Measuring the Magnetic Free Energy Available for Solar Activity

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*[based in part on Metcalf, Leka & Mickey, ApJ 2005 , **653**, L53.*

Goal: Directly measure the energy in solar active regions available to power solar flares, as a method of evaluating active regions for imminent geo-effective activity.

What is the Magnetic Free Energy?

- The amount of magnetic energy *above* the potential energy that is stored and available for solar energetic events (flares, CMEs).
- Measurable using the magnetic virial theorem with the assumptions:
  - Full vector field is measured of all flux crossing the surface.
  - Field is force-free where it is measured, i.e. $J \times B = 0$
  - No magnetic flux leaves the measured area.

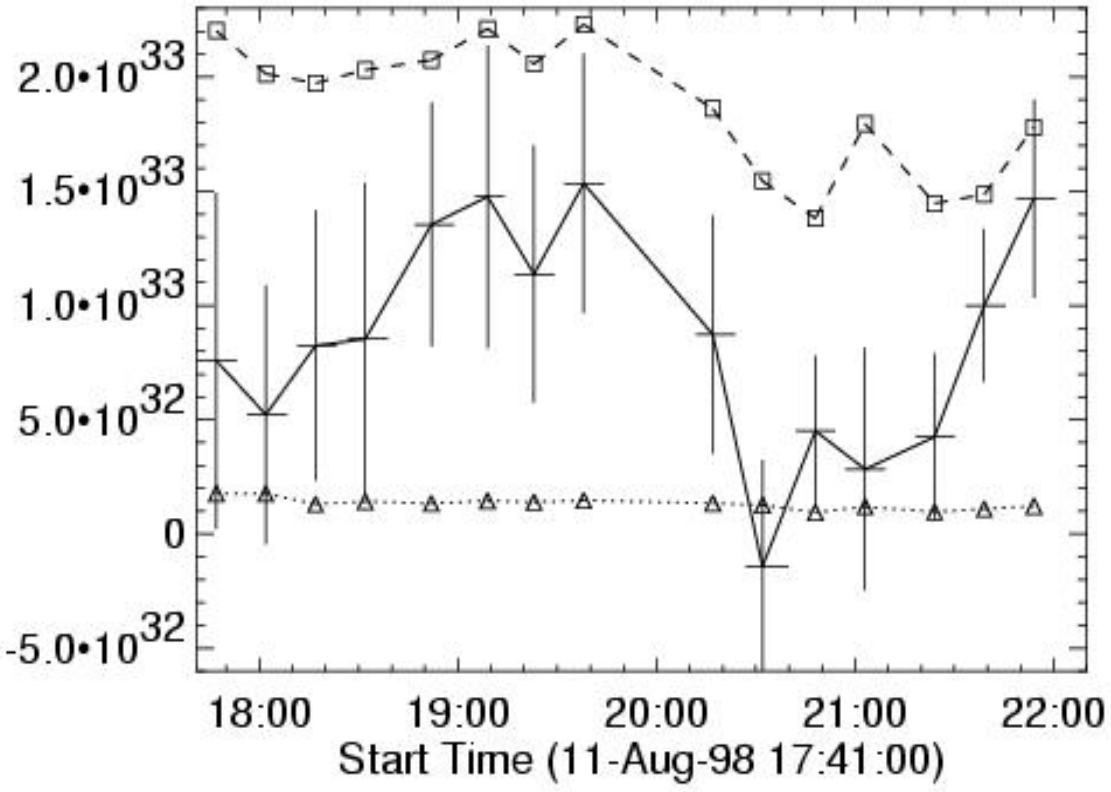
- Then, the *total* energy can be measured as:

$$E_{total} = 1/4\pi \int (xBx + yBy)\, Bz\, dx\, dy$$

- Subtracting the *potential* energy yields the *free* energy.
- If all assumptions are valid, the coordinate dependence disappears.
- Uncertainties in ***Bx, By, Bz*** as well as non-zero Lorentz forces and flux imbalance manifest as "errors" associated with E_{free}

