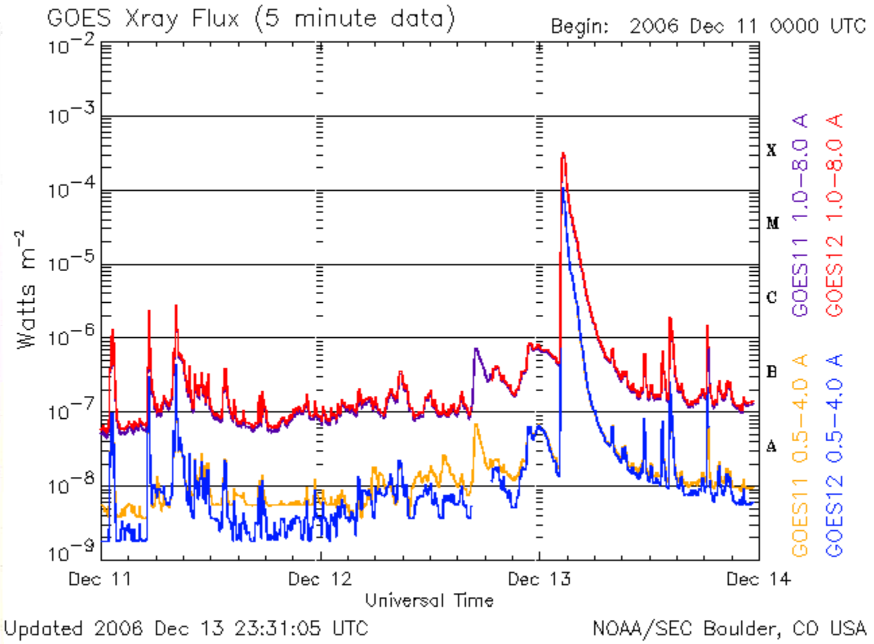
supported by the Air Force Office of Scientific Research under contracts

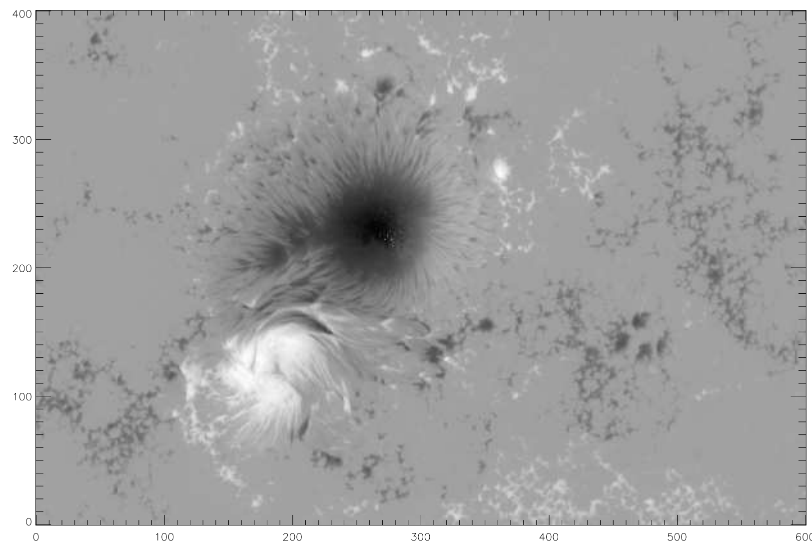
F49620-03-C-0019 and FA9550-06-C-0019,

and by the NASA/JSC Space Radiation Analysis Group

Flares: What and Where?







Overview

- Why use magnetic field observations?
- How do we characterize the magnetic field?
- Some statistical analysis.
- How well do predictions from magnetic field observation perform compared to predictions generated by the Space Weather Prediction Center?
- Summary

Motivation for Using Magnetic Field Observations

- The energy released by flares is stored in the coronal magnetic field.
- Magnetic reconnection in the corona is needed to trigger the flare.
- Routine observations of the coronal magnetic field are not (yet) available, but photospheric magnetic field measurements are available.
- MHD modeling may guide the selection of empirical parameters for use in forecasting.
- Various researchers have recently developed different ways to make flare forecasts from photospheric magnetic field measurements - how well do the forecasts do?

