NORTHWEST RESEARCH ASSOCIATES

Are we there yet?
A Journey to Understand and Predict Solar Energetic Events

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Introduction: What, who cares and why

Observing the Magnetic Field in the Solar Photosphere

The roads we've been traveling and where they seem to be leading....

But first....

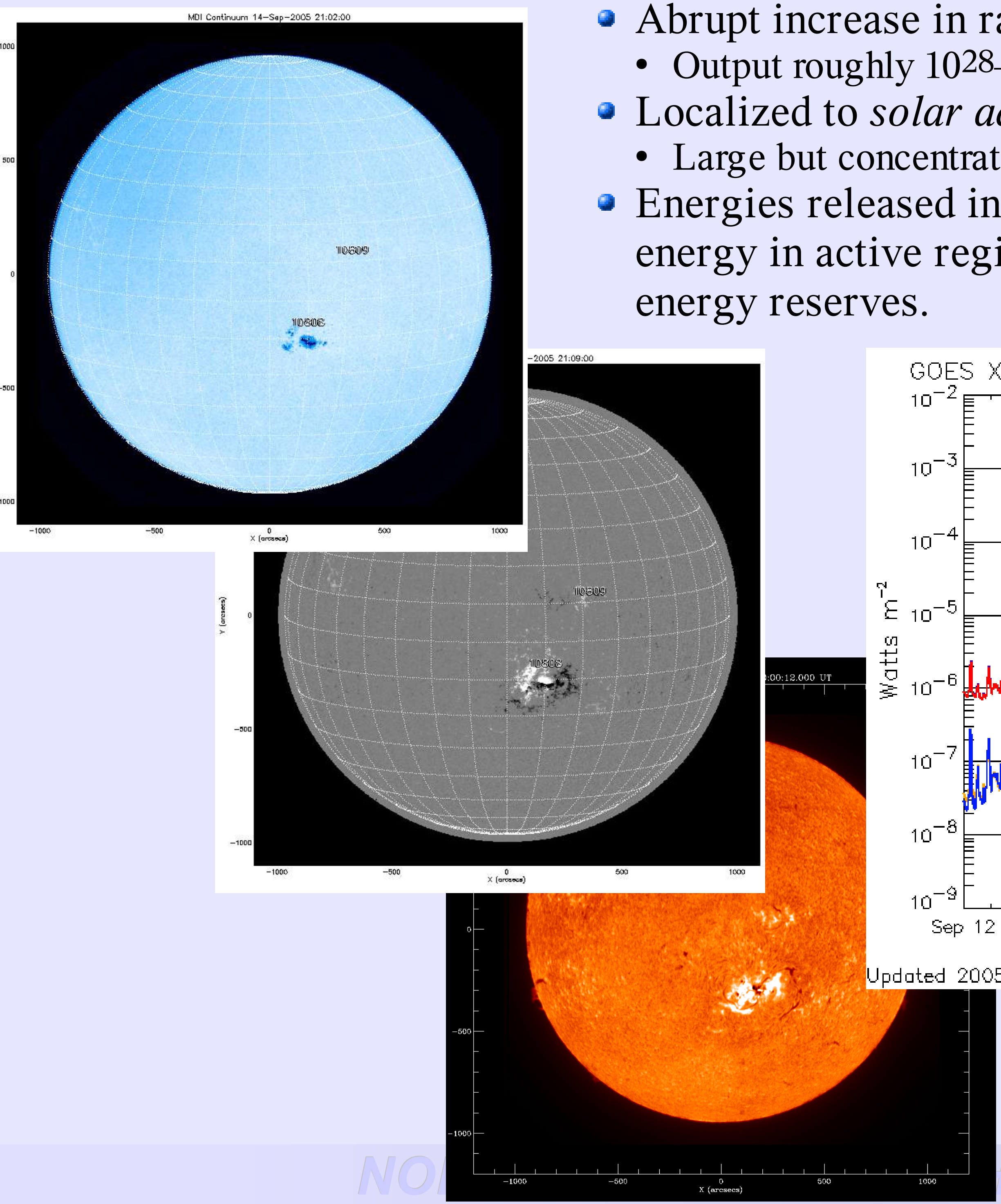
Mechanics, Navigators, Sponsors, and Back-Seat Drivers

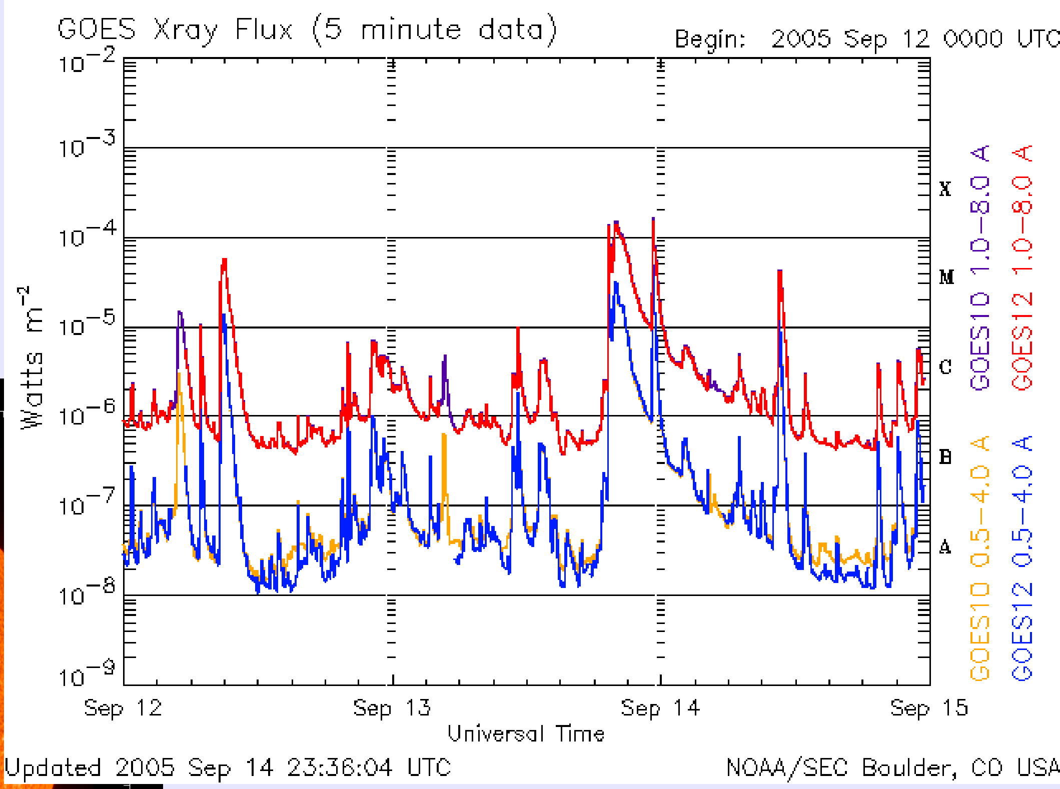
Graham Barnes
Richard Canfield
Devin Della-Rose
Yuhong Fan
Gary Heckman
Barry LaBonte
Dana Longcope
Tom Metcalf
Don Mickey
Gary Nitta
Evelyn Schumer
Mark Waterson
Mark Weber
The forecasters at NOAA/SEC

Air Force Office of Scientific Research
National Research Council
NASA
NOAA/Space Environment Center

Solar Flares: what?

- Abrupt increase in radiative output at all wavelengths
  - Output roughly 10^{28}—10^{32} erg over 10—1000 minutes.
- Localized to *solar active regions:*
  - Large but concentrated regions of strong magnetic field
- Energies released in solar flares consistent with magnetic energy in active regions, and inconsistent with other energy reserves.





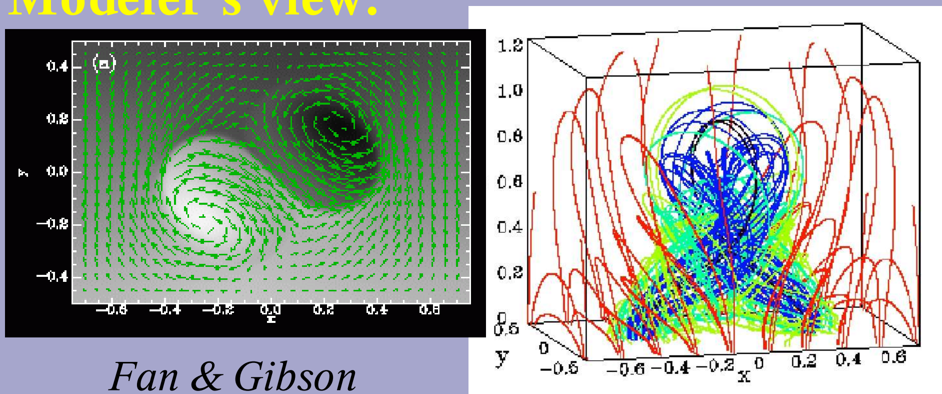
Solar Flares: why and who cares?