Example: Time-series of energy measurements of AR8299 and a *possible* CME

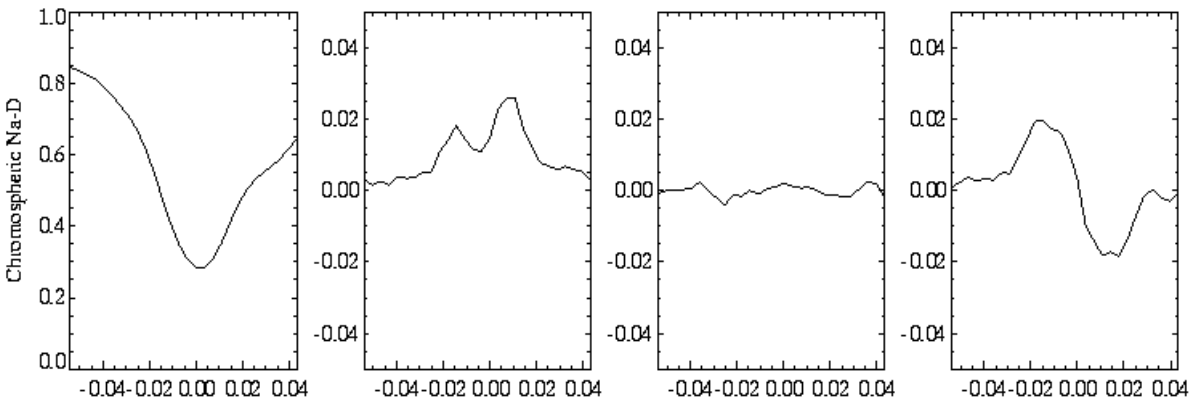
- ***B(x,y)*** measured using the Na D-2 line, formed in the force-free chromosphere, as pioneered a decade ago (*cf* Metcalf et al 1995).
- Resulting time-series indicated changes in magnetic free energy *coincident with* coronal reconfiguration (seen in Yohkoh images) although no GOES/SXR event was detected (Metcalf et al 2002).



The total magnetic energy (ergs) above the chromosphere in AR8299 (solid line) dips to value consistent with zero around the time of a CME. The vertical error bars indicate both statistical and systematic errors. The horizontal error bars indicate the time interval over which each observation was averaged. The dotted line shows the energy of the equivalent potential field and the dashed line shows the equivalent open field energy.