How Well do Researchers Think They are Doing?

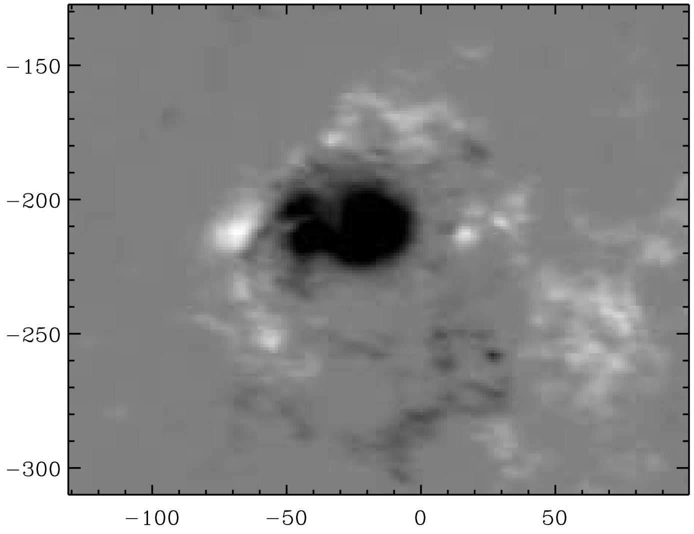
Different researches have reached wildly different conclusions about how well one can forecast flares using magnetic field observations.

- Leka & Barnes (2007) “conclude that the state of the photospheric magnetic field at any given time has limited bearing on whether that region will be flare productive.”
- McAteer et al. (2005) state “the fractal dimension does not fully capture the relationship between active region complexity and flare rate.”
- Schrijver (2007) states “Clearly, R is a far more significant measure for major flare potential than the unsigned flux”.
- Georgoulis & Rust (2007) “find that B_{eff} is a robust criterion for distinguishing flaring from nonflaring regions.”
- Who is correct, and perhaps equally importantly, what is meant by a clear or robust measure for distinguishing flaring from nonflaring active regions?

Forecasting from Magnetic Field Observations

Two things needed to make a forecast:

- One or more parameters which characterize the properties of the active region.
- A statistical technique for converting the values of the parameters to an actual forecast.



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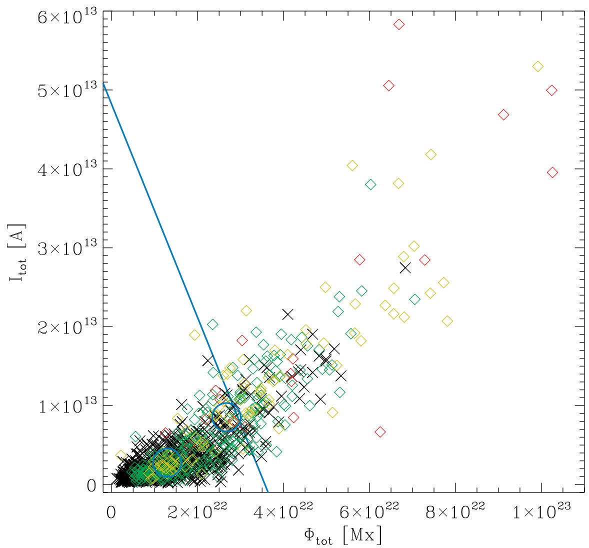


