


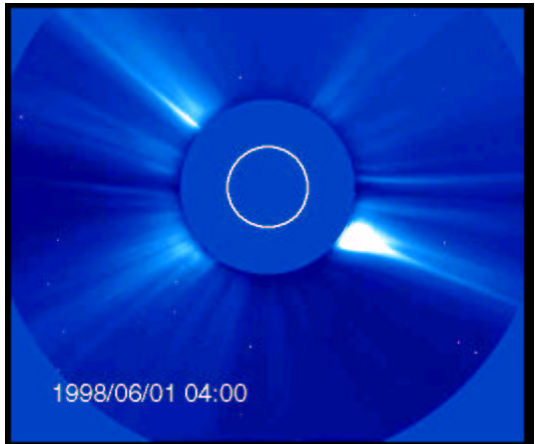
## The Magnetic Free Energy in Active Regions

T. Metcalf, K. D. Leka, D. Mickey, B. LaBonte,  
and L. Ryder

### Energetic Events on the Sun are Common - I



- A Coronal Mass Ejection (CME) Observed with SOHO/LASCO
- Typically, these events have energies of  $10^{32}$  ergs.



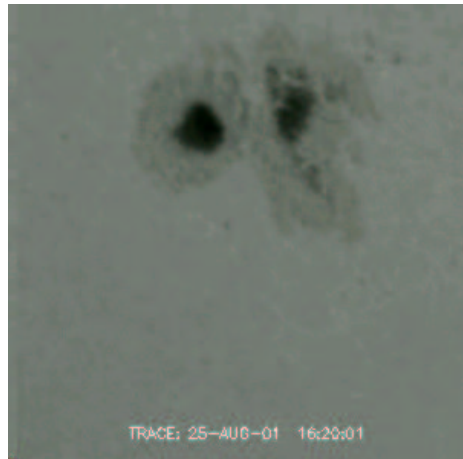
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## Energetic Events on the Sun are Common - II



- A White Light Flare observed by TRACE.
- Large flares have typical energy release in excess of  $10^{32}$  ergs.



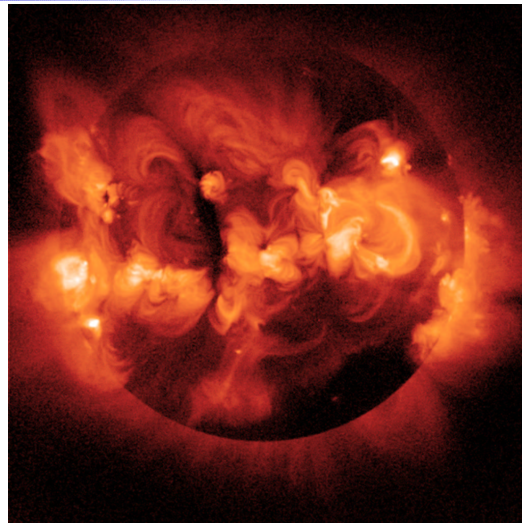
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## Energetic Events on the Sun are Common - III



- A full-disk X-ray image from Yohkoh/SXT
- The solar corona is heated in some way that is related to the magnetic field.



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## 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

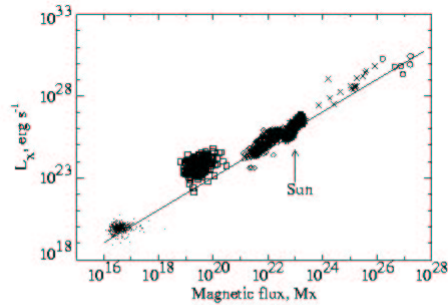


Fig. 1.— X-ray luminosity  $L_x$  vs. total unsigned magnetic flux for solar and stellar objects. Dots represent quiet Sun, squares are X-ray bright points, diamonds are solar active regions, pluses are solar disk averages, crosses are G, K, and M dwarfs and circles are T-Dauri stars. Solid line shows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

Pevtsov et al, 2001

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## 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.**

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## The Magnetic Virial Theorem

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

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

where the Lorentz force is

$$\mathbf{F}_M = \frac{\mathbf{j} \times \mathbf{B}}{c}, \quad \mathbf{E} = 0. \quad (\text{A2})$$

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

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

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

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

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## Application of the Virial Theorem

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

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

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.