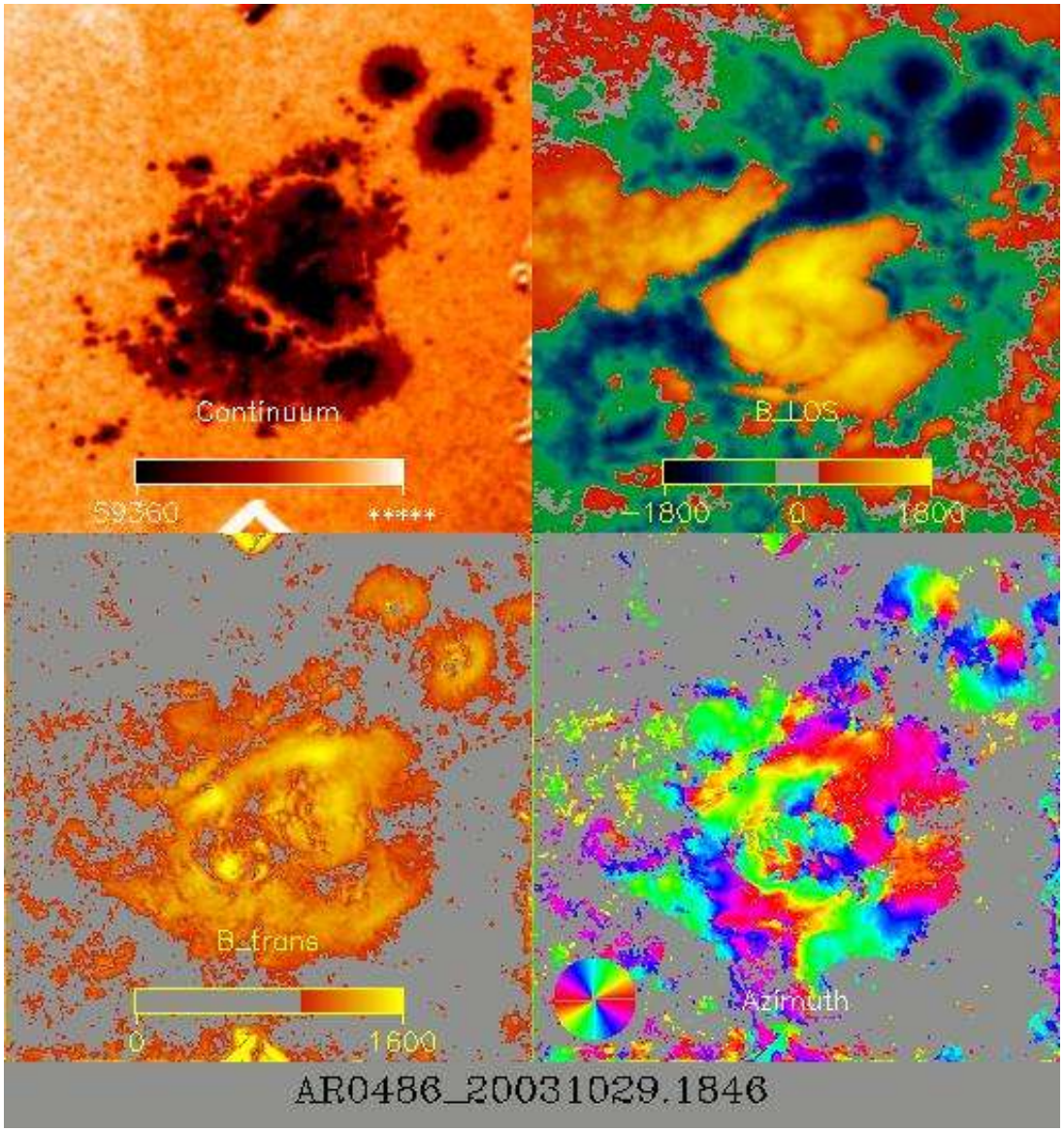
Stated (and Funded!) Goal: Routine Chromospheric Vector Magnetic Field Measurements and Routine Measurements of the Magnetic Free Energy in Solar Active Regions.

- Late 2003, the Imaging Vector Magnetograph (U. Hawai`i/ Mees Solar Observatory) was upgraded to enable *routine* vector field measurements in the chromospheric Na D-2 line:
  - High time cadence, large field of view.
  - Two observing modes:
    - single snapshot ("survey") magnetograms, daily
    - time-series on daily Max Millenium target
  - Data reduction is almost routine but not yet real-time.
    - "Jefferies/Lites/Skumanich" -based inversion
    - "minimum energy" ambiguity resolution method.

