Hinode 6 Abstract

The Limit of Free Magnetic Energy in Active Regions

Ron Moore, David Falconer, Alphonse Sterling

By measuring from active-region magnetograms a proxy of the free energy in the active region's magnetic field, it has been found previously that (1) there is an abrupt upper limit to the free energy the field can hold that increases with the amount of magnetic field in the active region, the active region's magnetic flux content, and (2) the free energy is usually near its limit when the field explodes in a CME/flare eruption. That is, explosive active regions are concentrated in a main-sequence path bordering the free-energy-limit line in (flux content, free-energy proxy) phase space. Here, from measurement of Marshall Space Flight Center vector magnetograms, we find the magnetic condition that underlies the free-energy limit and the accompanying main sequence of explosive active regions. Using a suitable free-energy proxy measured from vector magnetograms of 44 active regions, we find that (1) in active regions at and near their free-energy limit, the ratio of magnetic-shear free energy to the non-free magnetic energy the potential field would have is ~1 in the core field, the field rooted along the neutral line, and (2) this ratio is progressively less in active regions progressively farther below their free-energy limit. This shows that most active regions in which this core-field energy ratio is much less than 1 cannot be triggered to explode; as this ratio approaches 1, most active regions become capable of exploding; and when this ratio is 1 or greater, most active regions are compelled to explode. From these results we surmise the magnetic condition that determines the free-energy limit is the ratio of the free magnetic energy to the non-free energy the active region's field would have were it completely relaxed to its potential-field configuration, and that this ratio is ~1 at the free-energy limit and in the main sequence of explosive active regions.

This work was funded by NASA's Science Mission Directorate through the Living With a Star Research & Technology Program, the Heliophysics Guest Investigators Program, and the *Hinode* Project, and is published in The Astrophysical Journal (Moore, Falconer, & Sterling 2012, ApJ, 750:24).

The Limit of Free Magnetic Energy in Active Regions

Ron Moore, David Falconer, Alphonse Sterling

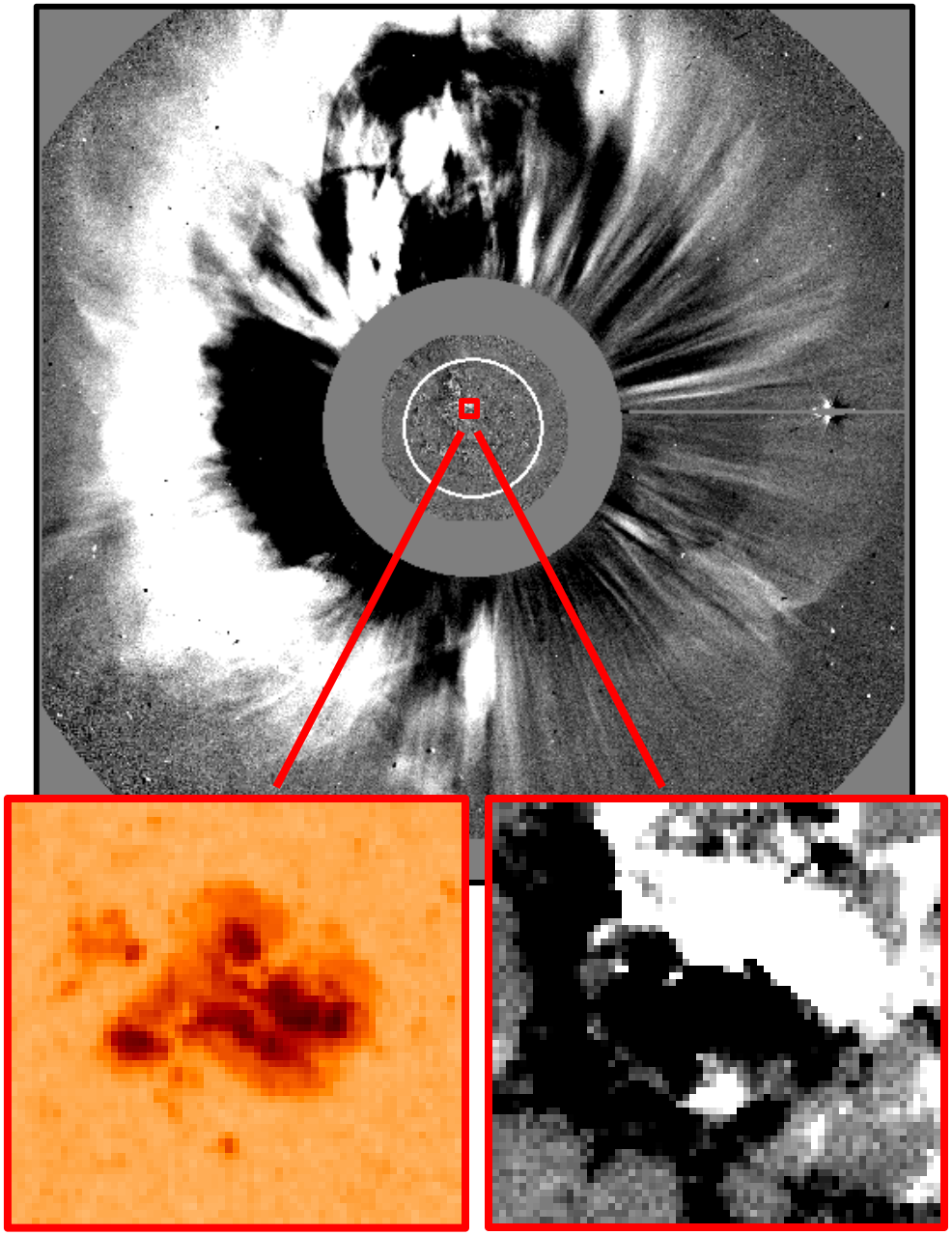
NASA/MSFC/UAHuntsville
National Space Science and Technology Center