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### 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.

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

$$F_x = \frac{1}{4\pi} \int_{z=z_0} B_x B_z dx dy$$

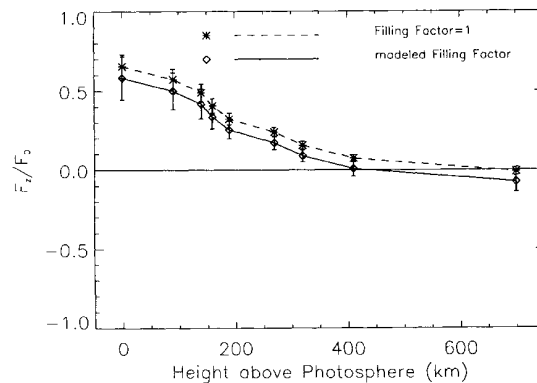
$$F_y = \frac{1}{4\pi} \int_{z=z_0} B_y B_z dx dy$$

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### The Vector Field in the Chromosphere

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

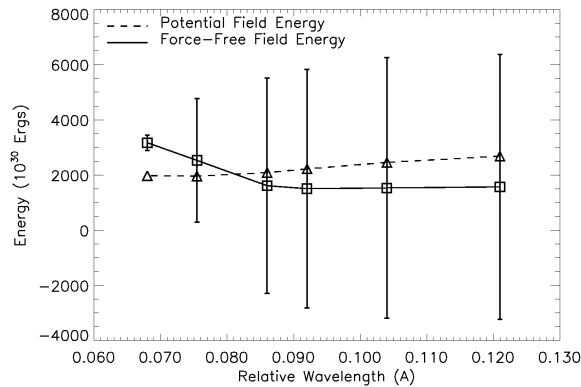


Metcalf et al., 1995

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## First Observations of the Free Energy