- Unique role in solar physics research
  - “The Sun would be a boring star if it had no magnetic field”
    - Solar Flares are the most dramatic examples of the magnetic field's influence.
  - Understanding the field's role in solar flares production requires:
    - Understanding magnetic reconnection and other MHD processes such as the instability of magnetic modes (kink, tearing). Modeling these processes challenges present computational bounds.
    - Understanding the magnetic field and its interaction with the plasma in the “whole box”, even though observations of the magnetic fields are only routine at the boundary.

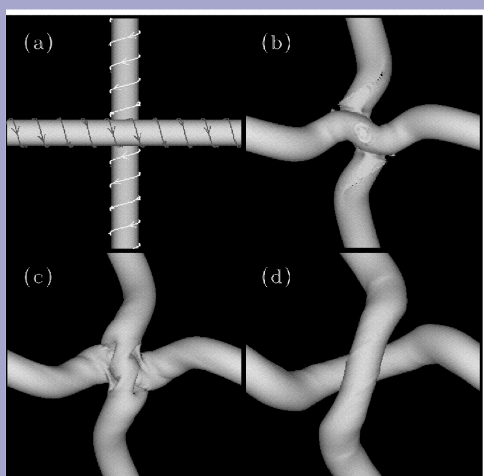
- Unique role in “Space Weather”
  - Ionizing radiation can disrupt communications and pose radiation hazards
    - Time-of-flight governed by *c*
  - True *forecasting* capabilities are required.

"So a numerical modeler and a flare forecaster walk into a bar and ask...how do I get to a solar flare?"

Modeler's view:

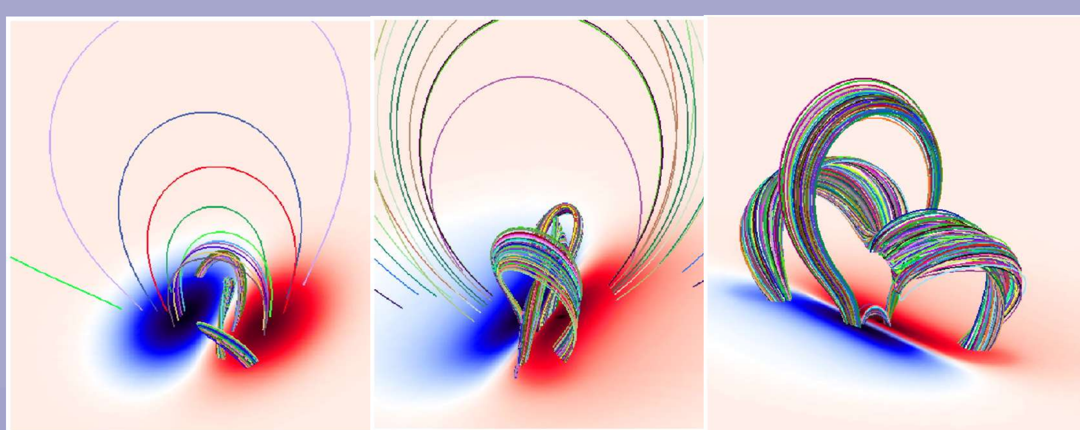


Fan & Gibson 2003, 2004

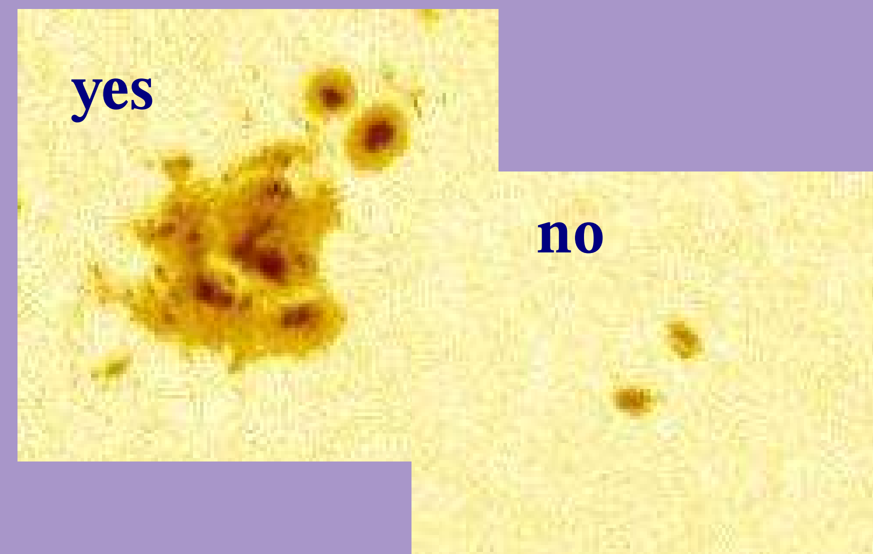


Linton & Antiochos 2002

Amari, Luciani, Aly, Mikic & Linker 2003



Forecaster's view:



Goals:

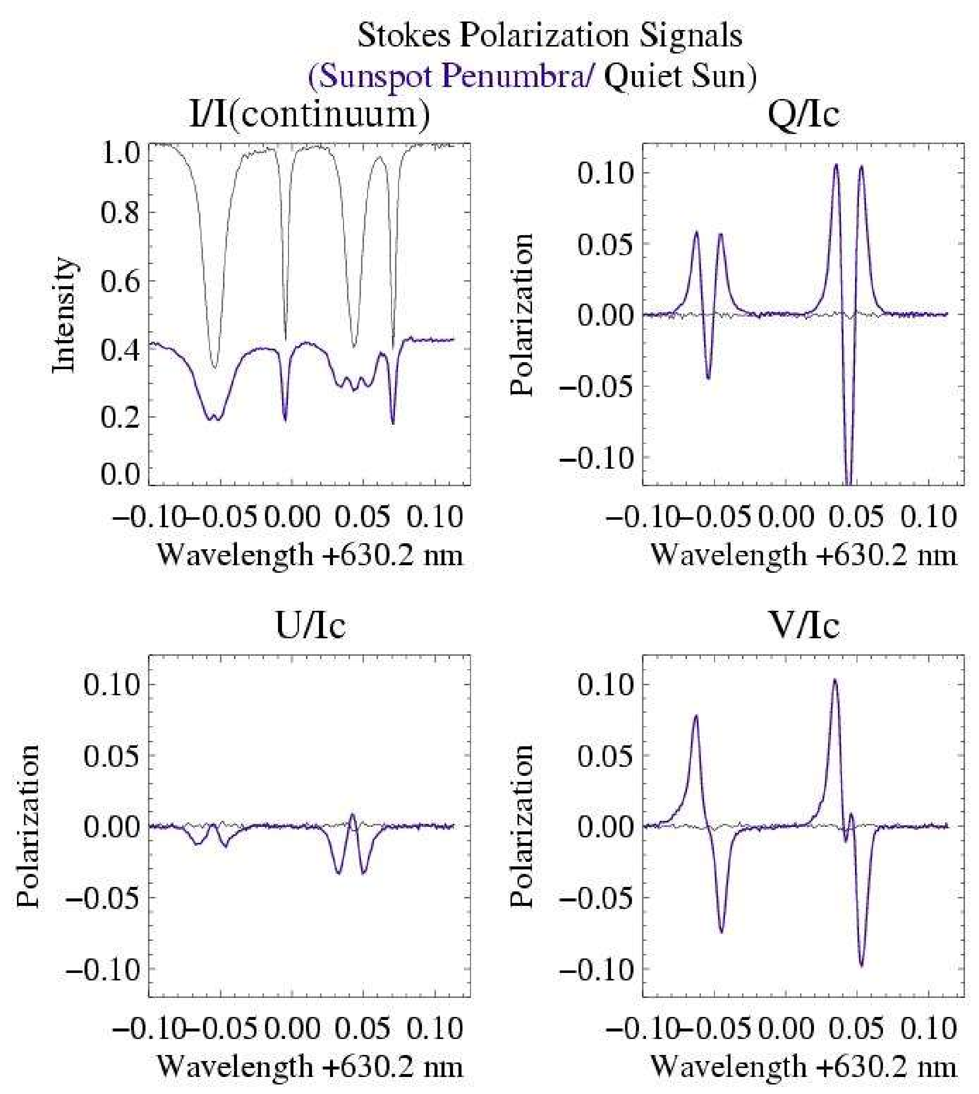
- Test the null hypothesis: There is no measurable distinction between a flare-imminent and flare-quiet active region magnetic field.
- If the null hypothesis is rejected, identify the *unique* signature in the magnetic field of a “flare-imminent” active region.
- Develop a physics-based objective flare-forecasting approach.