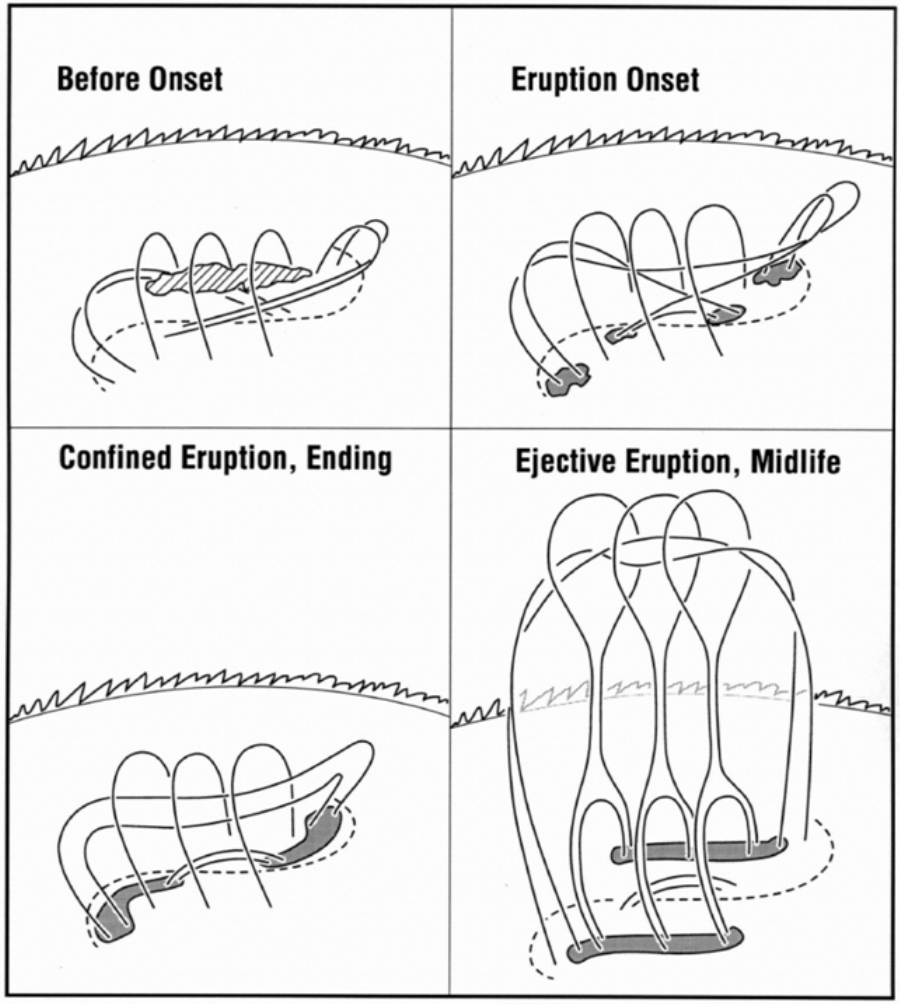
Abstract

By measuring from magnetograms a proxy of the free energy in active-region magnetic fields, it has been found previously that (1) there is an abrupt upper limit to the free energy the field can hold that increases with the amount of field in the active region, the active region's magnetic flux content, and (2) the free energy is usually near its limit when the field explodes in a CME/flare eruption. That is, explosive active regions are concentrated in a main-sequence path bordering the free-energy-limit line in (flux content, free-energy proxy) phase space. Here, from measurement of Marshall Space Flight Center vector magnetograms, we find the magnetic condition that underlies the free-energy limit and the accompanying main sequence of explosive active regions. Using a suitable free-energy proxy measured from vector magnetograms of 44 active regions, we find that (1) in active regions at and near their free-energy limit, the ratio of magnetic-shear free energy to non-free potential-field energy is ~1 in the core field, the field rooted along the neutral line, and (2) this ratio is progessively less in active regions progressively farther below their free-energy limit. Evidently, most active regions in which this core-field energy ratio is much less than 1 cannot be triggered to explode; as this ratio approaches 1, most active regions become capable of exploding; and when this ratio is 1 or greater, most active regions are compelled to explode. We conclude that an active region's field cannot hold much more free energy than non-free energy, and this results in the the field's ratio of free to non-free energy being ~1 at the free-energy limit and in the main sequence of explosive active regions.

This work was funded by NASA through the Living With a Star TR&T Program, the Heliophysics Guest Investigators Program, and the *Hinode* Project, and is published in The Astrophysical Journal (Moore, Falconer, & Sterling 2012, ApJ, 750:24).