= prediction

Parameterizing the Magnetic Field

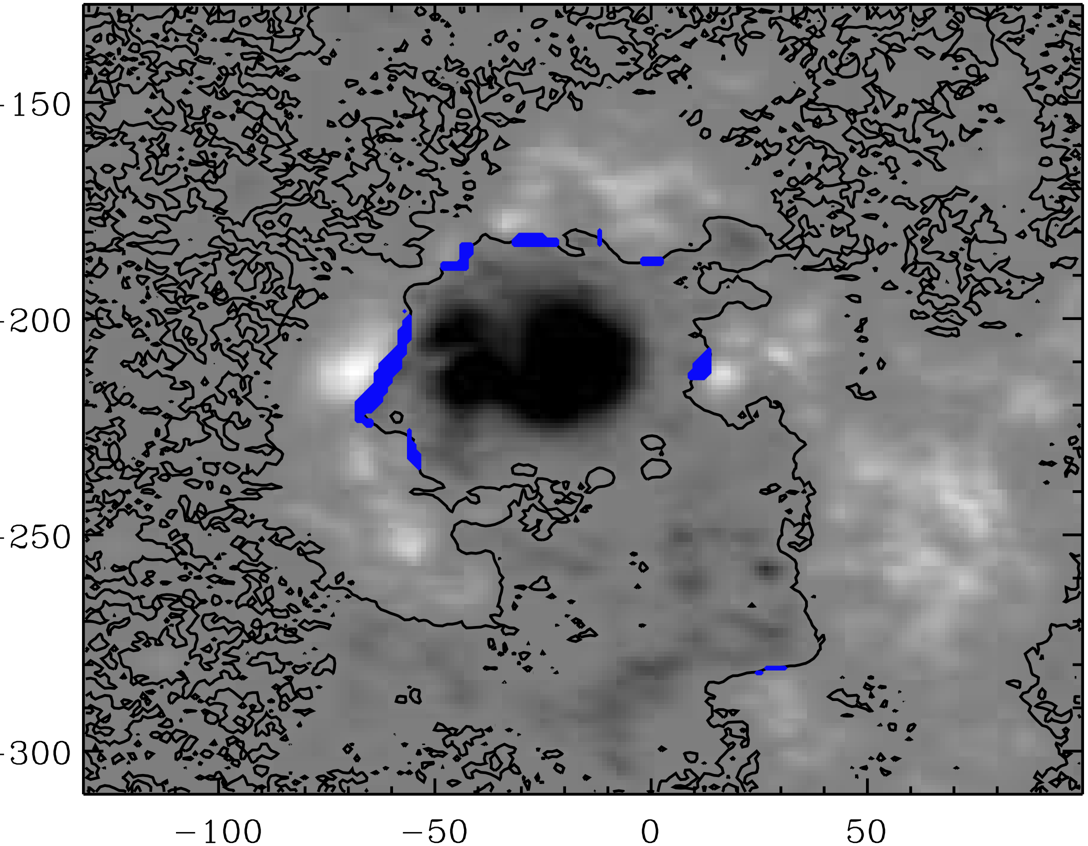
Goal: reduce a map of the observed magnetic field to a handful of parameters characterizing the active region's size, energy, polarity inversion lines, coronal magnetic topology, etc.

A few example parameters are:

- $\Phi_{\rm tot} = \int |B_z|$ - the total unsigned magnetic flux, often viewed as a standard for judging other parameters.
- $E_e = \int (\boldsymbol{B}^p - \boldsymbol{B})^2/8\pi$ - a proxy for the magnetic free energy (Leka & Barnes, 2003).
- $R = \int_{HGPL} |B_l|$ - the total unsigned line of sight field close to high gradient polarity separation lines (Schrijver, 2007).
- $\phi_{\rm tot} = \sum \psi_{ij}/|\boldsymbol{x}_i - \boldsymbol{x}_j|$ - the total of the flux connecting sources divided by the distance between sources in a magnetic charge topology (MCT) model (Barnes & Leka, 2006).

Many other parameters have been proposed.