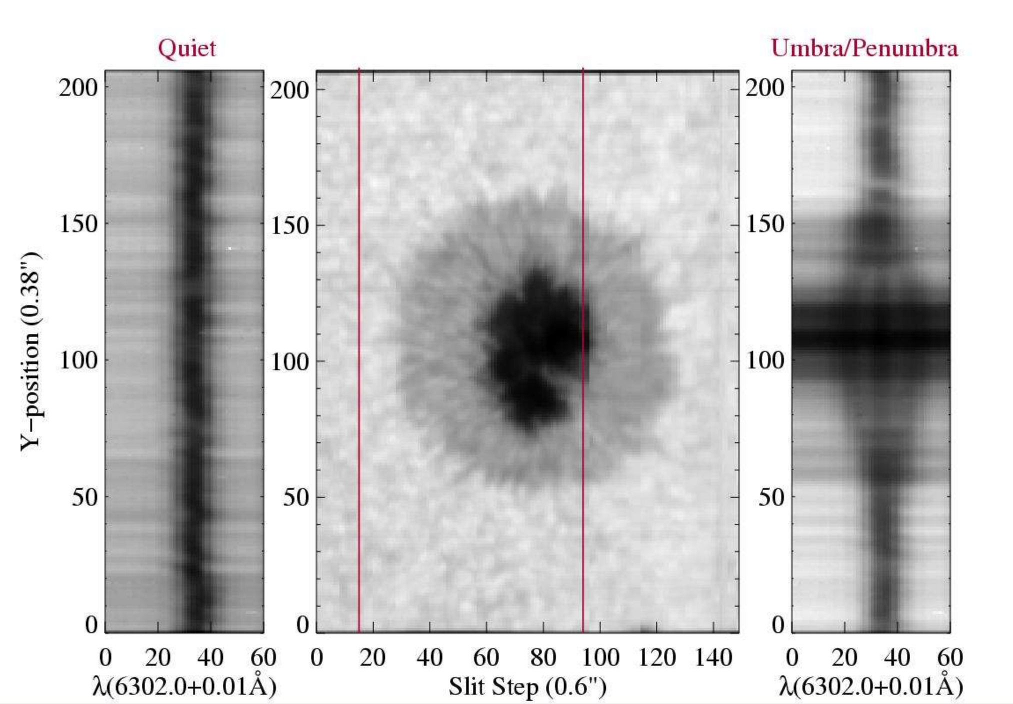
General Considerations:

- Utilize appropriate data
  - Routinely obtained, synoptic, photospheric vector magnetic field data
  - Ensure sufficient data for statistical significance
  - Include data for targets which did not flare, even though expected to.
- Rely on objective calculations and statistics
  - Minimize “operator influence”
  - Account for flare “misses” as well as false alarms
- Wear two hats:
  - Balance and consider requirements of both flare forecaster and the numerical modeler.

Measuring the photospheric magnetic field: **Stokes spectropolarimetry:**

- Zeeman effect: magnetic field induces both energy-level splitting and polarization to emergent light of magnetically sensitive lines.





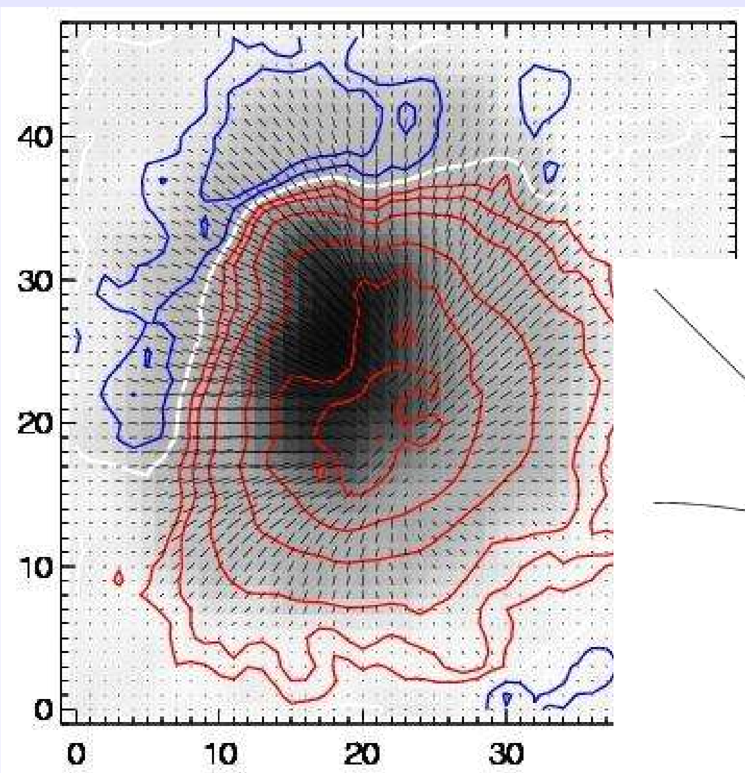
- Shape of polarization spectra and degree of polarization due to: strength, direction of magnetic field, thermodynamics of plasma, spatial and spectral resolution.

Measuring the photospheric magnetic field cont'd:

- Inversion procedure: I, Q, U, V spectra → B_{los}, B_{trans}, ϕ
  - Myriad methods exist, each with strengths and weaknesses
  - Inversion based on Milne-Eddington atmosphere, accounting for Faraday rotation, thermodynamics, magnetic fill-fraction.
- 180° Ambiguity in B_{trans} inherent in Zeeman-polarization observations
  - Myriad methods exist, each with strengths and weaknesses
  - Minimize divergence and current simutaneously
  - Results transformed to heliographic ***B***

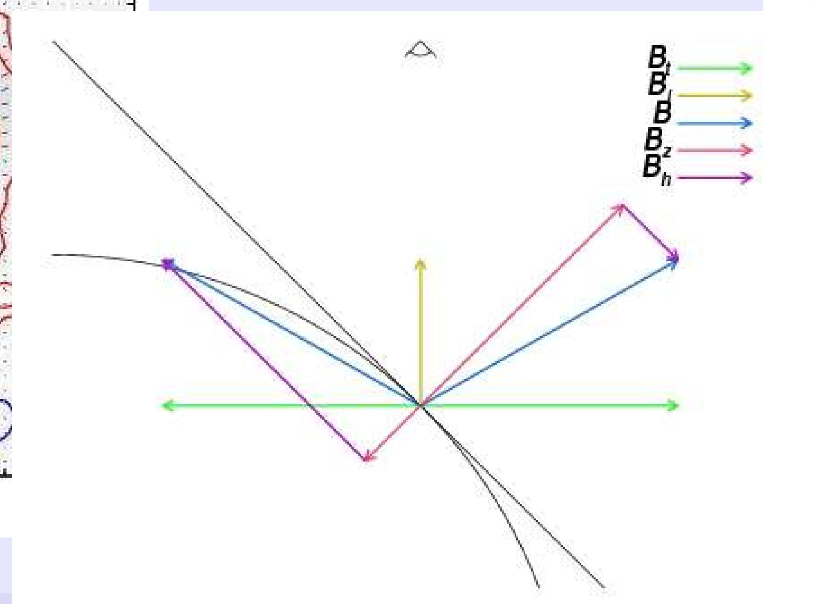
Heliographic *B* results.

