The Magnetic Free Energy in Active Region 10486

T. Metcalf, K. D. Leka, D. Mickey

Coronal Energization by the Magnetic Field

- The corona is energized by the magnetic field through some poorly understood mechanism.
- The energization of the corona has a remarkable correlation with X-ray luminosity over **15** orders of magnitude

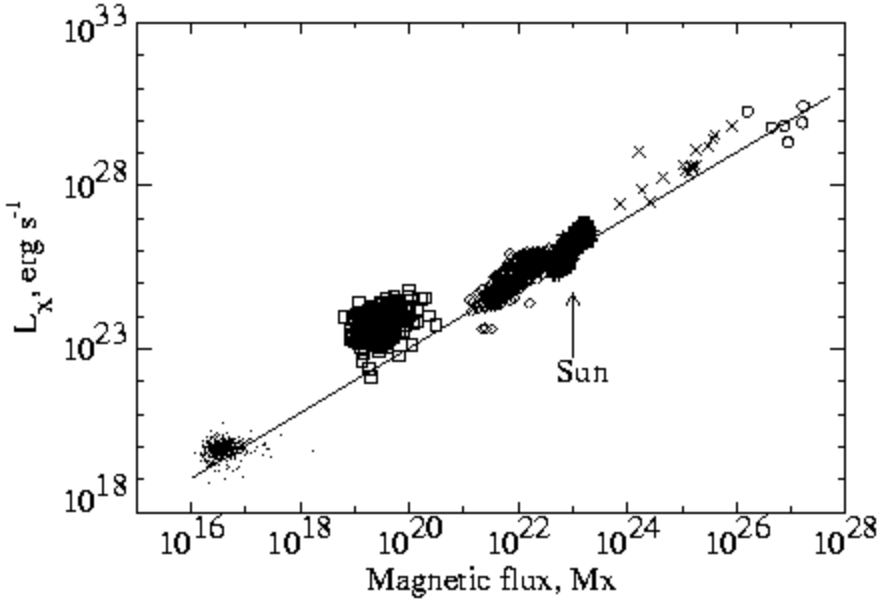


Fig. 1.— X-ray luminosity L_x vs. total unsigned magnetic flux for solar and stellar objects. Dots represent quiet Sun, squares are X-ray bright points, diamonds are solar active regions, pluses are solar disk averages, crosses are G, K, and M dwarfs and circles are T-Tauri stars. Solid line shows first degree polynomial approximation of all 6 data sets.

Pevtsov et al, 2001

What is the Energy Source for the Solar Corona?

- The only reasonable energy source is the magnetic field, but only by supposition. How much energy is really available?
- A current-free (potential) magnetic field carries significant energy, but this energy cannot be tapped: The potential field is the "minimum energy state".
- The *free energy* that is available to power the solar corona is the energy of the current-carrying system less the energy of the potential field, i.e. the energy that could be released in relaxing the field to a potential state.
- **We can now directly measure the free energy of the non-potential magnetic field.**

The Magnetic Virial Theorem

The virial theorem can be stated as an integral over a coronal volume (V):

$$\int dm\, \mathbf{F}_M \cdot \mathbf{r} = \int dV\, \mathbf{r} \cdot (\mathbf{j} \times \mathbf{B}) \ , \tag{A1}$$

where the Lorentz force is

$$\mathbf{F}_M = \frac{\mathbf{j} \times \mathbf{B}}{\rho c}, \ \mathbf{E} = 0 \ . \tag{A2}$$

The volume integral is converted to a surface integral using Gauss' Theorem and the current ($\mathbf{j}$) is eliminated using $\nabla \times \mathbf{B} = \frac{4\pi}{c}\mathbf{j}$:

$$\int dm\, \mathbf{F}_M \cdot \mathbf{r} = \frac{1}{8\pi} \int B^2\, dV + \int_S (\mathbf{B} \cdot \mathbf{r}) \frac{\mathbf{B} \cdot d\mathbf{S}}{4\pi} - \int_S B^2 \frac{\mathbf{r} \cdot d\mathbf{S}}{8\pi} \ , \tag{A3}$$

where S is the surface bounding the integration volume in equation (A1).

$$\frac{1}{8\pi} \int B^2\, dV = - \int_S (\mathbf{B} \cdot \mathbf{r}) \frac{\mathbf{B} \cdot d\mathbf{S}}{4\pi} \ .$$

Application of the Virial Theorem

- All the terms in the Magnetic Virial theorem are, in principle, observable:

$$E_{ff} = \frac{1}{4\pi} \int_{z=z_0} (xB_x + yB_y) B_z \, dxdy$$

Chandrasekhar & Fermi (1953); Molodenskii (1969); Low (1984); Aly (1984)

- BUT, The virial theorem is applicable only when:
  - the field is force-free
  - the field falls to zero on the boundary.

