Predicting Solar Flares Using Solar Magnetic Field Data

a progress summary for AFOSR contracts
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with

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What?

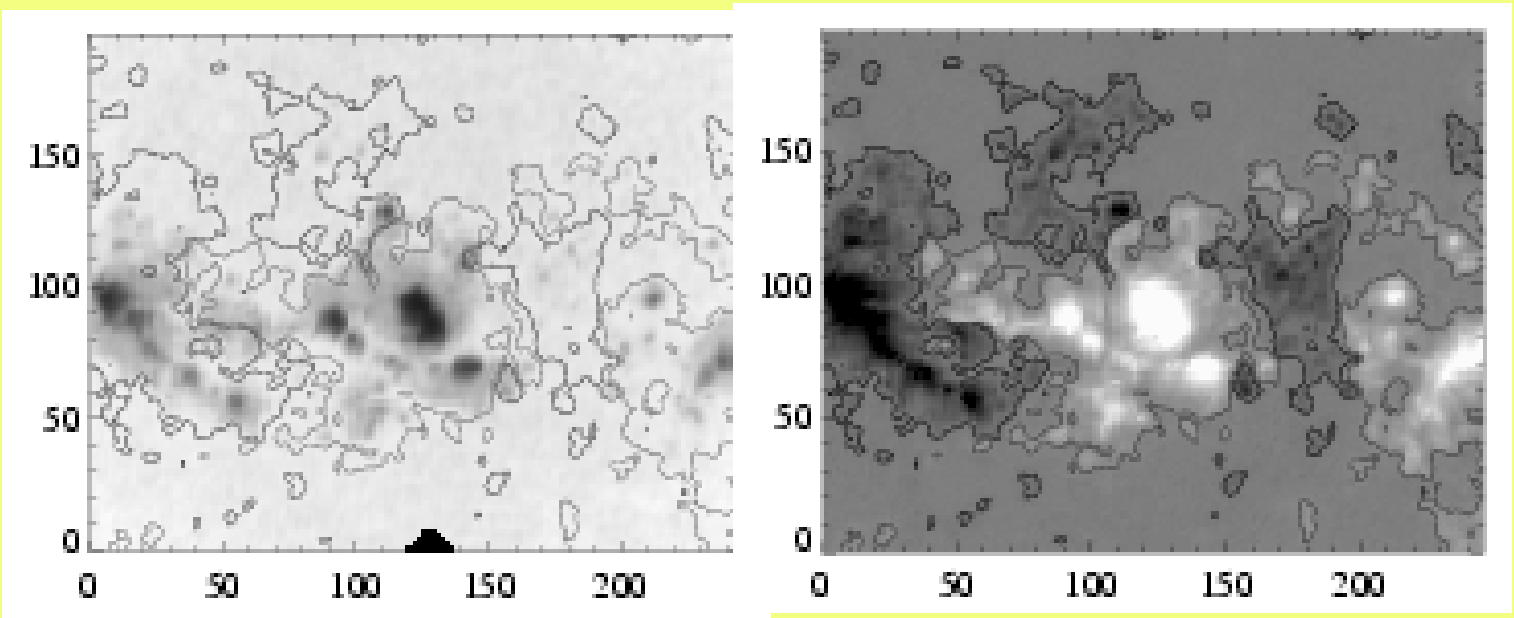
Physics-based prediction algorithm for solar flares based on the observed magnetic fields in solar active regions.

Why?

Solar flares disrupt communications operations and can cause radiation hazards instantaneously from first observation. Thus, *true forecasting abilities* are required.