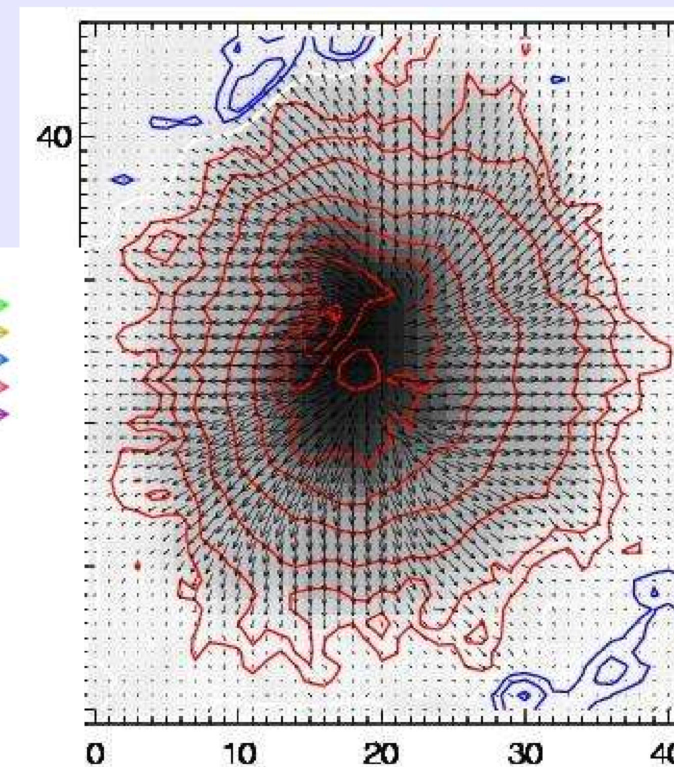
↓ (note shift in neutral line)



← Observed B_{los}, B_{trans}, ϕ

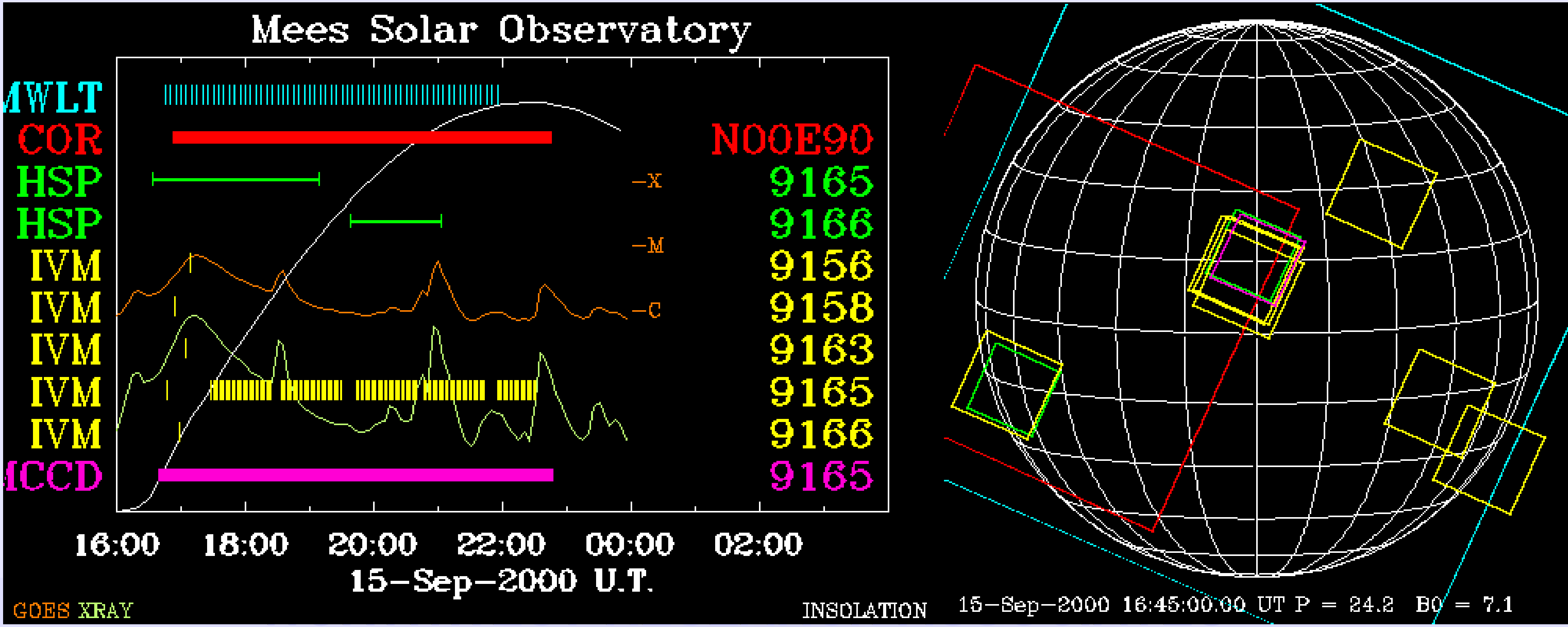
↓ B_{trans} direction is chosen.





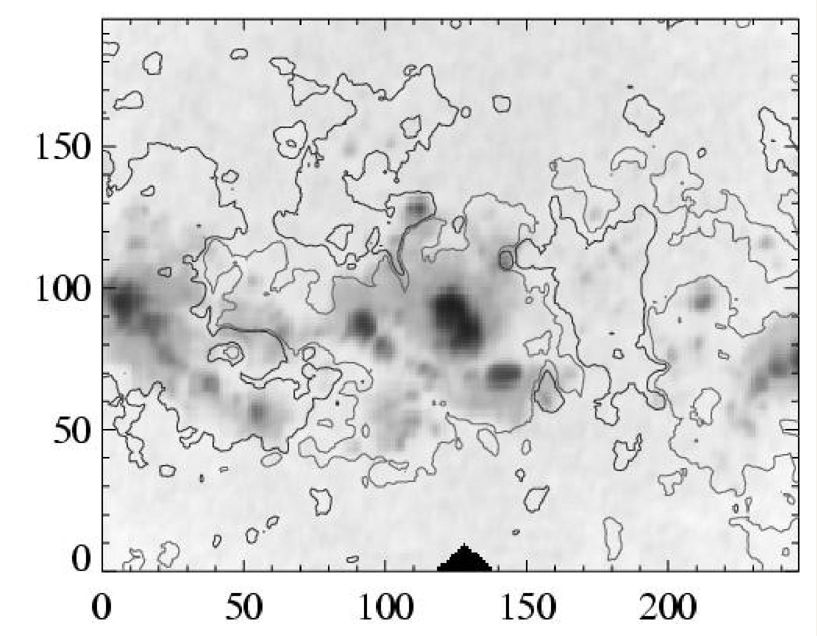
Measuring the Photospheric Magnetic Field cont'd: **Instrument**

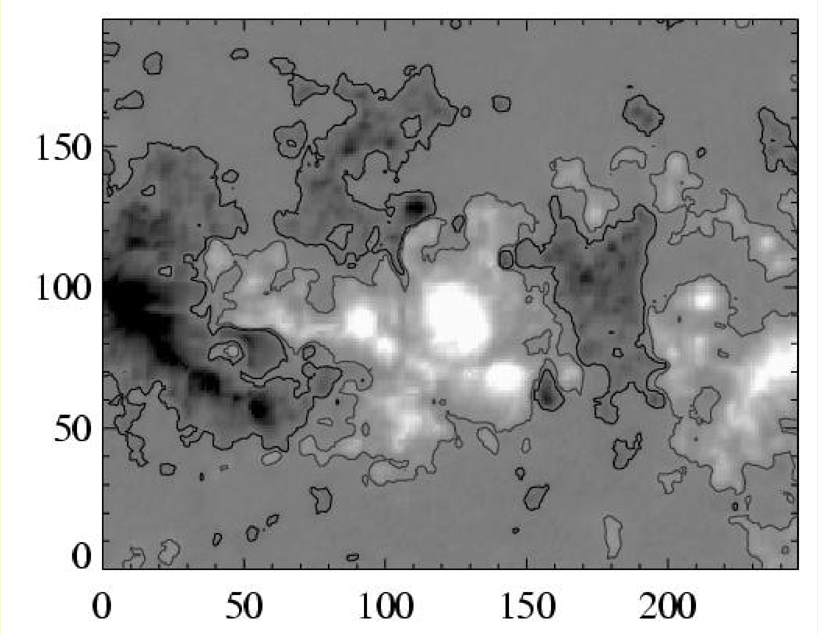
- Imaging Vector Magnetograph at U. Hawai`i/Mees Solar Observatory
  - Imaging Fabry-Perot system
  - 4' field-of-view, 0.55" spatial resolution, 0.07nm spectral resolution
  - polarization spectra sampled @ 30 positions across FeI 630.25nm line, g_L=2.5
  - Few-minute cadence
- Routine observing sequence:
  - "Survey" magnetograms (single magnetograms of every visible active region)
  - Time-series observations of target region (chosen by Max Millenium program or similar campaign).
  - Generally synoptic operation since 1992; large data base available.