High Gradient Polarity Separation Lines



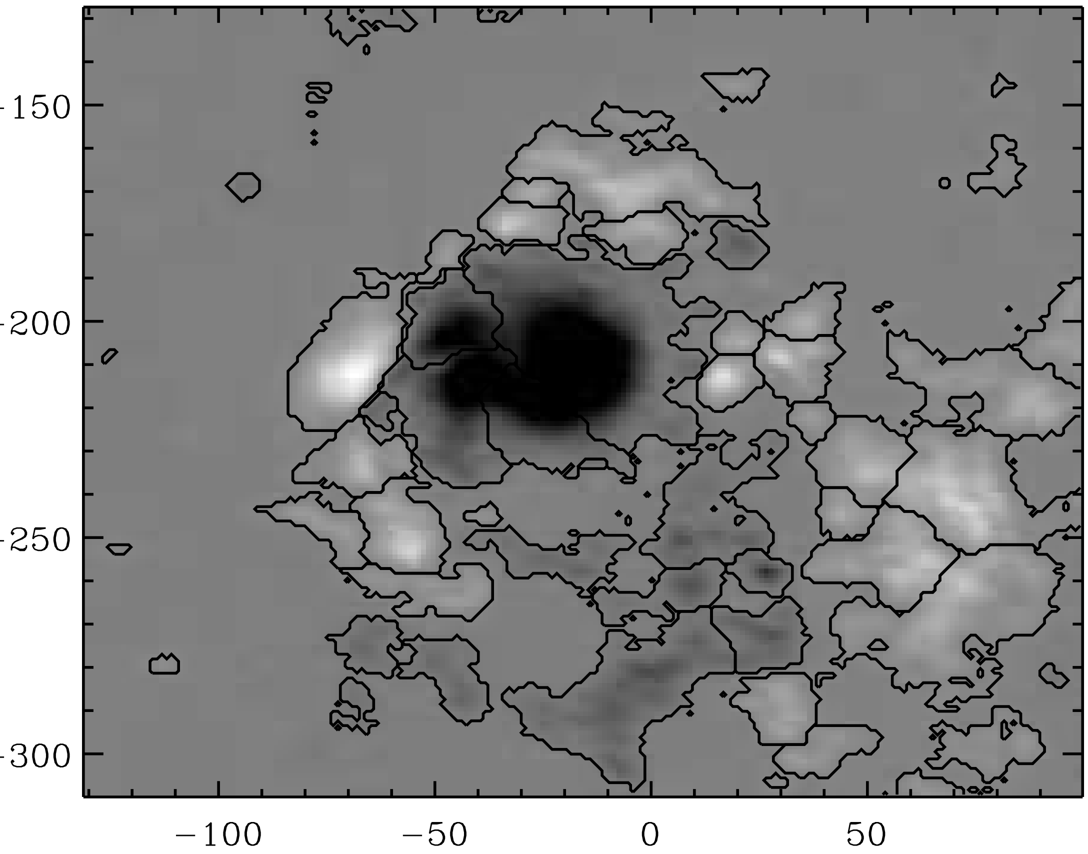
- Dilate bitmaps of where the magnitude of the positive and negative flux density exceeds 150 Mx cm^{-2} with kernels of 6"x6".
- Areas where the dilated bitmaps overlap are regions where strong opposite polarity fields lie within 5" – HGPL.
- Convolve an area-normalized Gaussian with FWHM of 15 Mm with the unsigned flux to measure the amount of flux close to HGPL.

Vertical magnetic field strength (greyscale) with polarity inversion line (black).
High Gradient Polarity Separation Lines (HGPL).

Define a flare forecasting parameter:
$R = \int_{HGPL} |B_l|$ (Schrijver, 2007)

R is a proxy for the emergence of current-carrying magnetic flux.