Metcalf et al., 1995

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

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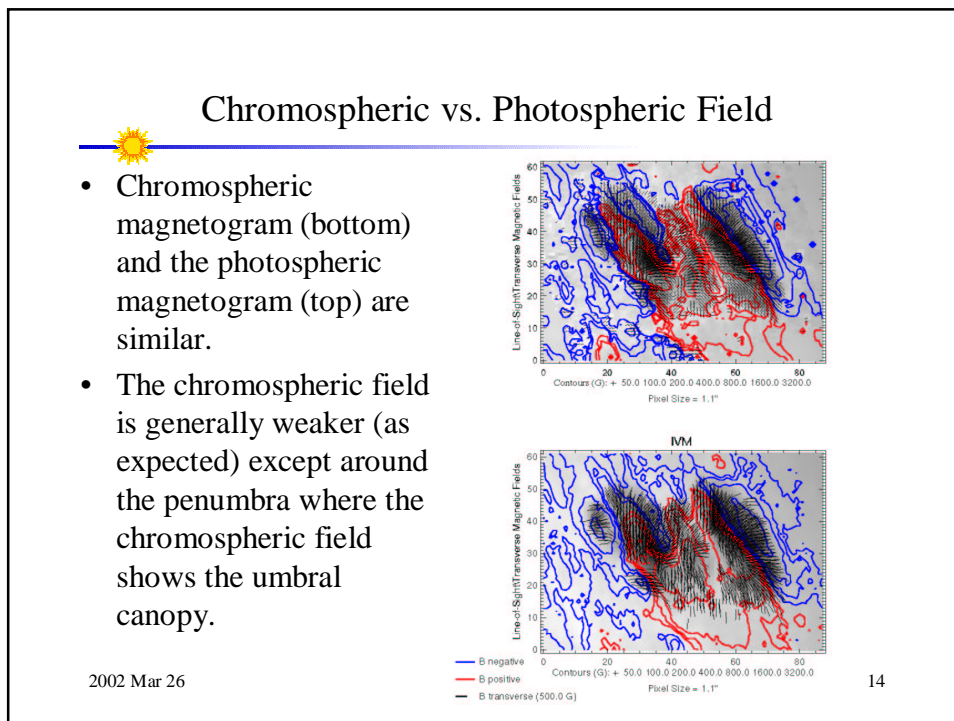
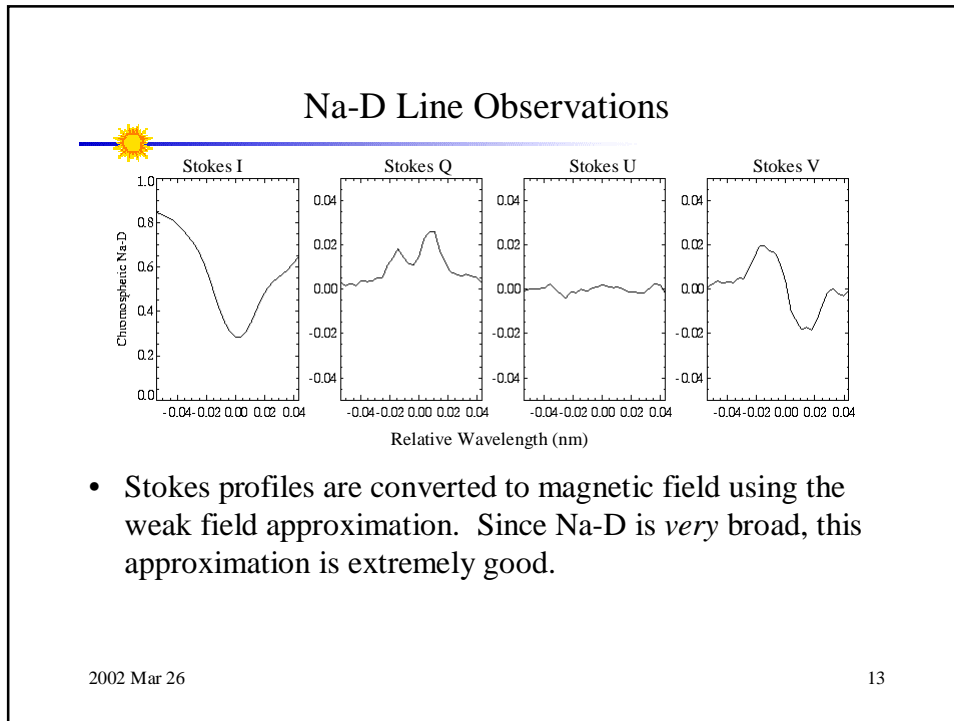
## New Observations of the Free Energy



- Recently, Metcalf, La Bonte, Mickey, and Ryder obtained observations of the free energy as a function of time using the Imaging Vector Magnetograph (IVM) at Mees Solar Observatory.
- The Na-D 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 15 minute time resolution to increase the S/N.
- The pixel size is 1.1"
- Noise level: 50 G in LOS and 150 G in transverse field.

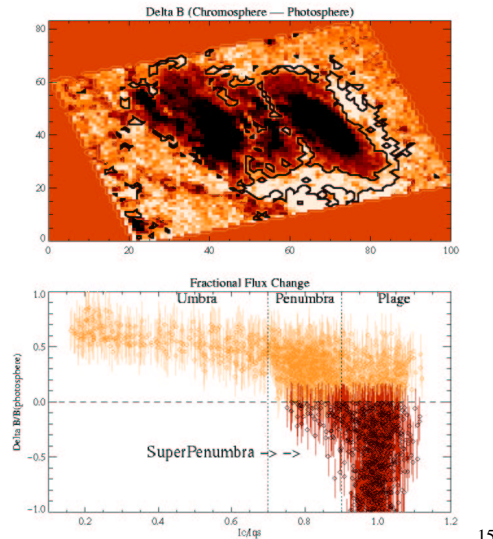
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## Chromospheric vs. Photospheric Field - II

- The umbral canopy is seen around the edge of the sunspot penumbra.