Path #1: Time-Series of active region *B*

- **Data**:
  - Focus on 1-hr prediction windows:
    - 10 "flare" *vs*. 14 "flare-quiet" epochs
    - 7 Solar Active Regions, all with moderate—high flare activity
  - Full consideration of errors and uncertainties, including "seeing"



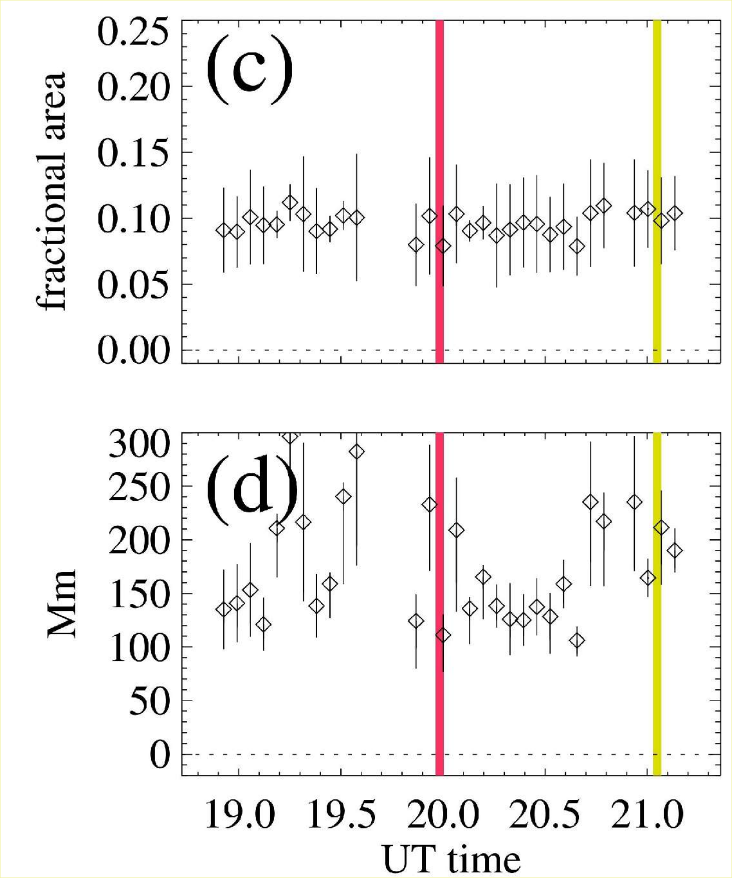


Data from the IVM of NOAA AR10030, 15 July 2001.
Left: continuum image, scale is in Mm; *Right*: Radial component of the magnetic field, positive/negative (white/black). For each "pixel", the full magnetic vector ***B*** is measured.

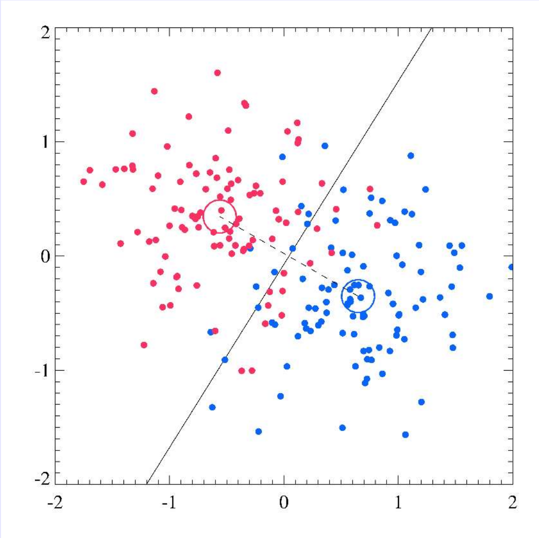
Leka & Barnes 2003 a,b

- **Analysis**:
  - Characterize the distribution, morphology, and complexity of the photospheric magnetic field.
    - Consider >100 variables derived from ***B****(x,y)*
    - Variables based on spatial gradients, comparisons to a potential field, twist, current helicity, energy density
  - Parameterize to get "single number" descriptors
    - Use moments of the spatial distributions.

Time series from AR10030, parameters derived from the magnetic shear angle ψ (angular difference between the observed horizontal field and that expected from a potential field). *Top*: fractional area of the active region with ψ ≥ 80°, *Bottom*: length of magnetic neutral line with ψ ≥ 80°. The start times for GOES X-class and M-class flares are indicated by vertical bars.



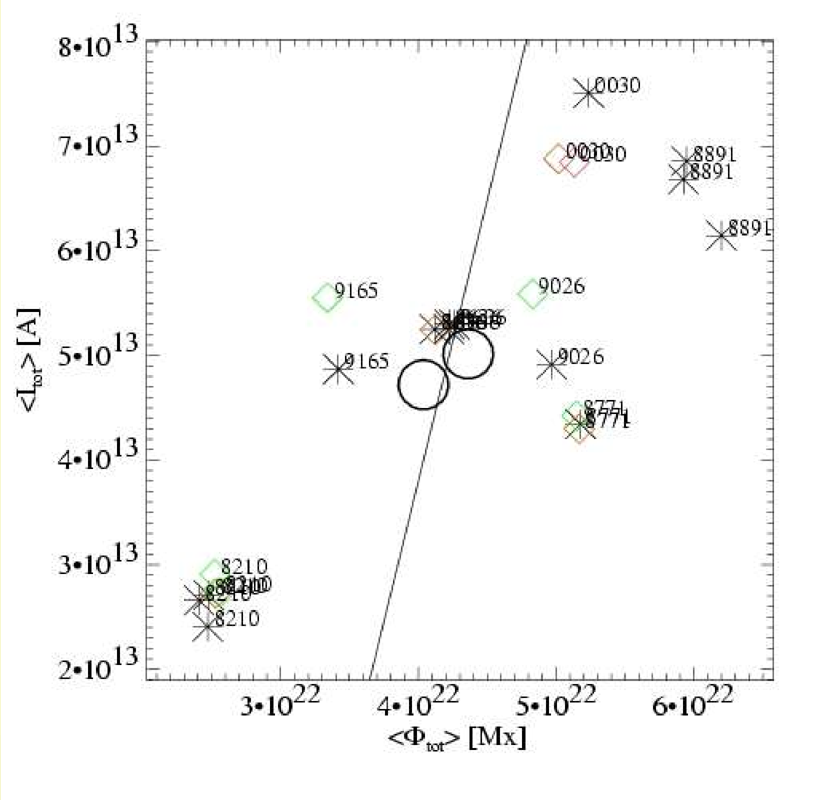
Analysis, cont'd: **Discriminant Functions**



- Data sample two known populations (*e.g.*, flaring vs. flare-quiet)
- Discriminant function is constructed to best separate the samples (minimize the number of “misses”):

$$f(x_1, x_2, \ldots x_n) = a_0 + a_1 x_1 + \ldots a_n x_n$$

- Statistical evaluation of whether samples originate from different populations via Hotelling's T^2 test
  - Power of variable x_n for “prediction” described by $|a_n|$
  - A new observation is “classified” as flaring/flare-quiet according to its observed $x_1, \ldots x_n$, and where it falls relative to the DF line



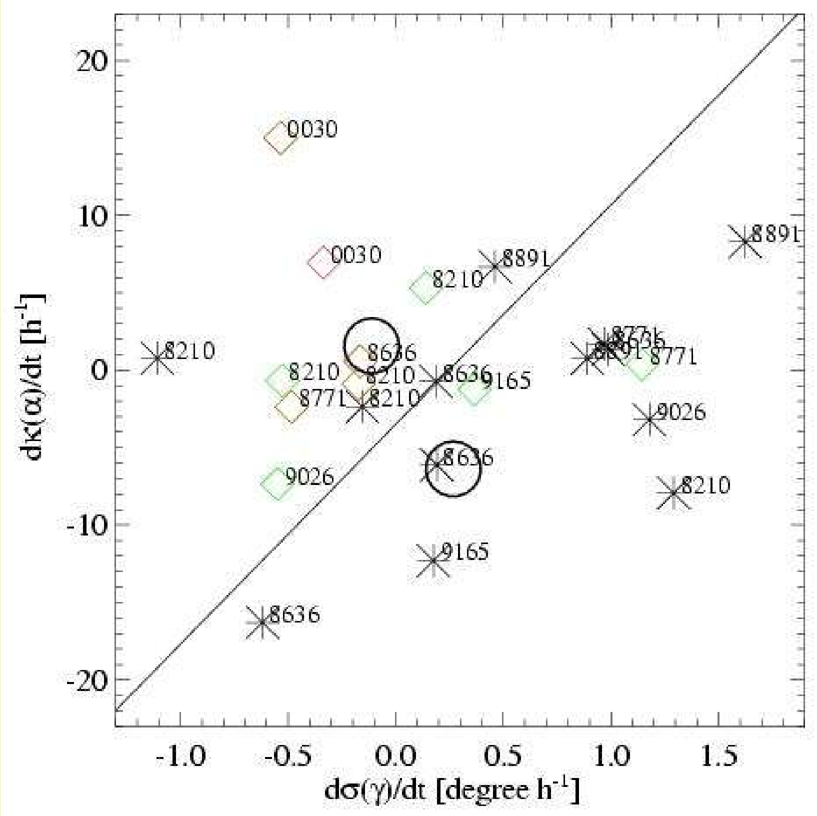
Example 1: Discriminant function regarding the total magnetic flux and the total electric current in active regions:

$$f = 0.0052 - 0.289 \langle \Phi_{tot} \rangle + 0.067 \langle I_{tot} \rangle$$

Graph: DF and the data for Flare-quiet (*) and flaring (◊,◊,◊ for C, M, X flares) points, plus the distribution means (O) are shown.