Approach 1:
Analysis of Solar Photospheric *B* Time Series

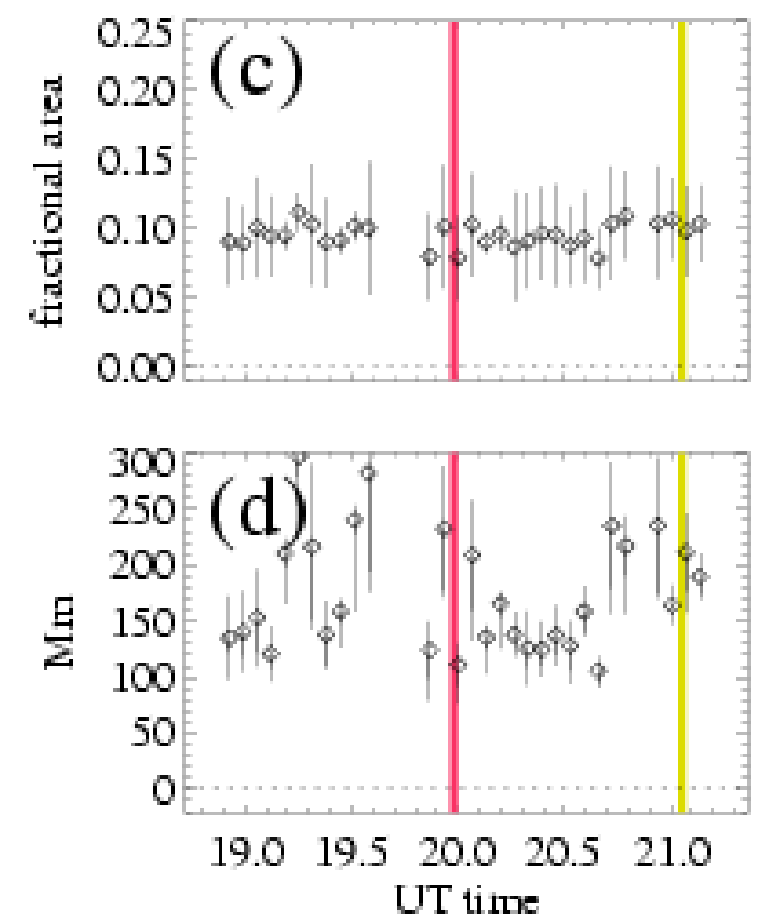
- Solar Coronal Magnetic Fields store the energy available for release in solar flares
- Photospheric ***B*** data measures the lower boundary
- **Data**:
  - Time series of ***B*** maps from the Imaging Vector Magnetograph (U. Hawai`i).
  - 1" spatial resolution, 4 min. cadence.
  - 7 Solar Active Regions
  - Focus on 1-hr prediction windows:
    - 10 "flare" *vs*. 14 "flare-quiet" epochs



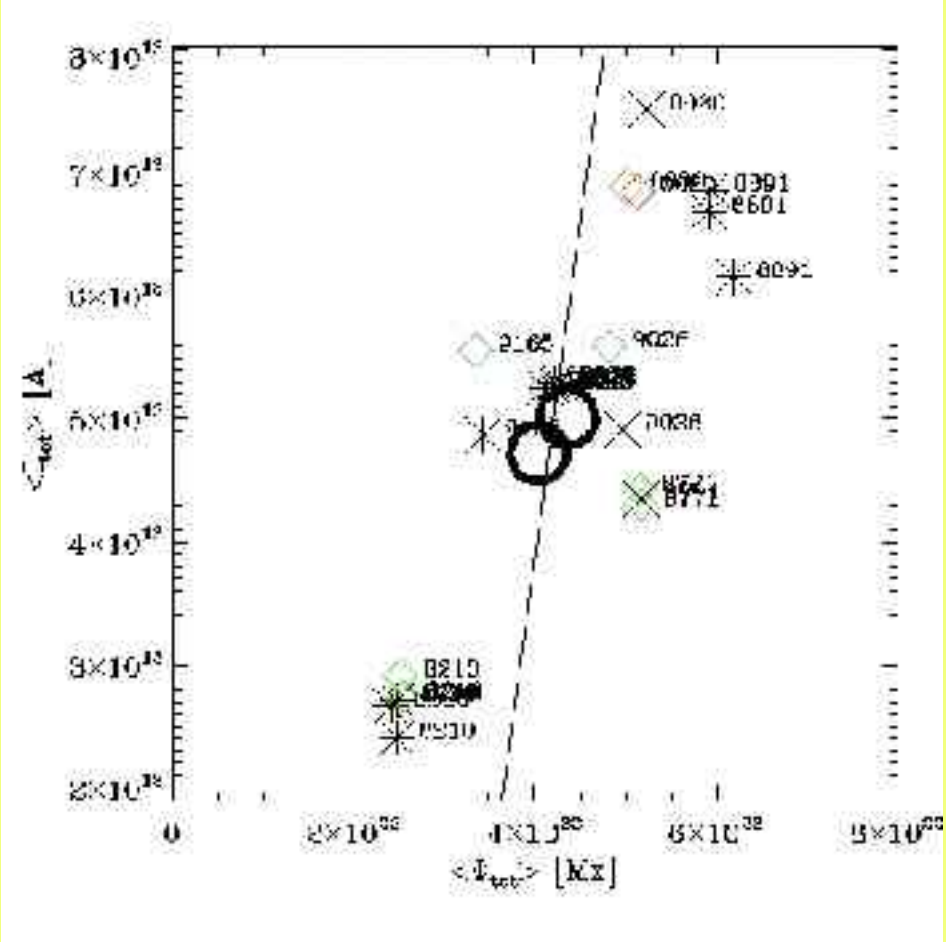
Data from the IVM of NOAA AR10300, 15 July 2001. Left: continuum image, scale is in Mm; Right: Radial component of the magnetic field, positive/negative (white/black). For each "pixel", the full magnetic vector ***B*** is measured.