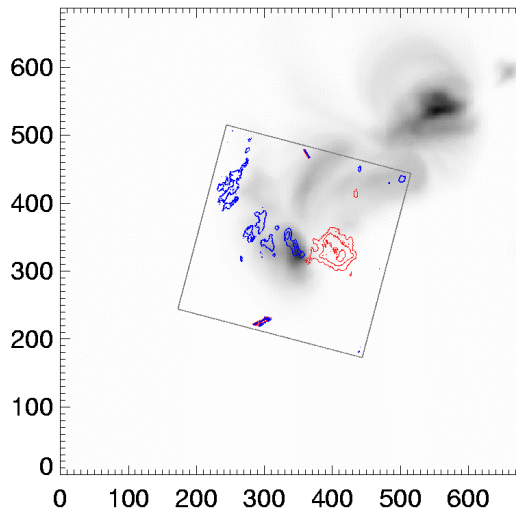


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## AR 8299 - Free Energy

- SXT image with chromospheric magnetic field.
- AR8299 and AR8297 are connected.
- Does the virial theorem apply?



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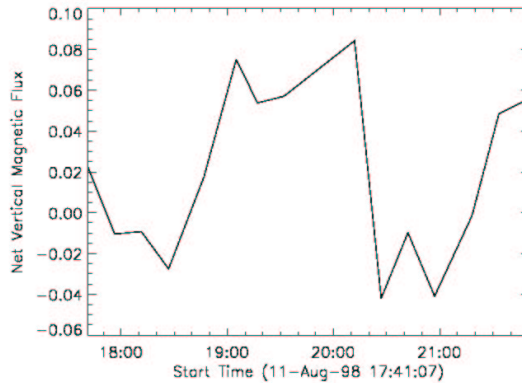
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### Flux Transfer to AR8297



- Using  $\nabla \cdot \mathbf{B} = 0$ , the net vertical field is the net field leaving the active region. The flux loss is no more than 8% and the virial theorem is applicable.



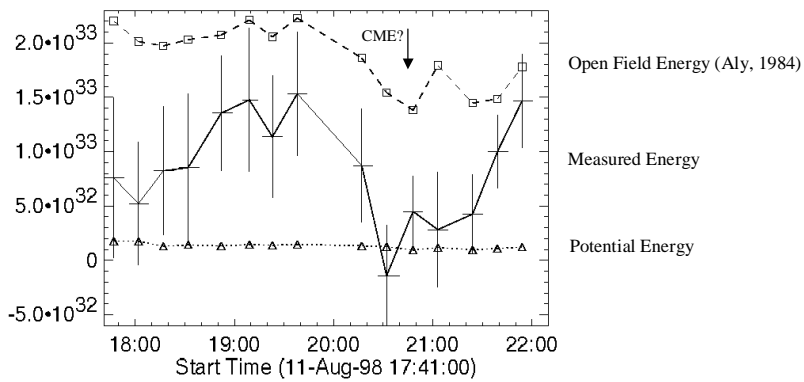
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### The Magnetic Free Energy