T^2 probability that the samples originate from different populations: 0.33.

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



Example 2: Better performing and *completely* unintuitive:

$$f = 0.115 - 1.312\, d(\sigma(\gamma))/dt + 1.434\, d(\kappa(\alpha))/dt$$

T^2 probability that the samples originate from different populations: 0.94.

Predicted / *Observed*

	flare	no flare
flare	8	2
no flare	4	10

- ***Multiple Variables can be included simultaneously.***
  - 6-variable example:

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

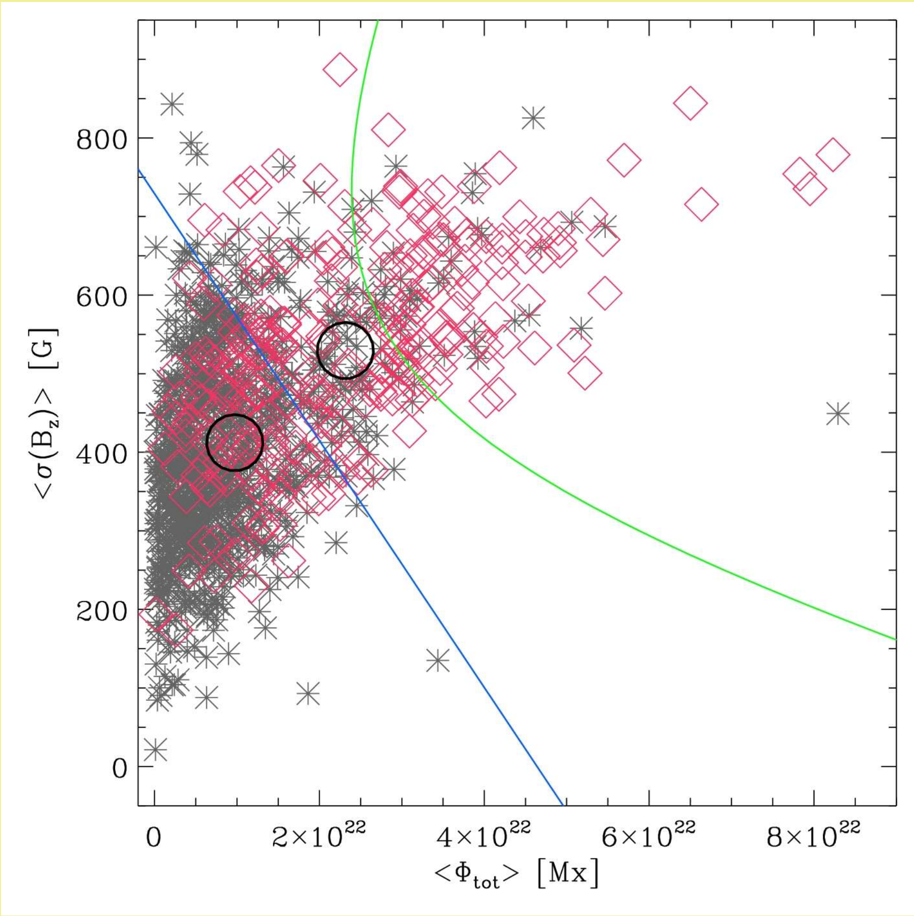
Predicted / *Observed*

	flare	no flare
flare	10	0
no flare	0	14

  - T^2 Probability: 0.9999
- Statistical flukes are highly likely: this is a *demonstration*.

Path #2: Quantifying, Objectifying Daily Flare Forecasts

- Focus on *1-day* prediction window with IVM "survey data" archive
  - Same parameterization of ***B*** morphology
  - Better statistics: over 1,100 data points (2000, 2001, part of 2002 so far...)
  - More sophisticated implementation of Discriminant Analysis, accounting for:
    - Unequal covariance matricies
    - Unequal population sizes



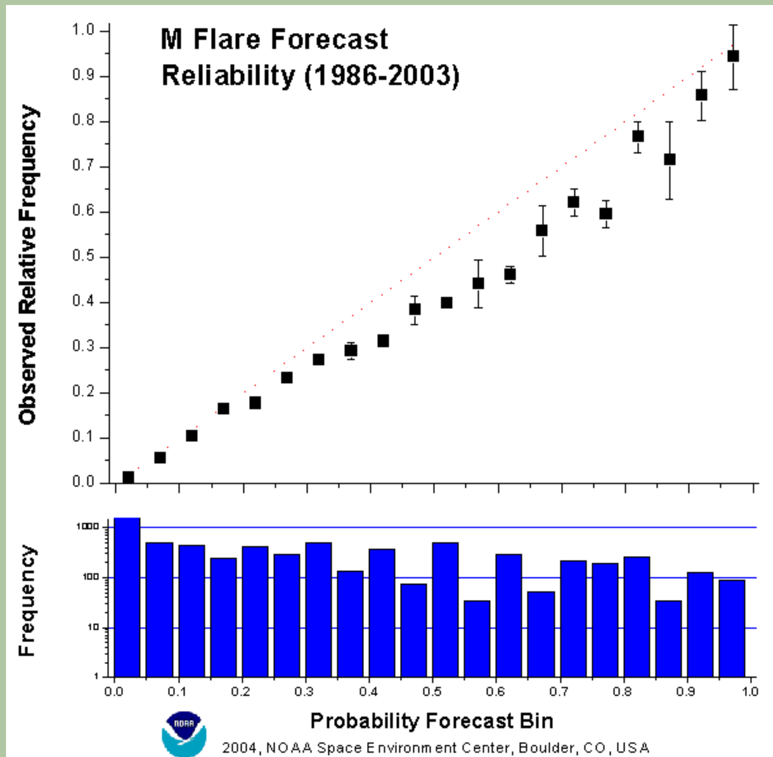
Discriminant functions for daily ***B*** data, relating aspects of the total magnetic flux and the distribution of *Bz*. Flare-quiet (*) and flaring (◊) points, and the distribution means (O) are shown, as are linear DF assuming equal covariance of the populations (—), and quadratic DF accounting for unequal populations (—).

T^2 probability of separate populations: 1.0000

(—) success rate: 0.816

(—) success rate: 0.820 :