- **Analysis**:
  - Characterize the distribution, morphology, and complexity of the photospheric magnetic field.
  - Parameterize ***B*** to get "single number" descriptors

Example: Time series from ***B*** of AR10030 concerning the magnetic shear angle ψ (difference from a potential field). Top: fractional area of the active region with $\psi \geq 80°$, Bottom: length of magnetic neutral line with $\psi \geq 80°$. Red/Yellow lines indicate start times for a GOES X-class and M-class flares.



- Employ Discriminant Analysis to the two populations (flaring and flare-quiet)
- 2-Variable Example:



Example of discriminant function relating the total magnetic flux and the total electric current in active regions. field gradients. Flare-quiet (*) and flaring (◊,◊,◊ for C, M, X flares) points, and the distribution means (O) are shown.

Observed \ Predicted	flare	no flare
flare	5	5
no flare	8	6

- **With Discriminant Analysis: *Multiple Variables can be employed simultaneously.***
  - 6-variable example:

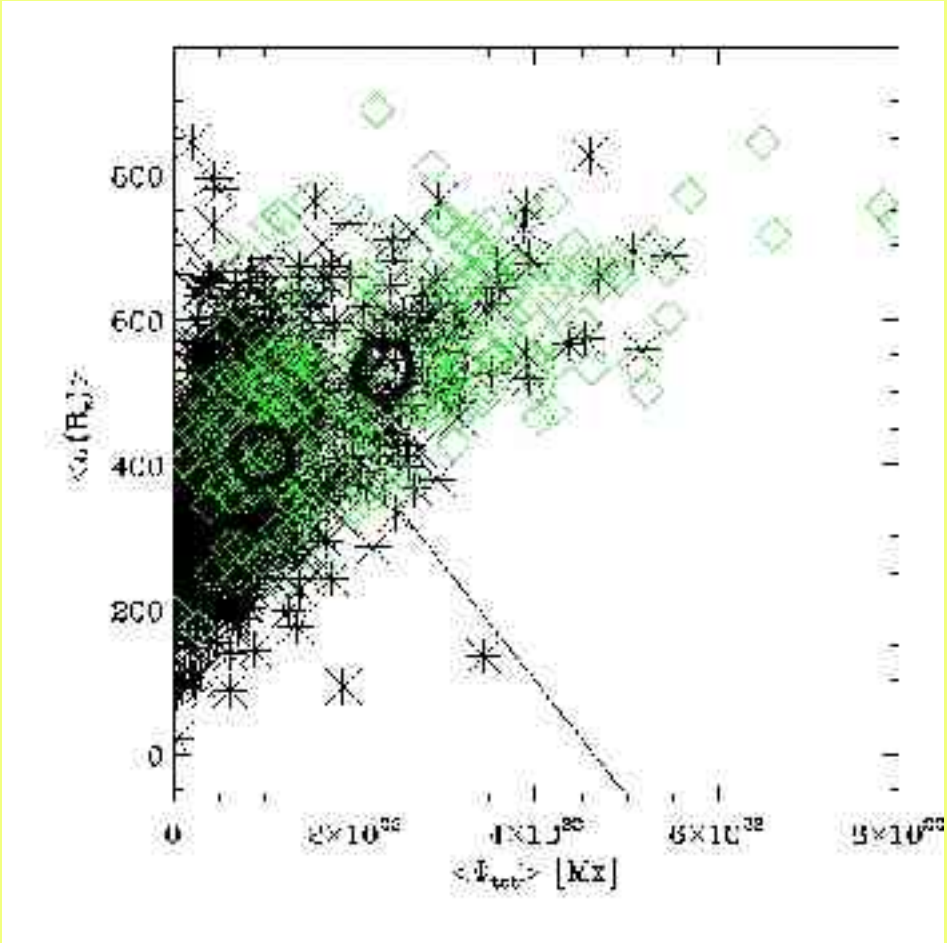
$$f = 1.021 - 11.098\,\langle\sigma(B_h)\rangle + 7.460\,d\overline{B_z}/dt + 8.330\,\langle\varsigma(J_z^h)\rangle - 3.829\,\langle\kappa(J_z^h)\rangle - 7.718\,\langle A(\psi > 80^\circ)\rangle - 3.834\,d|\alpha_{ff}|/dt$$

Observed \ Predicted	flare	no flare
flare	10	0
no flare	0	14

Statistical flukes are highly likely: this is a demonstration.