Validity of the Virial Theorem

- So, the magnetic field must be observed above the photosphere where the field is force-free before the virial theorem can be applied.
- The energy equation itself can be used to demonstrate the validity of the assumptions that go into the calculation using the dependence on the coordinate system.

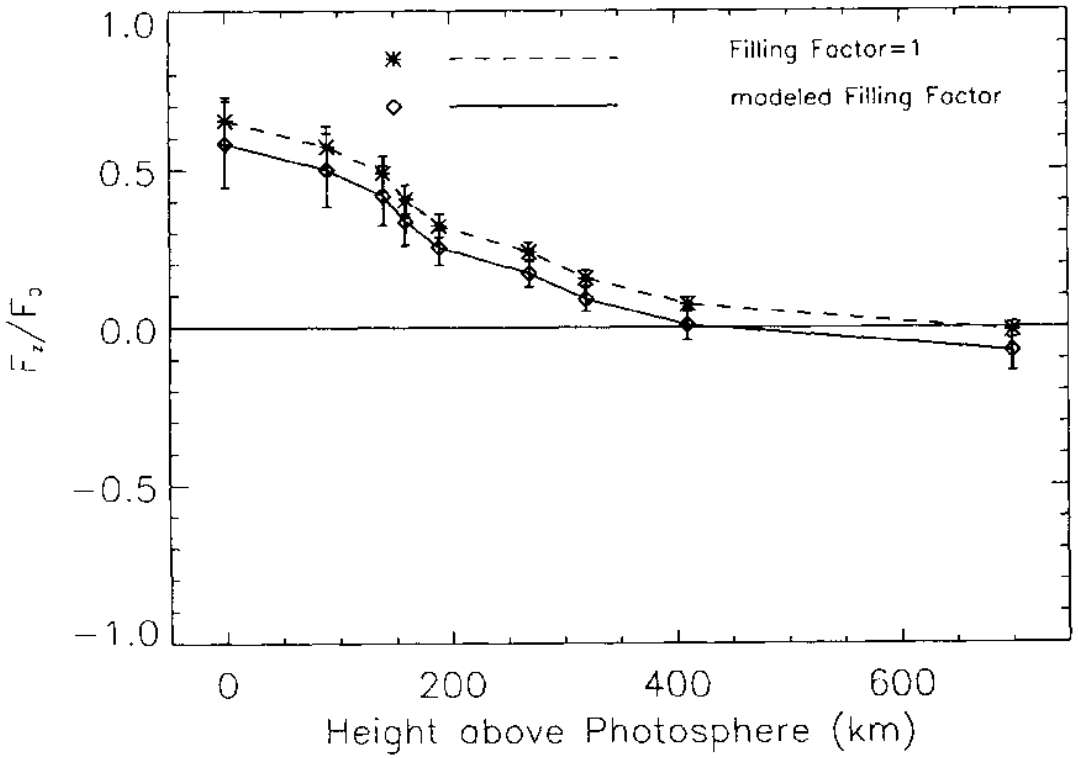
$$E_{ff} = \frac{1}{4\pi}\int_{z=z_0}(xB_x + yB_y)B_z\ dxdy$$