Observed \ *Predicted*	flare	no flare
flare	93	170
no flare	42	877

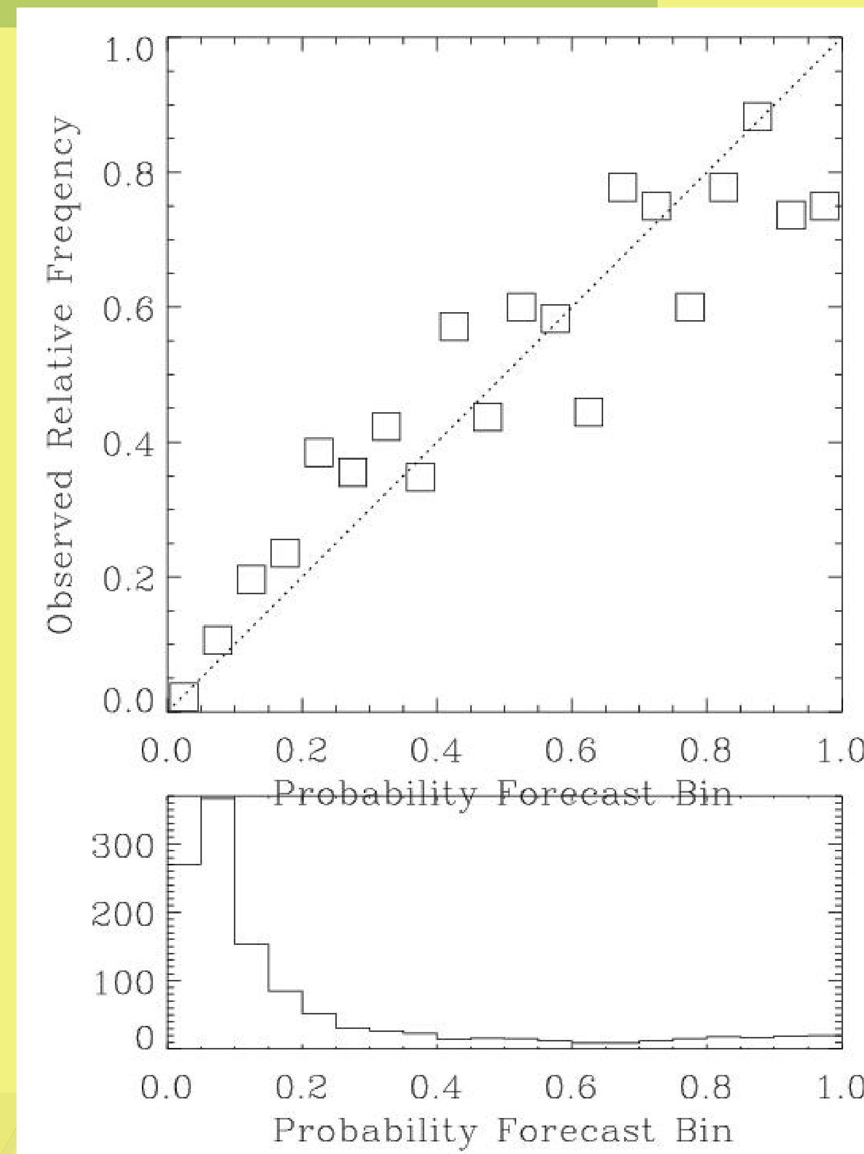


NOAA/SEC:

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

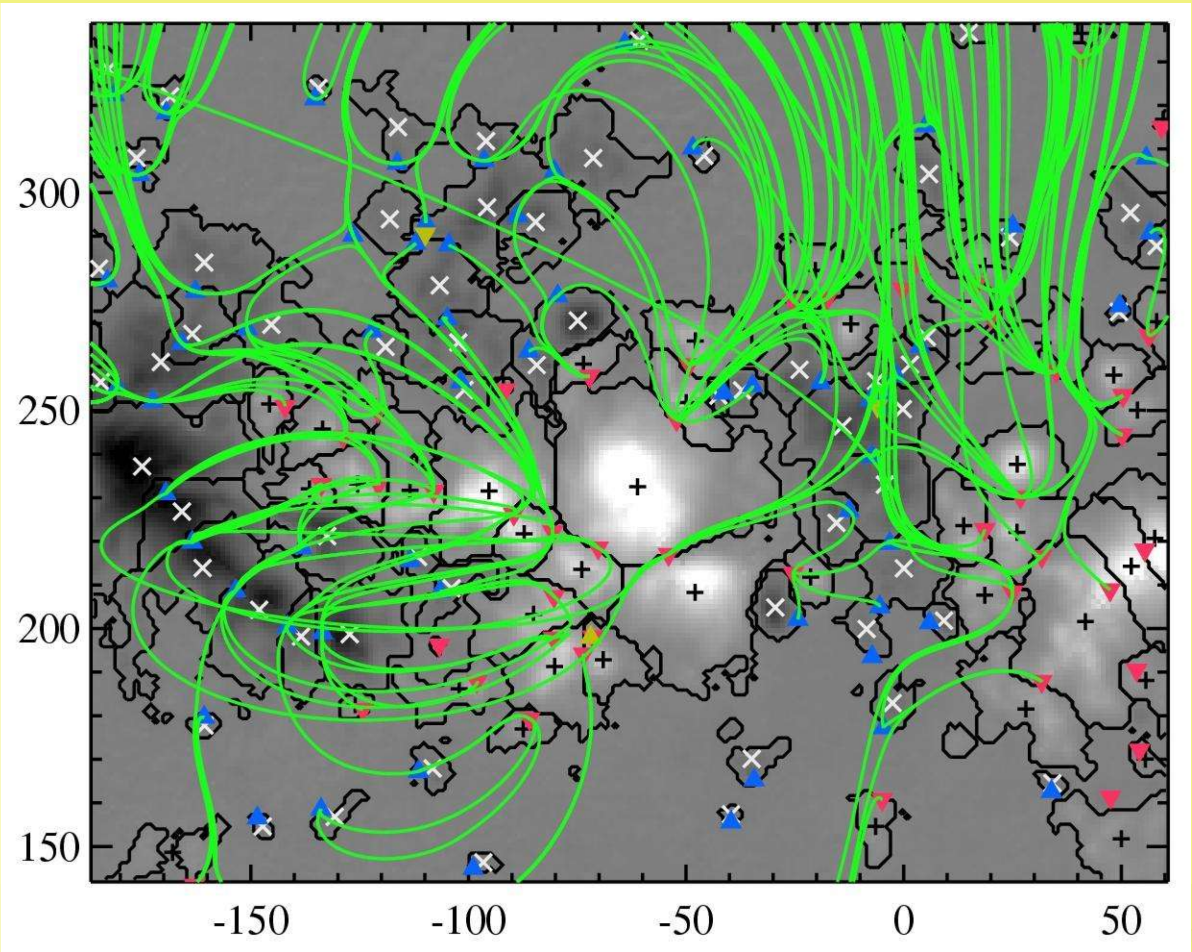
Magnetic Field & DFA:

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



Path #3: The Coronal Complexity

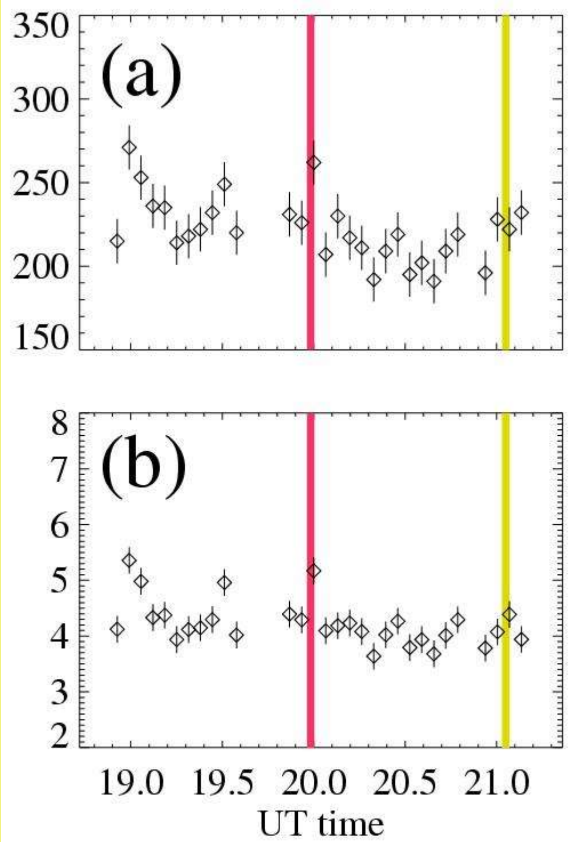
- Magnetic reconnection believed to occur in the solar corona
  - Use photospheric ***B*** to investigate *coronal* ***B***
- **Magnetic Charge Topology** model
  - Partition the ***B*** maps, model as point sources, potential-field extrapolation, determine the coronal connectivity matrix
  - Characterize the coronal topology by the magnetic connectivity, distribution and character of magnetic nulls and separators.

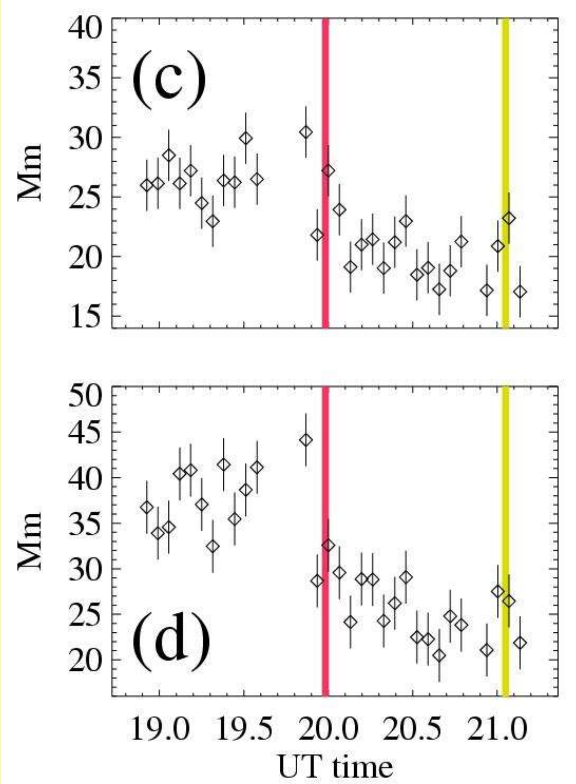


MCT analysis of NOAA AR10030 with 113 sources. “A” , “B” and upright null points (▼ , ▲ , ▽) and separator field lines (—). Axes are in megameters.