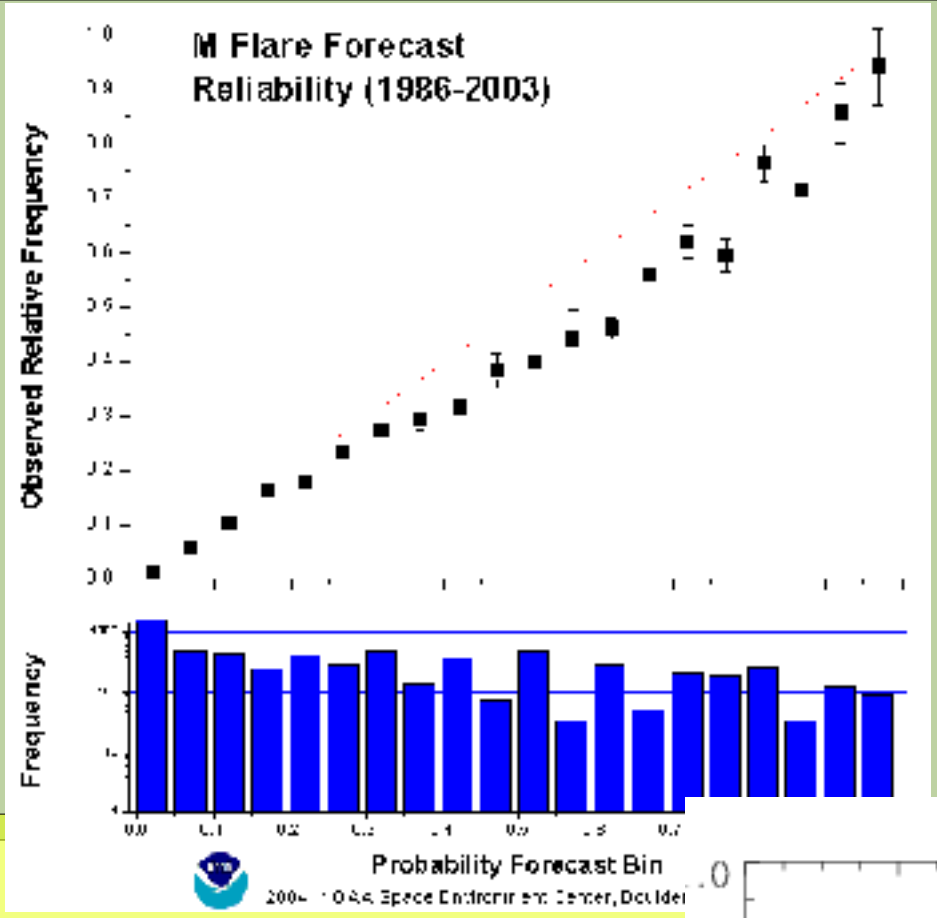
Approach 2:
Quantifying, Objectifying Daily Flare Forecasts

- Focus on *1-day* prediction window
- Quantitative, objective approach
  - Same parameterization of ***B*** morphology
  - Daily maps.
  - Same Discriminant Function analysis approach
  - Better statistics: over 1,100 data points so far
    (covering 2000, 2001, part of 2002)



Example of discriminant function for daily ***B*** data, relating aspects of the total magnetic flux and field gradients. Flare-quiet (*) and flaring (◊) points, and the distribution means (O) are shown.

- Direct Comparison to NOAA/SEC probability forecasts:

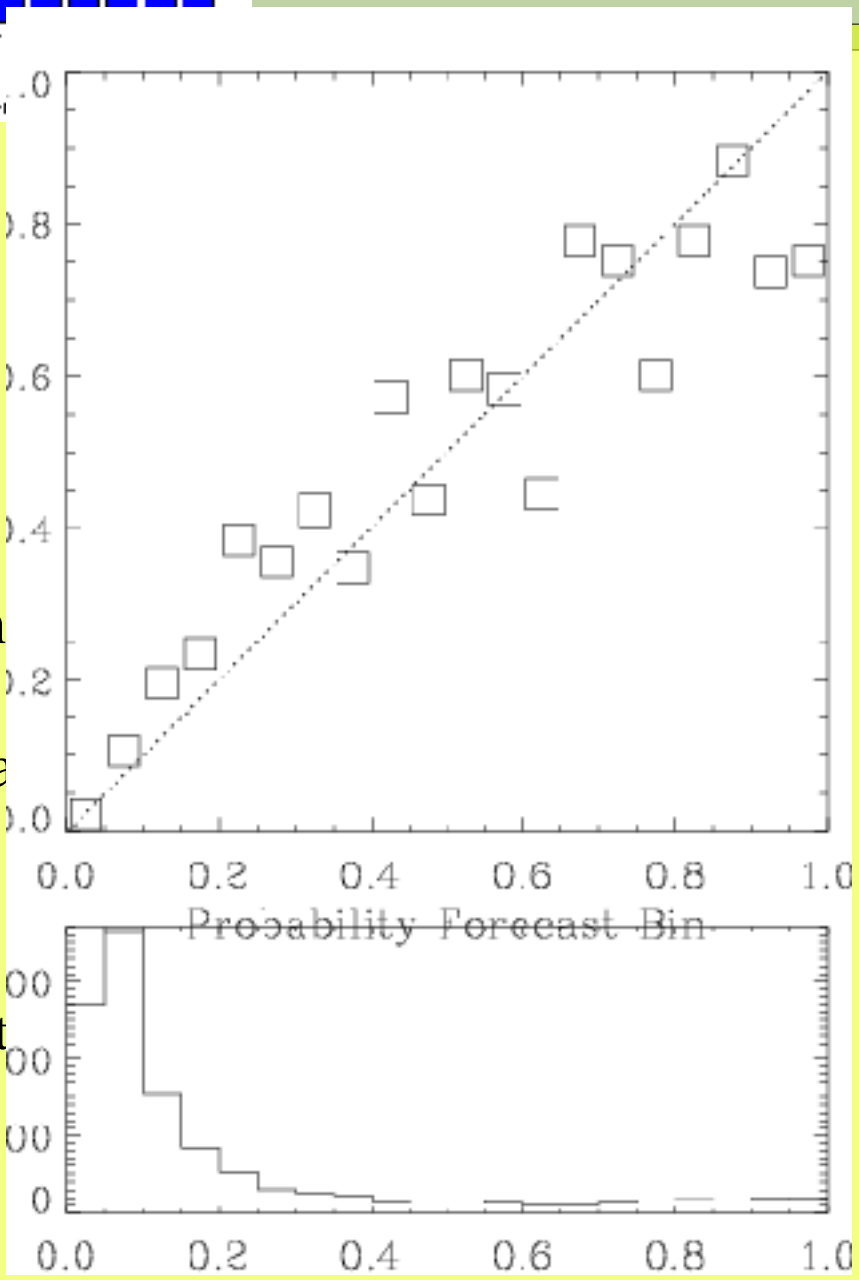


NOAA/SEC:

- 6,500 data points
- M-flares only
- Predictions based on flare history, visual assessment of sunspot complexity

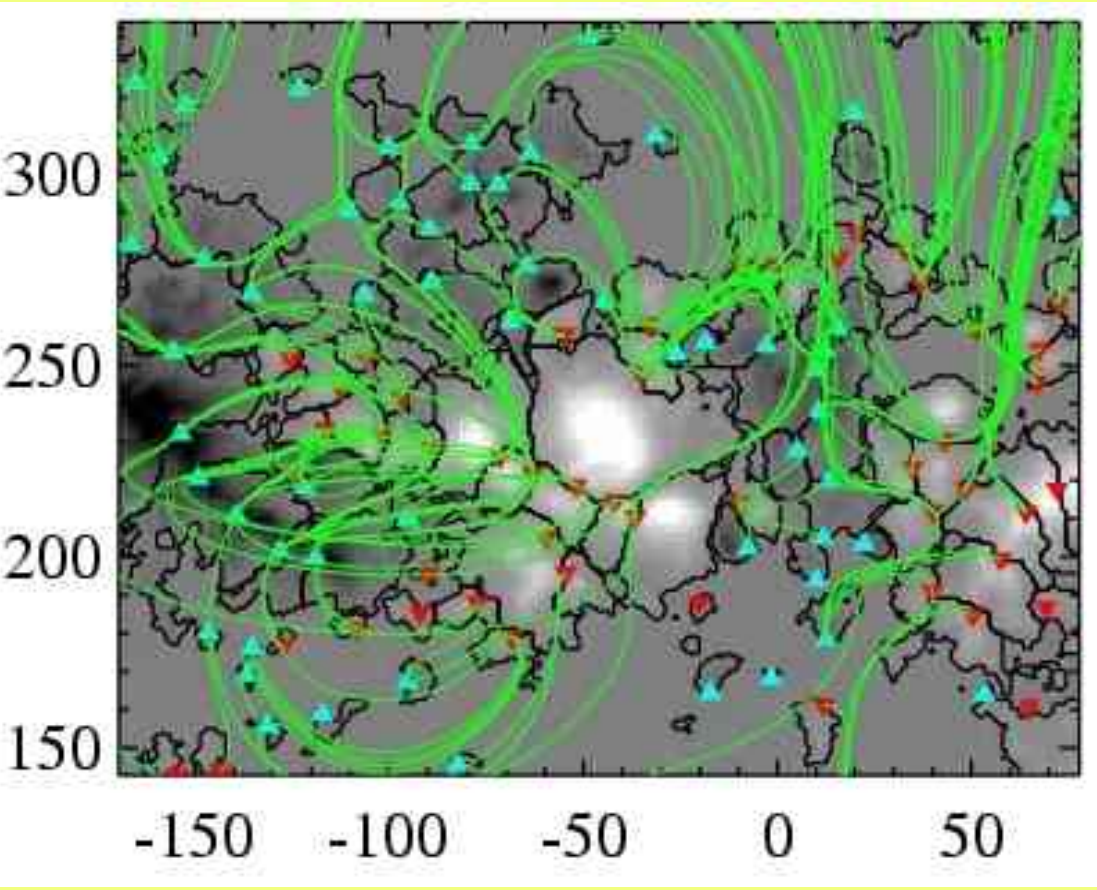
Magnetic Field & DFA:

- 1,182 data points
- All flares (C, M, and X)
- 5-variable function that includes total magnetic flux, magnetic shear angle, curren spatial gradients of the field.
- Performs basically as well a NOAA/SEC's, and is fully objective.
  - However, small-number statistics in high-probabilit bins



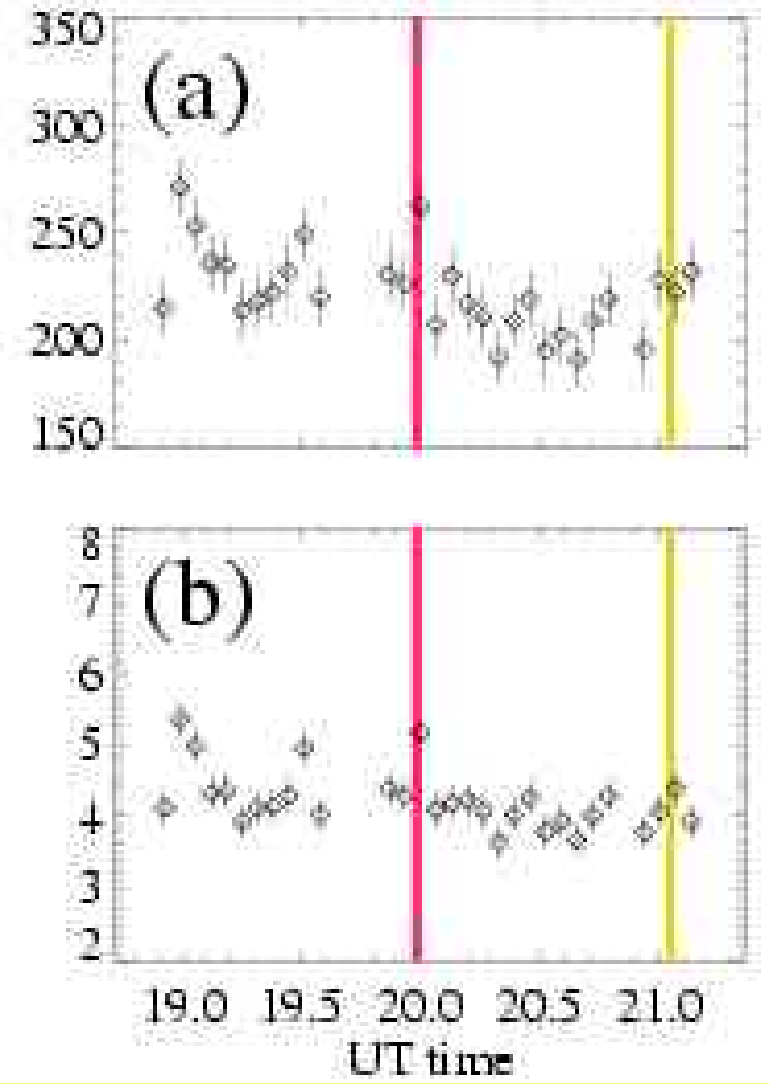
Approach 3:
The Coronal Complexity

- Magnetic reconnection believed to occur in the solar corona
  - Use photospheric ***B*** maps to investigate coronal B
- **Magnetic Charge Topology** model
  - Partition the ***B*** maps and determine the coronal connectivity matrix
  - Characterize the coronal topology using the connectivity, distribution of magnetic nulls and separators.