Explosive Solar Magnetic Fields



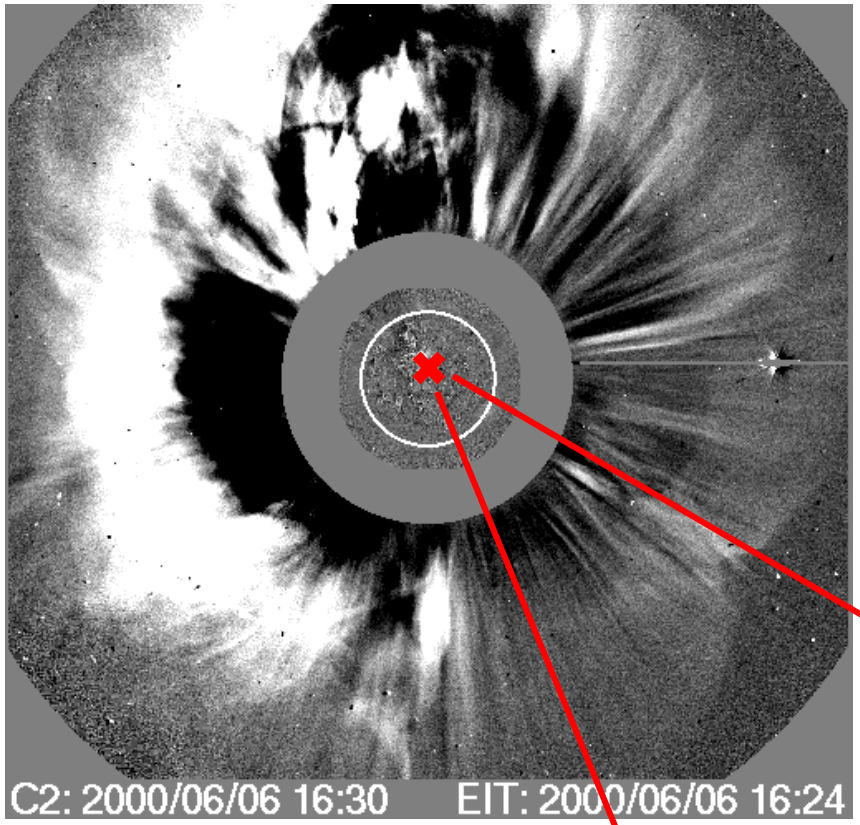


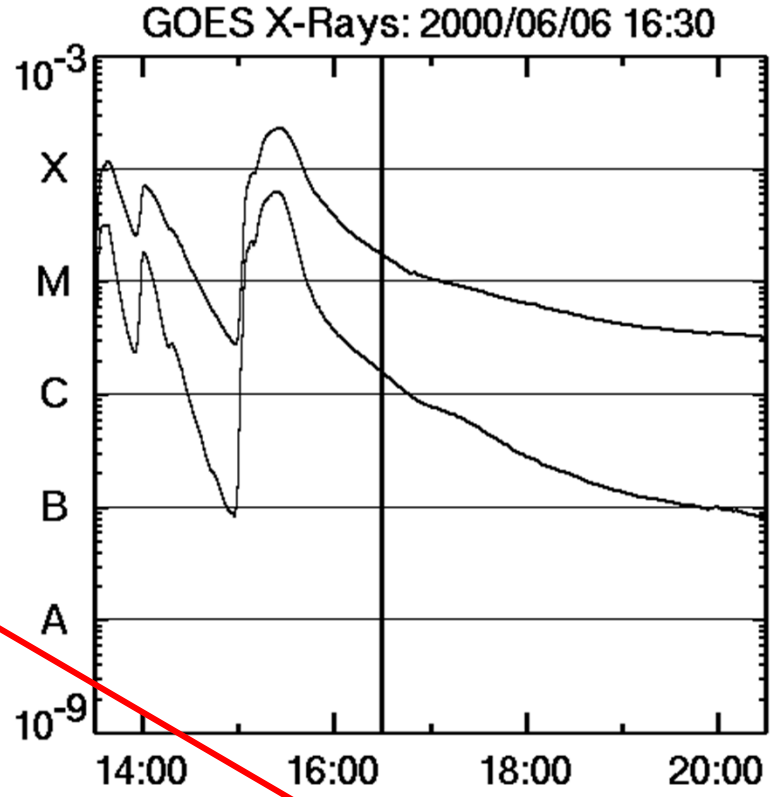
Main Points

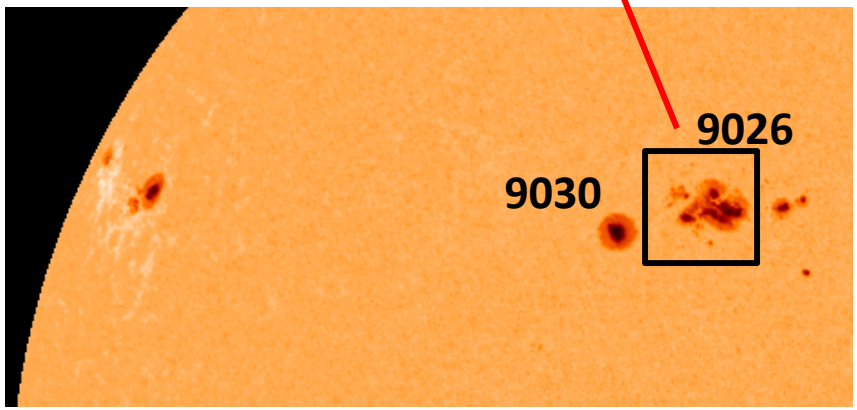
- The free energy in an active region's field is concentrated near the neutral lines in the form of shear in the field.
- This allows proxies of the free energy of the entire field to be measured from integrals along neutral lines in magnetograms.
- These magnetogram measures show:
  - There is a sharp limit to the free energy an active region's field can hold.