$$F_x = \frac{1}{4\pi}\int_{z=z_0} B_xB_z\ dxdy$$

$$F_y = \frac{1}{4\pi}\int_{z=z_0} B_yB_z\ dxdy$$

The Vector Field in the Chromosphere

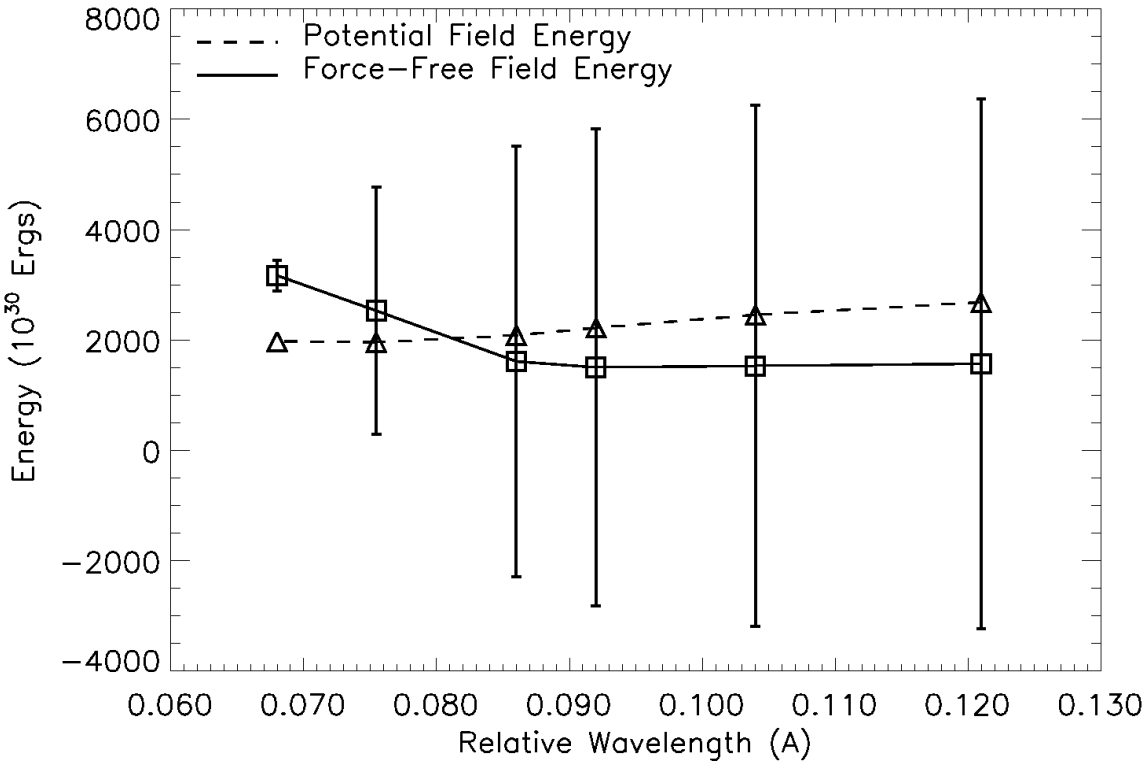
- The magnetic field in the chromosphere is force-free.



AR 7216
1992 July 3

Metcalf et al., 1995

First Observations of the Free Energy



AR 7216
1992 July 3

Metcalf et al., 1995

- The virial theorem does not apply in the photosphere where the field is forced but does apply in the chromosphere.