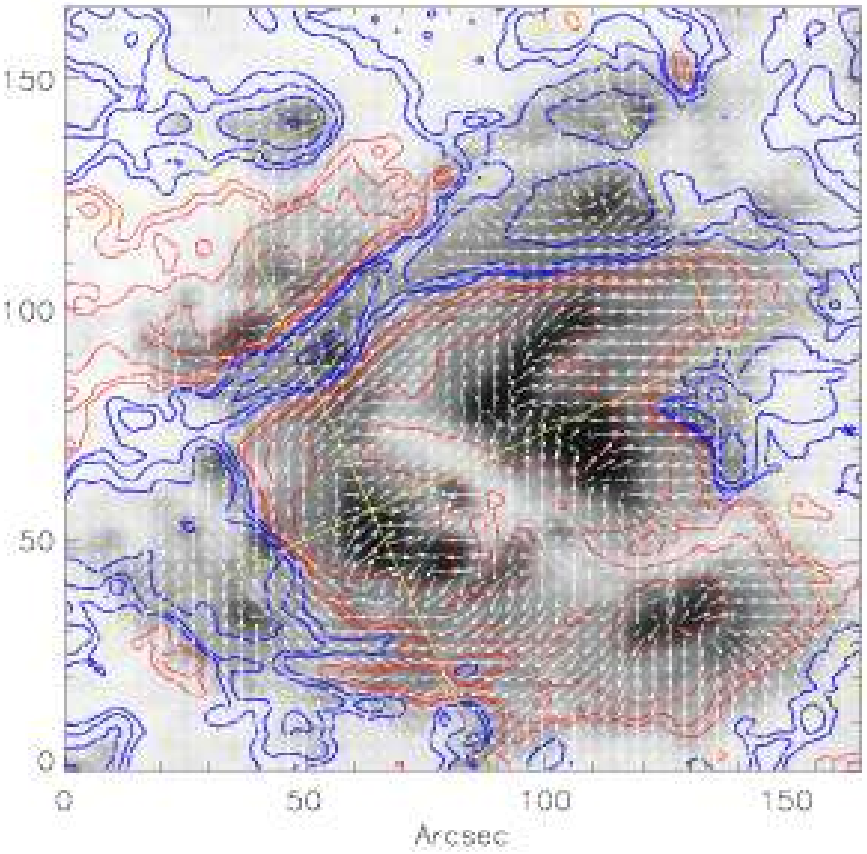


Example of Na D-2 spectra from the IVM, (left-right) I, Q, U, V from a sunspot penumbra; wavelength is in nm relative to 589.6nm line-center, and ordinates are continuum fraction (I) and polarization fraction (Q, U, V). Spectra such as these are sampled at 0.55" over 512^2 pixels from which the vector magnetic field is derived.

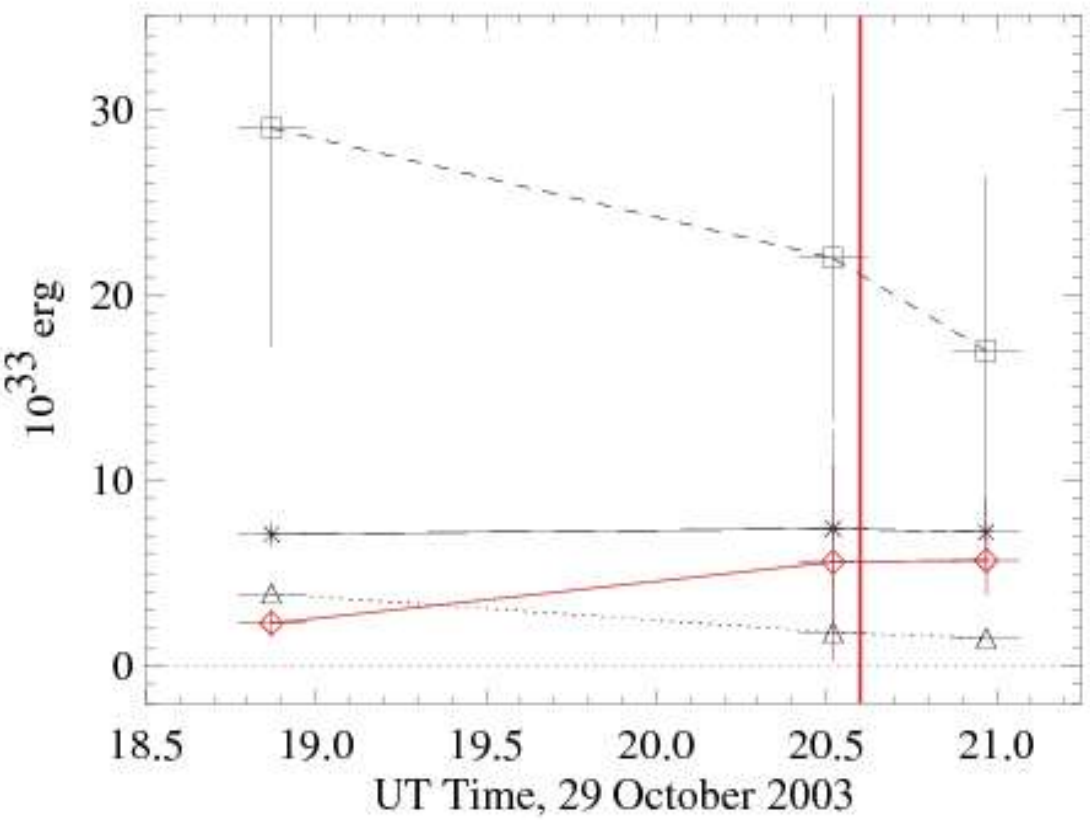
AR10486: Source of the 2003 Halloween Storms