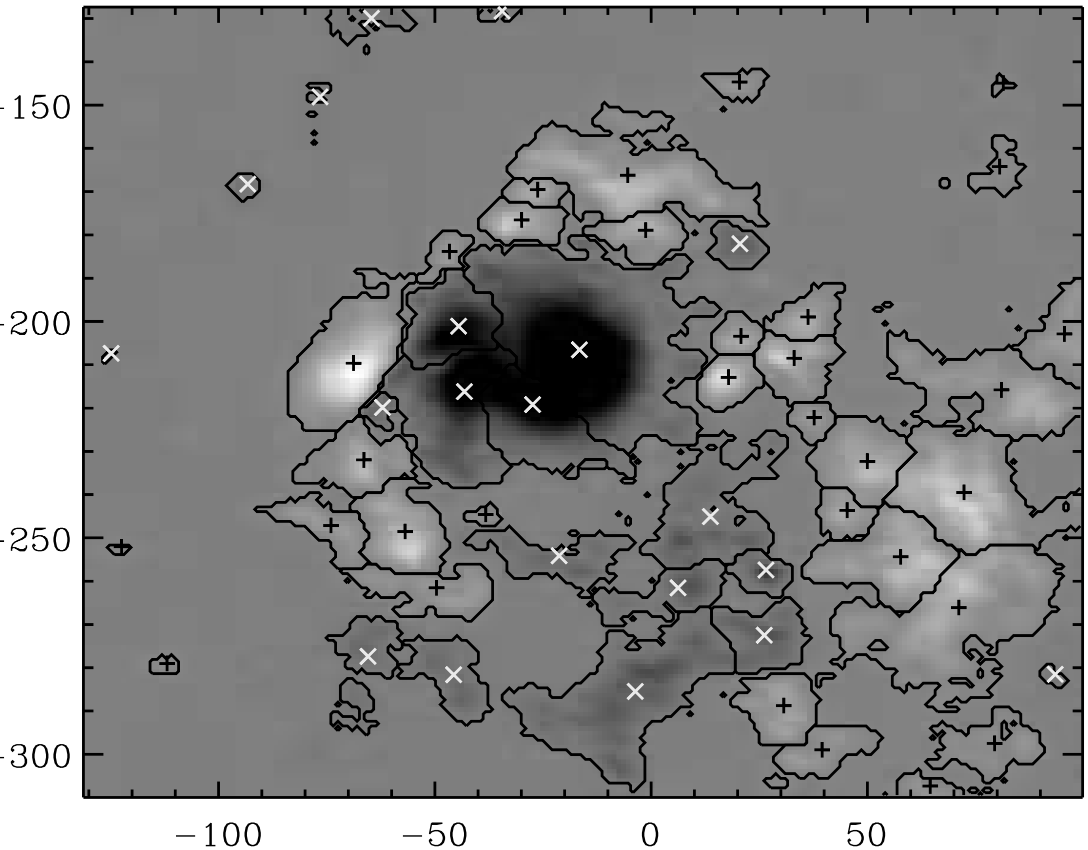
Magnetic Charge Topology Model



Partition the vertical magnetic field on the boundary into flux concentrations (Barnes, Longcope & Leka, 2005).