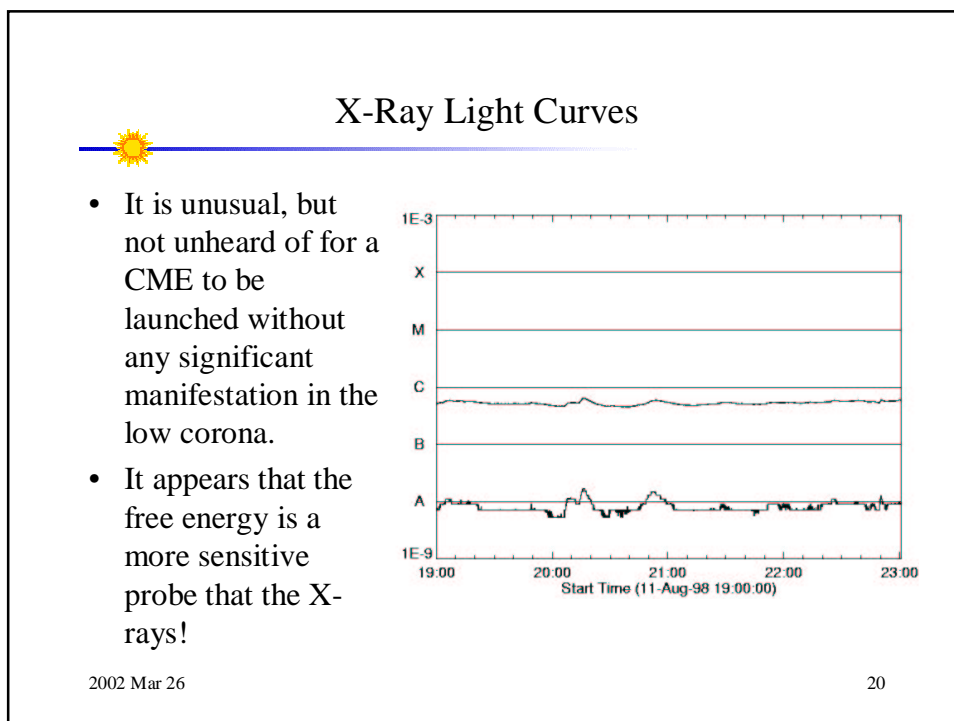
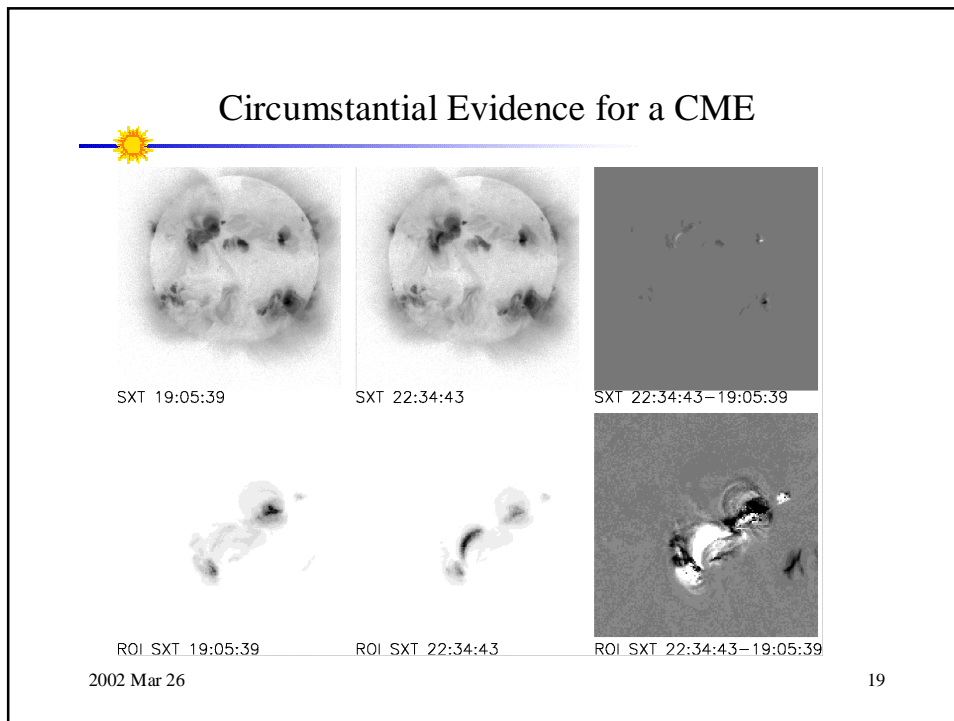


- We can measure the magnetic free energy with the chromospheric boundary condition.