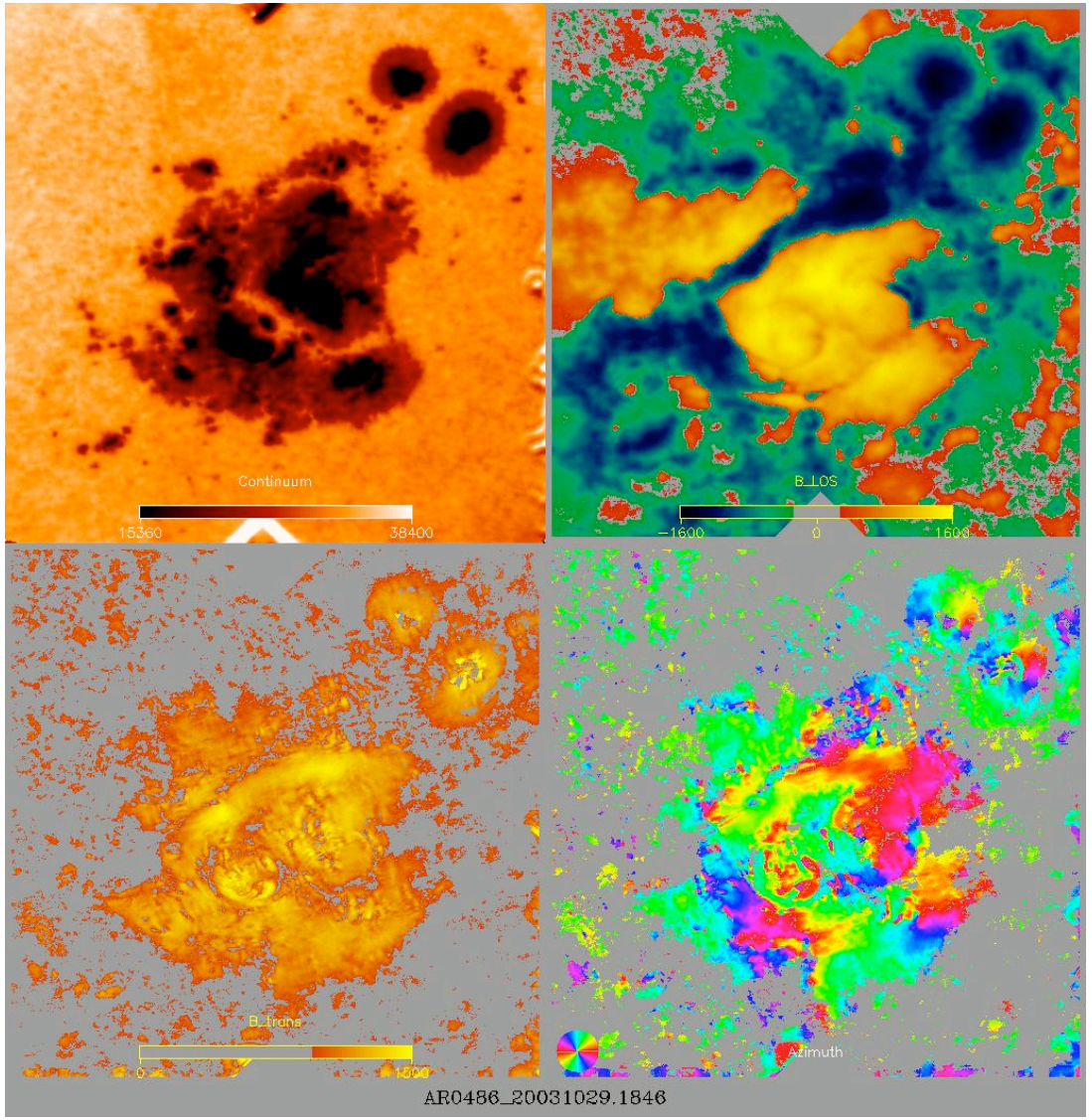
New Observations of the Free Energy

- To observe the chromospheric magnetic field, we use the Imaging Vector Magnetograph looking at the Na D1 line
- The Na-D1 line is imaged across the line using a Fabry-Perot etalon to select the wavelength. 4 images are used to derive the Stokes parameters at each wavelength.
- The Na-D line is observed every few minutes, but the data are averaged to a coarser time resolution to increase the S/N.
- The pixel size is 0.55"