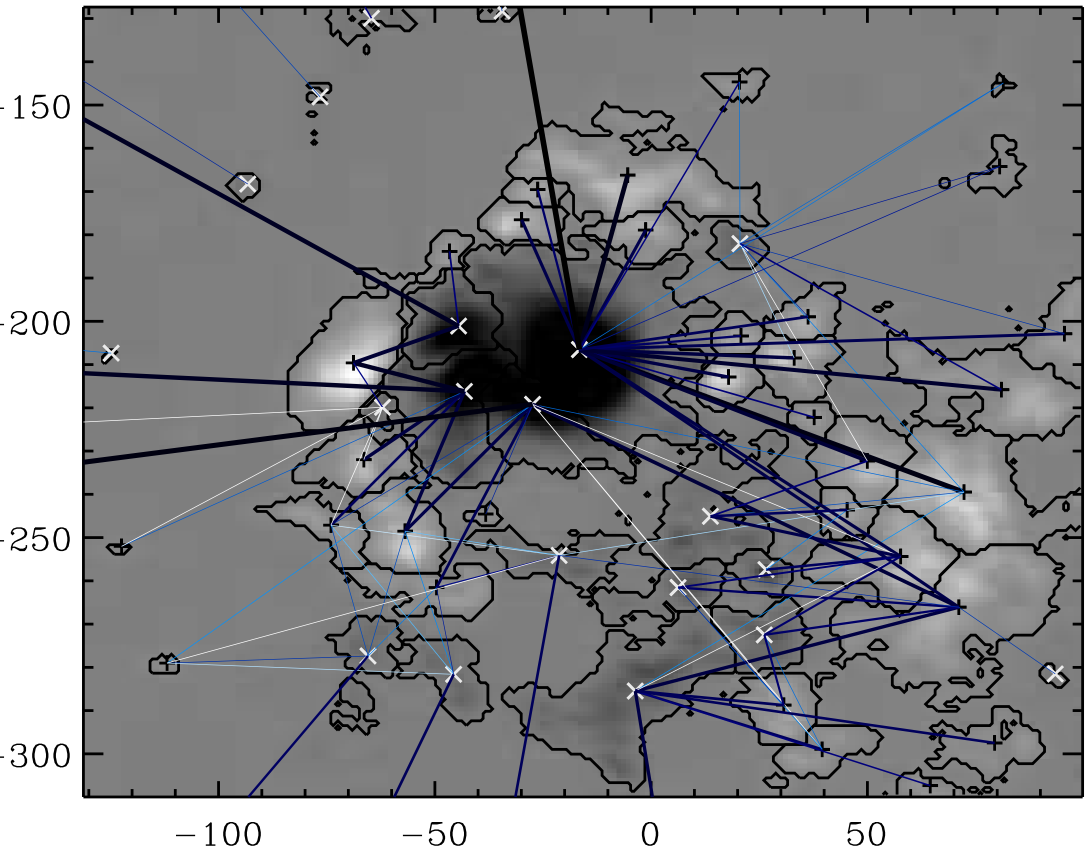
- Identify all local maxima in $|B_z|$.
- Use a down-hill gradient method to assign a label to each pixel above a threshold.
- Perform a saddle-point merging of partitions to reduce the number of same polarity sources in weak field areas, while retaining opposite polarity intrusions of flux.

Magnetic Charge Topology Model



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.

Magnetic Charge Topology Model



The connectivity matrix, ψ_{ij}, is defined as the flux connecting each pair of sources.

- Construct the potential field due to the collection of point sources.
- Trace field lines, initiated in random directions from each source.
- Estimate the connectivity from the number of field lines connecting each pair of sources.

One flare forecasting parameter:

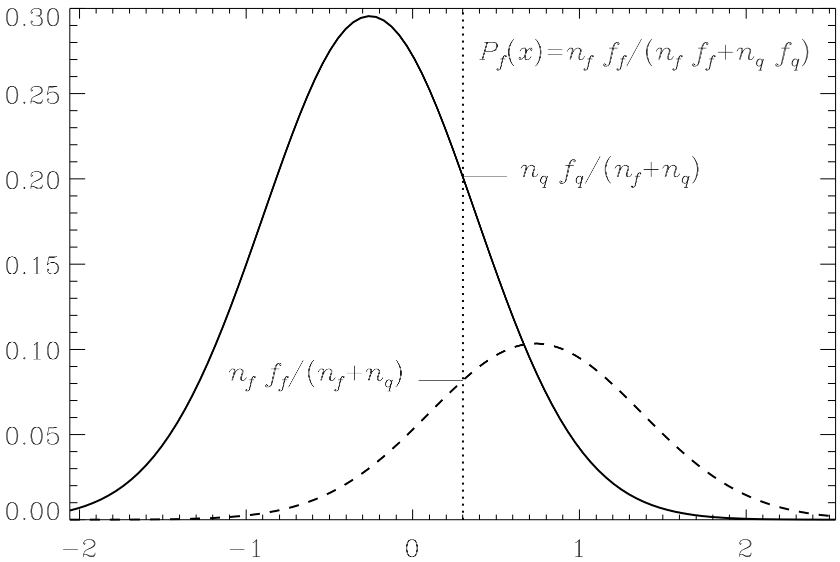
$\phi_{\mathrm{tot}} = \sum \psi_{ij}/|\boldsymbol{x}_i - \boldsymbol{x}_j|$ (Barnes & Leka, 2006)

The Data

- Daily "survey" vector magnetograms of each numbered active region on the disk, from the Imaging Vector Magnetograph (IVM) at Haleakalā (see Leka & Barnes, 2007 for details).
  - Only selection criteria are for data quality and distance from disk center.
- A region is defined to have flared if the event logs for *GOES* contain an event above a given magnitude within 24 hr after the magnetogram.
- Total is 1212 magnetograms from 2001–2004, including 111 which produced at least one M1.0 or greater flare and 20 which produced at least one X1.0 or greater flare.