Barnes, Longcope & Leka 2005

- **Analysis**:
  - Variables constructed from MCT model to reflect the likelihood for magnetic reconnection and the topological response to active region evolution
  - Parameterize to obtain “single number” description of the coronal fields' topology, again using distribution moments.
  - Focus (again) on 1-hr epochs in time-series data

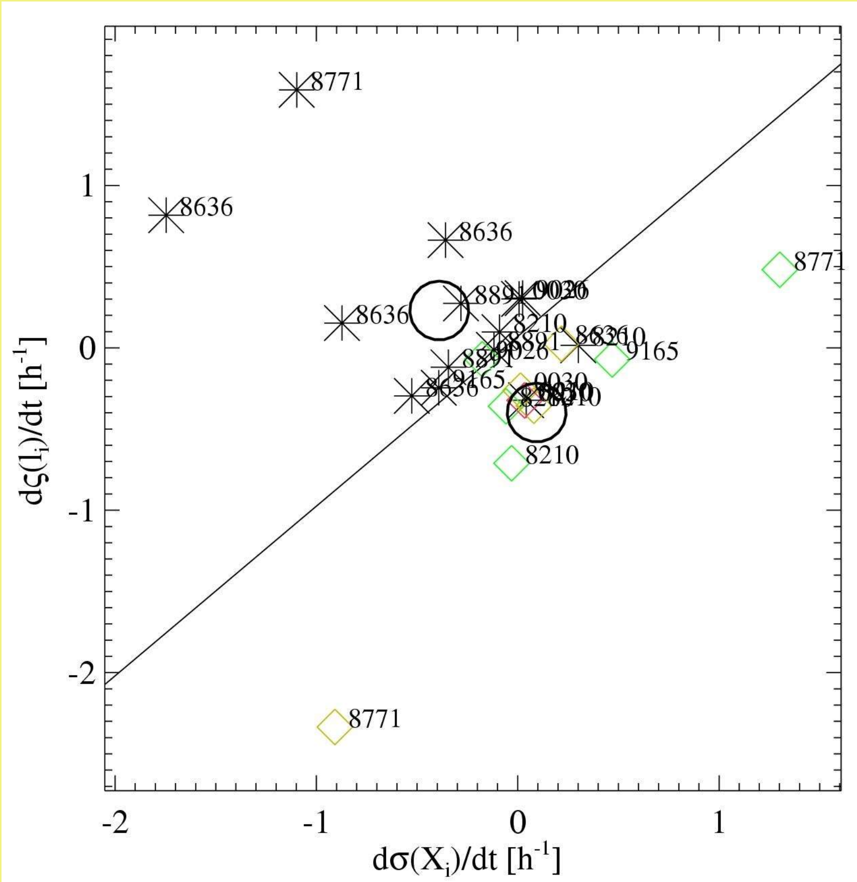




For NOAA AR10030, (a) the total number of separators and (b) the standard deviation of the number of separators associated with each magnetic null point, (c) the mean height of the separators and (d) the standard deviation of the heights. The start times for the X-class and M-class flares are indicated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

Barnes & Leka 2005, submitted

Discriminant Function Analysis of MCT model



Example: Two-variable DF for the temporal variation of the standard deviation of number of separators per null (x-axis) *vs.* the temporal variation of the skew of separator lengths (y-axis).

T^2 probability: 0.974

Observed \ *Predicted*	flare	no flare
flare	9	1
no flare	2	12

- ***Only 4 variables*** *now needed simultaneously for a "perfect" classification table:*

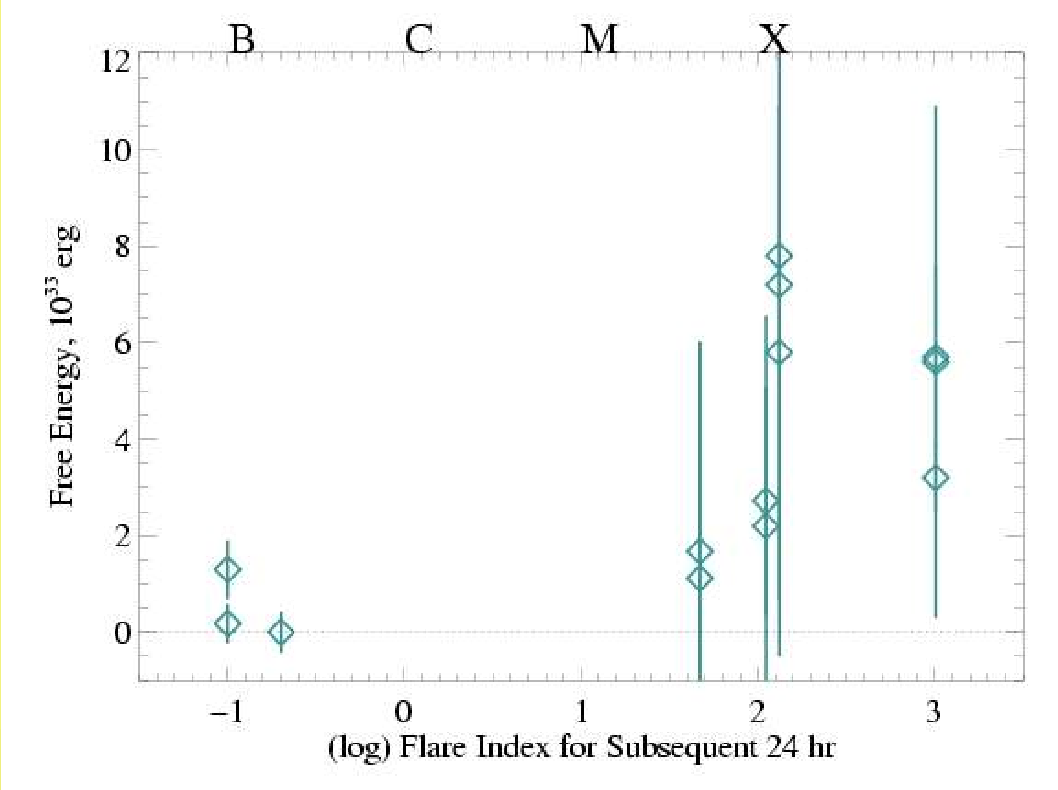
$$f = 0.26 - 1.02\frac{d}{dt}\varsigma(\psi_{ij}) + 1.80\frac{d}{dt}\sigma(X_i) - 1.62\frac{d}{dt}\varsigma(l_i) + 1.09\langle\sigma(r_{ij},\psi)\rangle$$

- MCT provides better probabilities overall of discriminating the populations: **the *Corona* may better indicate whether/when an active region will flare*.**

* statistical "gotchas" still *very* possible.

Path #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 using the ***magnetic virial theorem.***
- Results: preliminary.
  - Measurements are difficult.
  - New capability for the IVM, analysis is on-going
  - Goal: Parameterization and DF analysis of time-series, "survey", and MCT using chromospheric vector magnetograms.
  - *Preliminary:* Free energy associated with flare productivity (maybe?):



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…

Leka, Metcalf & Barnes 2005, in preparation

So, back with the numerical modeler and the forecaster, KD (*and collaborators*) join their table....

To the modeler:

"The flux emergence and shearing-footpoints are nice, but have you tried temporally increasing the kurtosis of the force-free twist parameter? A topology with a bigger skew in the flux enclosed by the magnetic separators?"

To the forecaster:

"We're working on it! Active-region class and coronal-brightness evolution should give way to parameters from the photospheric field and coronal topology. *Maybe,* shorter-range forecasts will even be possible."

Concluding Remarks

"Magnetic Field Properties of Flaring vs. Flare-Quiet Active Regions"

- The requisite approach: quantitative analysis including flare-quiet examples as control data, with an appropriate statistical analysis.
  - Obvious spin (AFOSR funding): produce physics-based objective solar flare prediction using observations of the solar magnetic field.
  - Side-benefit (why we keep having so much fun bugging our modeling friends): results to guide modeling efforts, as to the necessary boundary conditions and coronal topology.
- No single parameter derived from the photospheric magnetic field produces a unique flare signal.
- However, with
  - good vector-field data
  - multiple-variable statistical analysis
  - an approach to modeling the coronal topology
  - chromospheric field observations

we may have just found our way...