  - The bigger the active region (in flux content) the more free energy it can hold.
  - Most active regions are near their free-energy limit when they have a CME/flare explosion.
  - This makes a "main sequence" of explosive active regions in (flux content, free-energy proxy) phase space.

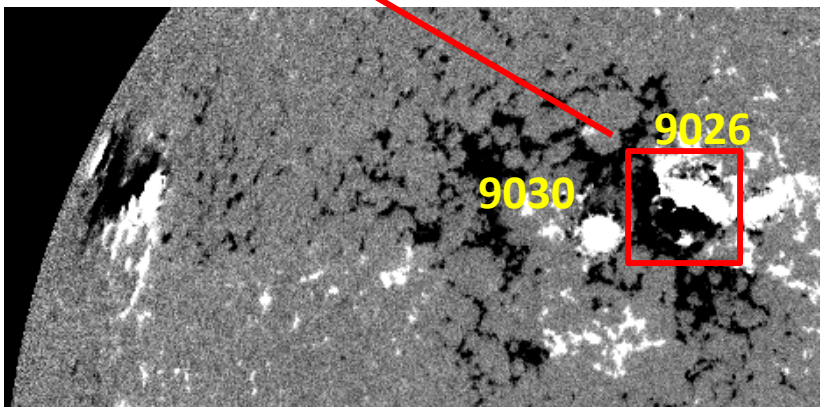
- Underlying cause: The free energy is self-limiting.
  When the field's free energy rises to the level of the non-free energy, the field sheds free energy by exploding.