Results of MCT analysis of NOAA AR10030 with 113 sources. "A" , "B" and upright null points (▼, ▲, ▼) and separator field lines (green). Axes are in megameters.

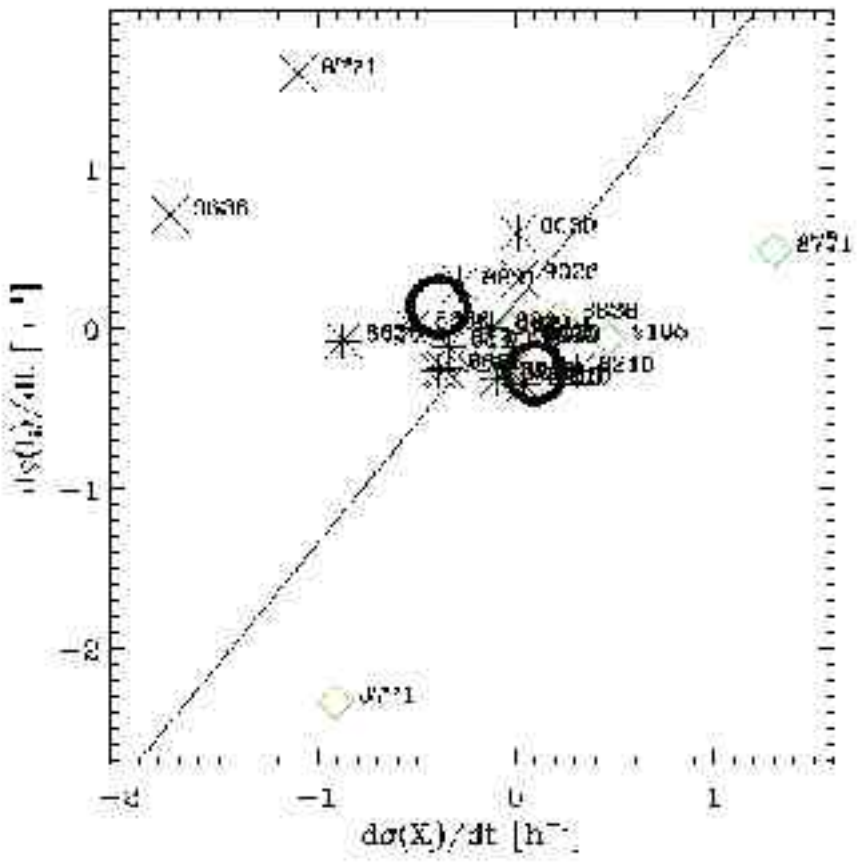
- **Analysis**:
  - Parameterize to obtain “single number” description of the coronal fields' complexity.
  - Focus (again) on 1-hr prediction windows



For part of the time series for NOAA AR10030, (a) the total number of separators and (b) the standard deviation of the number of separators associated with each magnetic null point. The start times for the X-class and M-class flares are indicated by vertical bars.

Discriminant Function Analysis of MCT results

- 2-variable example based on variation of separator number and lengths:



Discriminant function for two variables, for flaring (◊,◊,◊ for C, M, X flares) and flare-quiet (*) epochs; the distribution means are also shown (O).

Observed	Predicted: flare	Predicted: no flare
flare	9	1
no flare	2	12

- ***Only 4 variables*** *now needed simultaneously to construct a "perfect" classification table:*
  - Function includes parameters for variability of the magnetic connectivity, number and length of separators.

$$f = 0.26 - 1.02\frac{d}{dt}\varsigma(\psi_{ij}) + 1.80\frac{d}{dt}\sigma(X_i) - 1.62\frac{d}{dt}\varsigma(l_i) + 1.00\langle\sigma(r_{ij},\psi)\rangle$$

- **Evidence of better probabilities overall of discriminating the populations: the Corona may tell us more about whether an active region is going to flare.**