October 29, 2003, 18:46 UT

Chromospheric vector magnetogram before the X10 flare

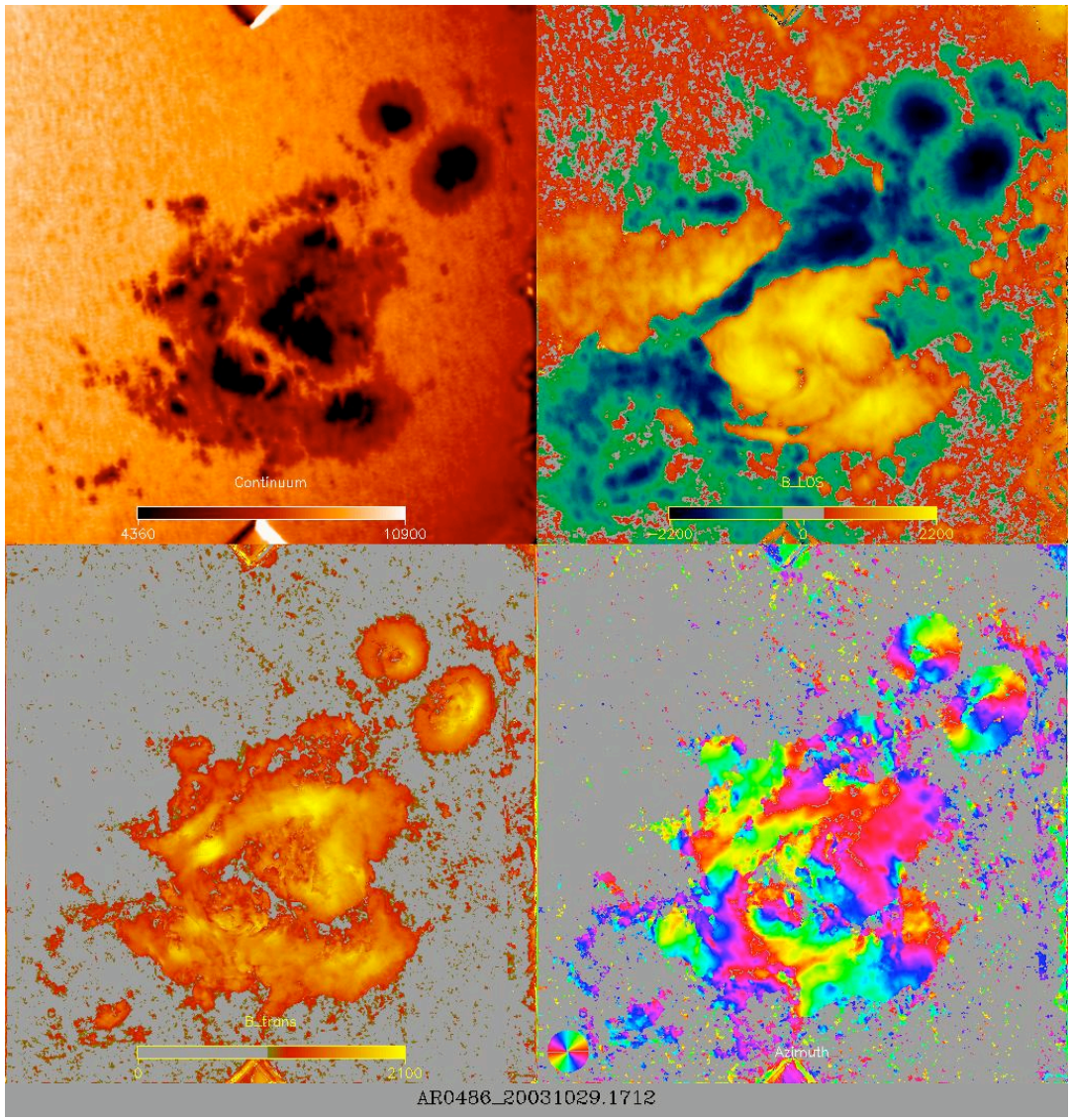
The X-flare started about 20:35 or so



October 29, 2003, 17:12 UT

For comparison, a *photospheric* vector magnetogram before the X10 flare

The X-flare started about 20:35 or so



October 29, 2003: Energetics

18:46 UT, Magnetic energy in ergs

Total Magnetic Energy	$(11.9 \pm 2.3) \times 10^{33}$
Potential Magnetic Energy	3.3×10^{33}
Free Magnetic Energy	$(8.6 \pm 2.3) \times 10^{33}$
"Open Field" Energy	67.1×10^{33}

- 2 hours before the large X flare, AR10486 had an unusually large amount of free energy.
- This is not really surprising, considering the level of activity.

October 29, 2003: Energetics

Energetics as a function of time

		$(8.6 \pm 2.3) \times 10^{33}$
18:46	Free energy (ergs)	$(19.3 \pm 8.2) \times 10^{33}$
20:26-20:36	Free Energy	
20:41-20:47*	Flare	$(9.5 \pm 5.5) \times 10^{33}$
20:52-21:03	Free Energy	

- There is plenty of free magnetic energy available to power the extreme activity in AR10486.
- Later in the day, the noise is much higher due to deteriorating seeing and due to the flare itself.
- The energy just before the flare may have increased, but the change is not statistically significant.

Future Observations

- Can we see a drop in the free energy in association with solar flares? Not on October 29 due to bad seeing, but this should be possible with better observations.
- How does the free energy build up prior to a CME or flare?
- What is the predictive power of the free energy observations? Is there an energy threshold beyond which an energetic event is likely to occur?
- Does the magnetic free energy heat the active region corona? Or does the magnetic field only act as an intermediary for some other heating mechanism?

Conclusions

- The magnetic field in the chromosphere is force-free.
- Hence the virial theorem is applicable and the free magnetic energy has been directly measured, for AR 10486 on October 29, 2003.
- AR10486 contained plenty of free energy to power the extreme activity.
- However, changes in the free energy associated with the Oct 29 flare are difficult to discern.