Discriminant Analysis and Probability Forecasts

Use discriminant analysis to turn parameter values into a forecast.



The probability density function, f_j, is defined by

$$P(x_a < x < x_b) = \int_{x_a}^{x_b} f_j(x)\, dx$$

Forecast a region to flare whenever the probability density estimate for flaring regions exceeds the probability density estimate for nonflaring regions:

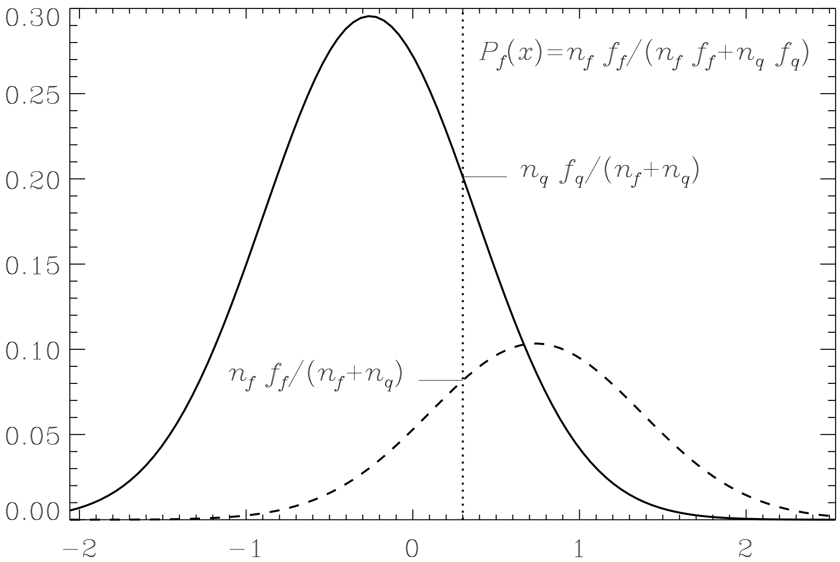
$n_f f_f(x) \geq n_n f_n(x) \;\Rightarrow$ predict a flare.

$n_f f_f(x) < n_n f_n(x) \;\Rightarrow$ predict flare quiet.

where n_j is the prior probability of belonging to population j, estimated as the sample size of population j.

Discriminant Analysis and Probability Forecasts

Use discriminant analysis to turn parameter values into a forecast.



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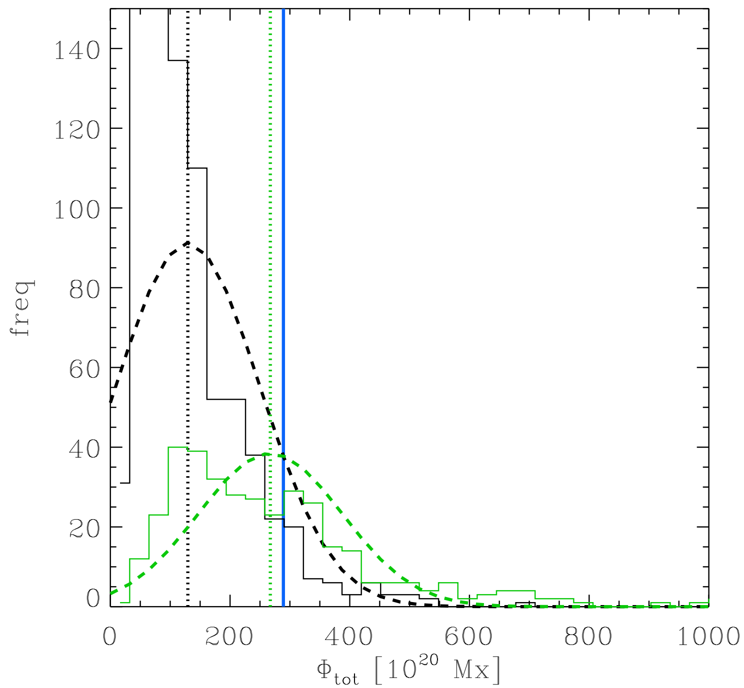
Alternatively, using Bayes' Theorem, estimate the probability of a flare occurring as