Full field of view of the IVM chromospheric data, showing (Clockwise from top left) continuum intensity, line-of-sight field, transverse field, and its 180° ambiguous direction.



Detail of central portion of the same magnetogram, now with the vertical and directionalized horizontal field, still with only every 5th pixel shown. The multiple sheared magnetic neutral lines and extremely complex morphology is evident. Qualitatively, the magnetogram is indistinguishable from a photospheric magnetogram obtained an hour earlier. Quantitatively, the chromospheric field being force-free allows a measure of the magnetic energy.



Energies plotted for AR10486: open-field energy (□), potential-field energy (Δ), total energy (*) and magnetic free energy (◊). The start time of the X10 flare is indicated by the red line. Note that while the magnetic free energy increases prior to the flare, the error bars do as well.

Overall level of magnetic free energy, 3-5 x 10^{33} erg, was *very* large:

- A factor of 3 larger than earlier measurements of other active regions:
  - AR 7216, 1.2 ± 0.2 x 10^{33} erg (Metcalf et al 1995)
  - AR 8299, 1.3 ± 0.5 x 10^{33} erg (Metcalf et al 2002).

Enough free energy to produce the extreme activity observed, including the X10 flare at 20:36 UT.

- *Some* indication of increasing free energy just prior to the X10 flare
  - Increasing error bars due to increasing horizontal Lorentz forces, or worsening seeing effects, or both.
  - In any case, later data points are less significant.

Present Projects and Future Plans

- Analyze additional time-series of chromospheric vector magnetograms associated with flares (and flare-quiet times) for:
  - Differences in free-energy between flaring and flare-quiet times?
  - Free-energy variation that occurs uniquely prior to energetic events?
    - Better data (more complete time-series) do exist and are being reduced and analyzed now.
- Examine in detail both *global* and *local* measures of whether the chromosphere is force-free. Analysis includes:
  - Balance of net forces
  - Identifying local regions where $J \times B \neq 0$: possible since $d\boldsymbol{B}/dz$ is available with these data
  - Equal (force-free) vs. unequal (forced) distribution of $\alpha = J_z/B_z$ as a function of magnetic polarity.
- Q: Could the existence of localized forced regions be relevant to flare productivity?

Present Projects and Future Plans, *cont'd.*

- How do active region magnetic fields *quantitatively* differ between the photosphere and chromosphere, especially for regions capable of producing geo-effective energetic events?
  - Examine relevant *chromospheric* parameters for statistically significant numbers of active regions using Discriminant Analysis.
  - *N. B.*: a statistically significant number of data points requires *years* of data acquisition. Such data are available for the photosphere (see poster by Schumer et al.), but not yet for the chromosphere.
  - We will request funding to build a replacement for this aging, but so far unique, instrument. Ideally, a replacement instrument is needed for the next solar cycle. Any bidders?
- It is clear that the *chromosphere* is "the place to be", where *vector magnetic field* maps can provide information *most relevant* to solar energetic events. Use of chromospheric magnetograms is not ready for real-time forecasting, but hints are that these data could be extremely useful for that purpose.

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