Summary

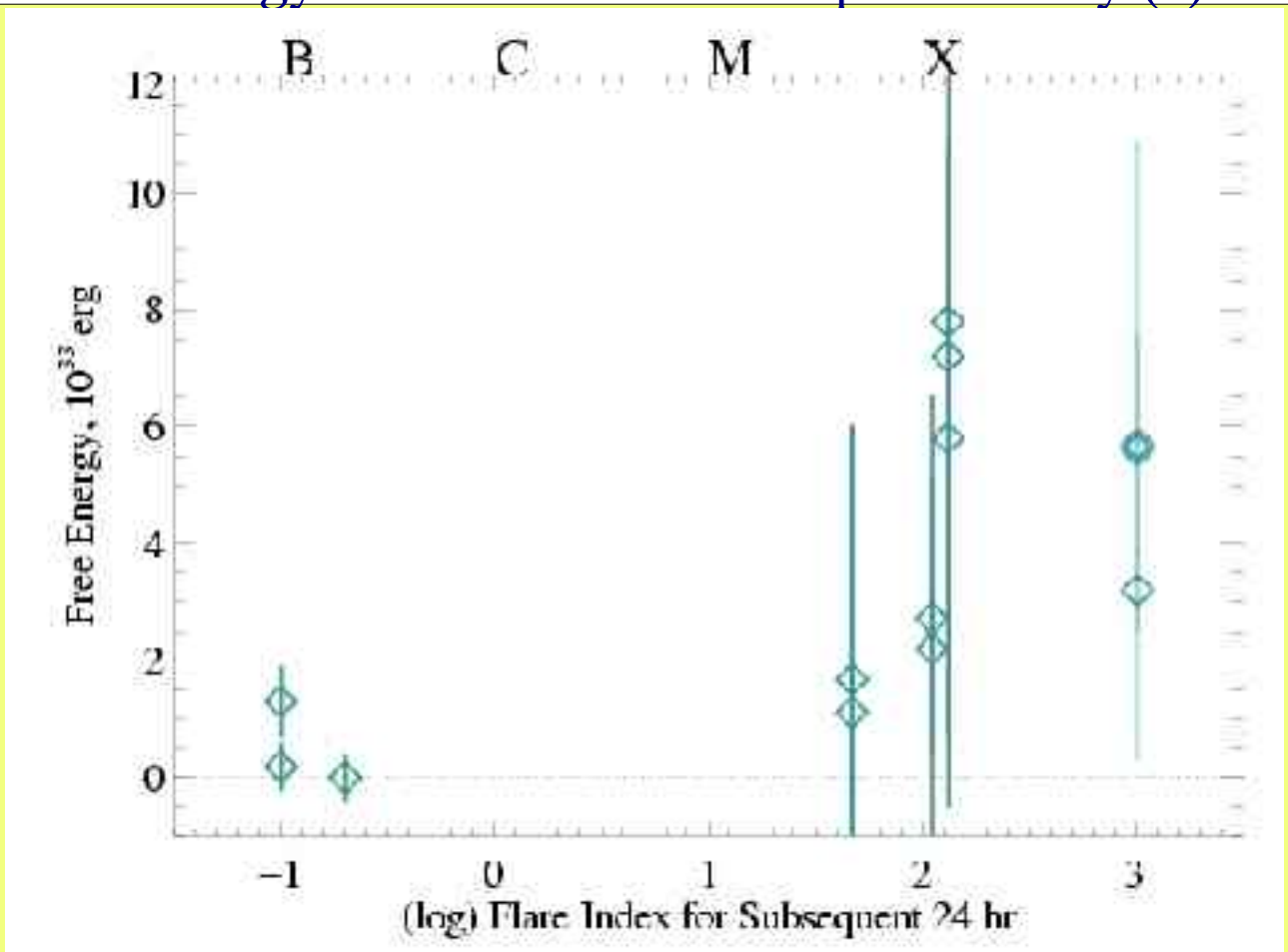
- **Novel, physics-based approaches to the question of solar flare prediction.**
- **Utilizes observations and models of the solar magnetic field at the solar surface and in the corona**
  - **Quantitative, objective, statistical approach with promising results.**
- **Results from the basic research here;**
  - **demonstration of technique *only*.**
- **Further research is required before technique become applicable algorithms to test.**
  - **Even more before any implementation.**

Approach 4:
Using The *Chromospheric* Magnetic Field

- Measure the solar ***B*** field at the chromosphere, where
  - $\boldsymbol{J} \times \boldsymbol{B} \rightarrow 0$ (Field is "force-free" in this layer)
  - Closer to the reconnection height
  - *Direct* measure of the free energy available for a flare using the ***magnetic virial theorem.***
- Results: preliminary.
  - Measurements are difficult.
  - New capability, analysis is on-going

But.....

- Free energy associated with flare productivity (?):



Magnetic free energy determined for 5 active regions as a function of flare productivity. Error bars reflect both uncertainties in the data and possible invalid assumptions used with the magnetic virial theorem.

Lots of data, lots of potential, lots of work to do.