$$P_f(x) = \frac{n_f f_f(x)}{n_f f_f(x) + n_q f_q(x)}.$$

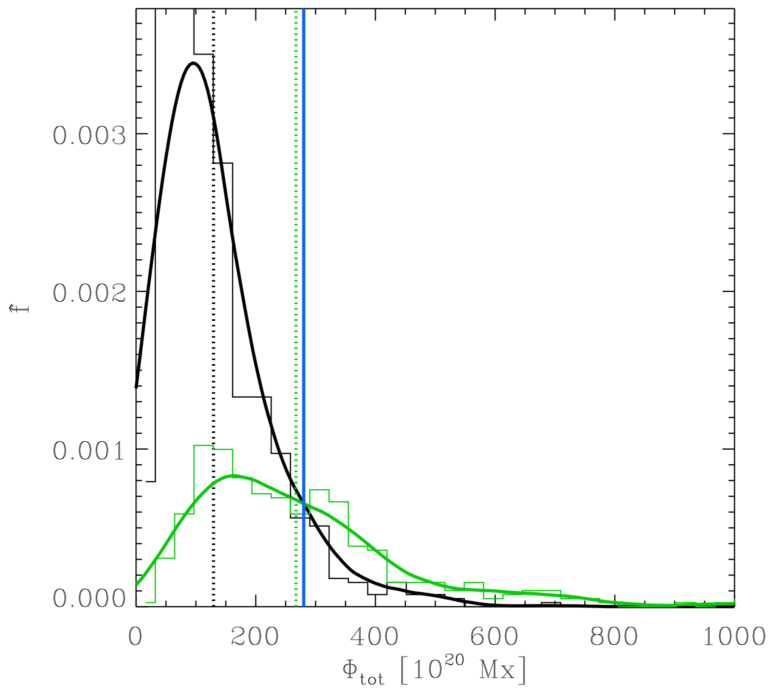
Discriminant Analysis: Why and How?

Why use discriminant analysis?

- Can consider multiple variables simultaneously.
- Minimizes the rate of incorrect classification (if the probability density function is accurately known).



Parametric density estimates assume a functional form for f_j, typically a Gaussian, and fit for the parameters.



Nonparametric density estimates approximate the distribution directly from the data.

Results of Discriminant Analysis

Judge the performance based on:

- Success rate - what fraction of regions are correctly classified?
- Climatological skill score - how much better is it than a uniform probability forecast?
- All-clear forecasts - if a region is predicted to remain quiet, how often does it produce an event?

approach	success rate	skill score	all-clear rate
climatology	0.908	0.000	0.908
magnetic/DA	0.928	0.246	0.961

For comparison, but based on different data, definitions of event:
Space Weather Prediction Center SS=0.262
Note: in the last 6 years, SS has ranged from -0.157 to +0.322

`http://www.swpc.noaa.gov/forecast_verification/mFlare.html`

Summary

- Because so few regions produce a large flare within a 24 hr period, it's relatively easy to produce "good" forecasts.
- When compared in a systematic fashion, there are no clear winners among present flare forecasting approaches.
- Combining independent parameters will result in improved forecasts. Helioseismology is one promising source for independent information.
- Considering the evolution of parameters may be important.
  - Expect that for a flare to occur, the coronal magnetic field must be in a state that is susceptible to (fast) reconnection and something must trigger the reconnection process.
  - Need to model the time evolution of the coronal magnetic field.

For more details, see poster S-9.