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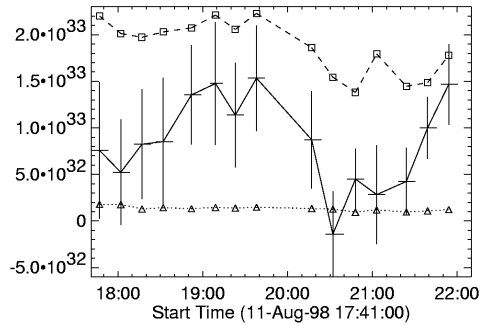
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### Implications - I



- The magnetic field recovers to a more open state after the dip in the free energy.
- The free energy recovers quickly after the “event”:  $3 \times 10^{29}$  ergs/sec
- This implies that either:
  - New energy is injected into the system
  - More than one flux system is involved



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### Implications - II



- It is barely possible that this rapid increase is due to twisting of the field by photospheric motions if the twisting is done over a large area:

$$\dot{E}_z = \left[ \frac{1}{4\pi} \oint (\mathbf{v} \times \mathbf{B}) \times \mathbf{B} dS \right] = \frac{1}{4\pi} \oint B_z (\mathbf{B}_t \cdot \mathbf{v}_t) dS, \quad v_z \ll v_t$$

- $v = 1$  km/sec,  $B = 1000$  G  $\Rightarrow A > 4000$  Mm<sup>2</sup>
- But it seems more likely that pre-existing energy is injected into the system from below the photosphere or from the other active region.
- There is no new flux emergence so it is likely that more than one active region is involved in the CME.

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### Implications - III

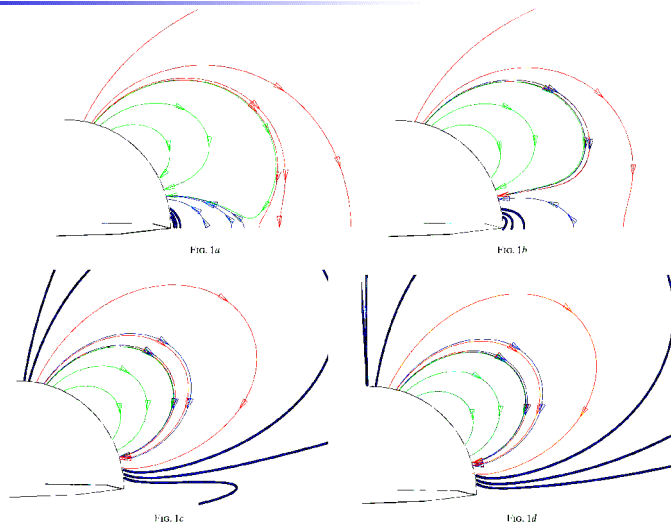


- The Aly-Sturrock theorem tells us that the open field has more energy than the closed field.
- It thus seems energetically impossible for the magnetic field to power a CME.
- However, if more than one flux system is involved, the theorem no longer applies.
- This is the “Breakout Model” of Antiochos, DeVore and Klimchuk.
- *Our observation is consistent with this model.*

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### Implications IV - The Breakout Model



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## Future Observations

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- Does the restructuring of the magnetic field result *from* the CME or *in* the CME? What is the cause and effect?
  - Are multiple flux systems always involved in CME's?
  - Can we see a similar drop in the free energy in association with solar flares?
  - 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?

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## Conclusions

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- 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 the first time.
  - This is the first *direct* demonstration that the corona can be energized by the free energy in the magnetic field.
  - In AR8299 a significant drop in the free energy apparently corresponded to a CME. After this event, the field was in a more open state, consistent with the Breakout Model.
  - More observations are clearly called for to verify this direct link from the magnetic free energy to the CME process.

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