Example Halo CME and X Flare Produced by Explosion of Magnetic Field Rooted In and Around a Large δ Sunspot

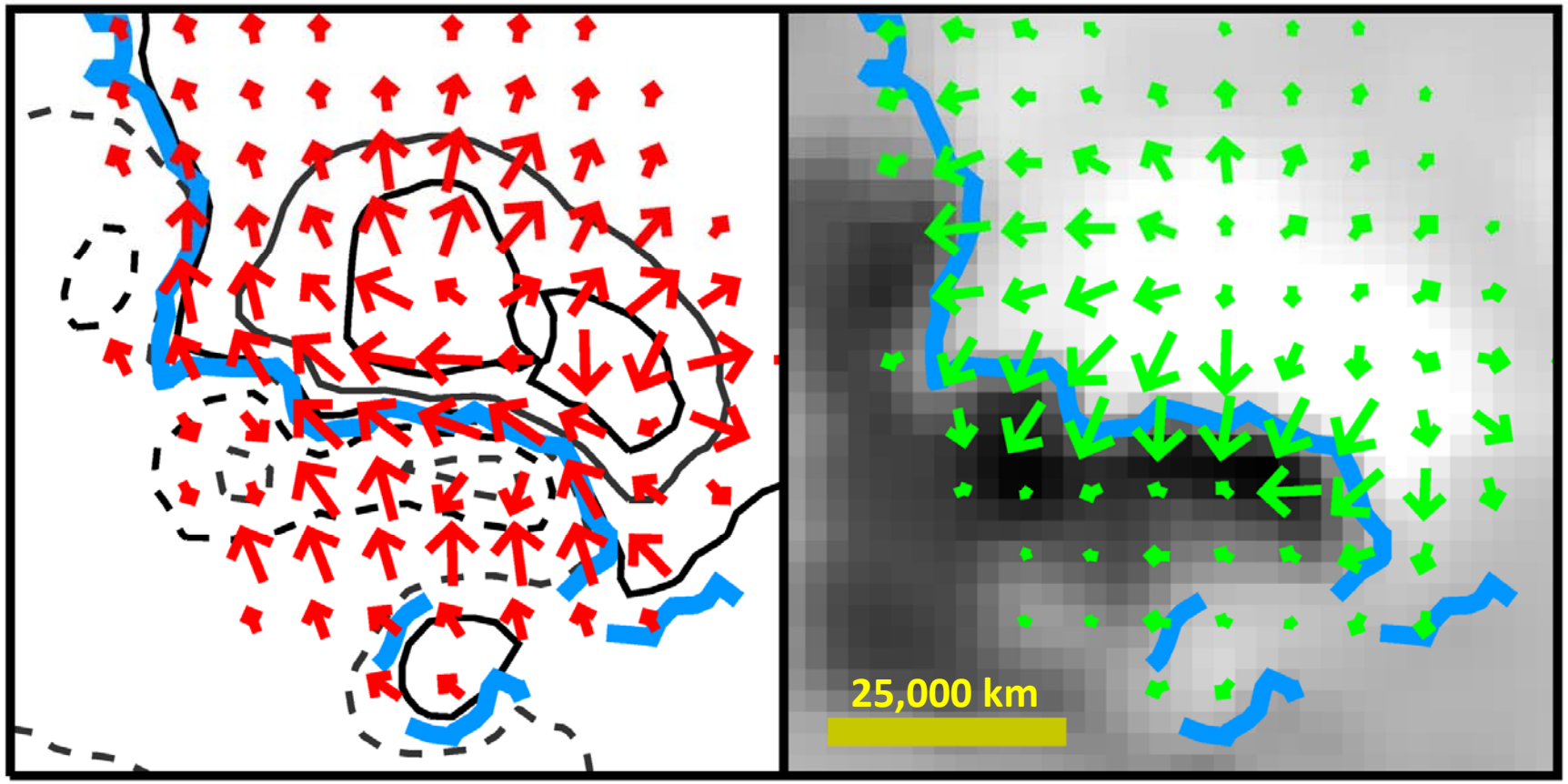








MSFC Vector Magnetogram of δ-Sunspot Source Region of the Example CME/Flare Eruption



An active-region field's horizontal shear is concentrated along neutral lines where the field's horizontal component is strong and the vertical component's horizontal gradient is steep.

Observed-field upward (downward) vert. comp. is shown by solid contours or light shading (dashed contours or dark shading); red arrows show observed hor. comp. ; green arrows show hor. comp. of pot. field computed from obs. vert. comp. ; strong-observed-field (>150G) intervals of neutral lines are blue.

Active-Region Magnetic Quantities Measured from MDI Magnetograms

- **Magnetic-Flux-Content Measure $^{L}\Phi$**
  - **$^{L}\Phi \approx$ active region's total magnetic flux**

$$^{L}\Phi \equiv \int |B_{LOS}| \, dA, \text{ for } |B_{LOS}| > 100 \text{ G}$$

- **Free-Energy Proxy $^{L}WL_{SG}$**
  - **At neutral lines, $|\nabla_{transverse} B_{LOS}|$ is a proxy for the shear in the core field.**

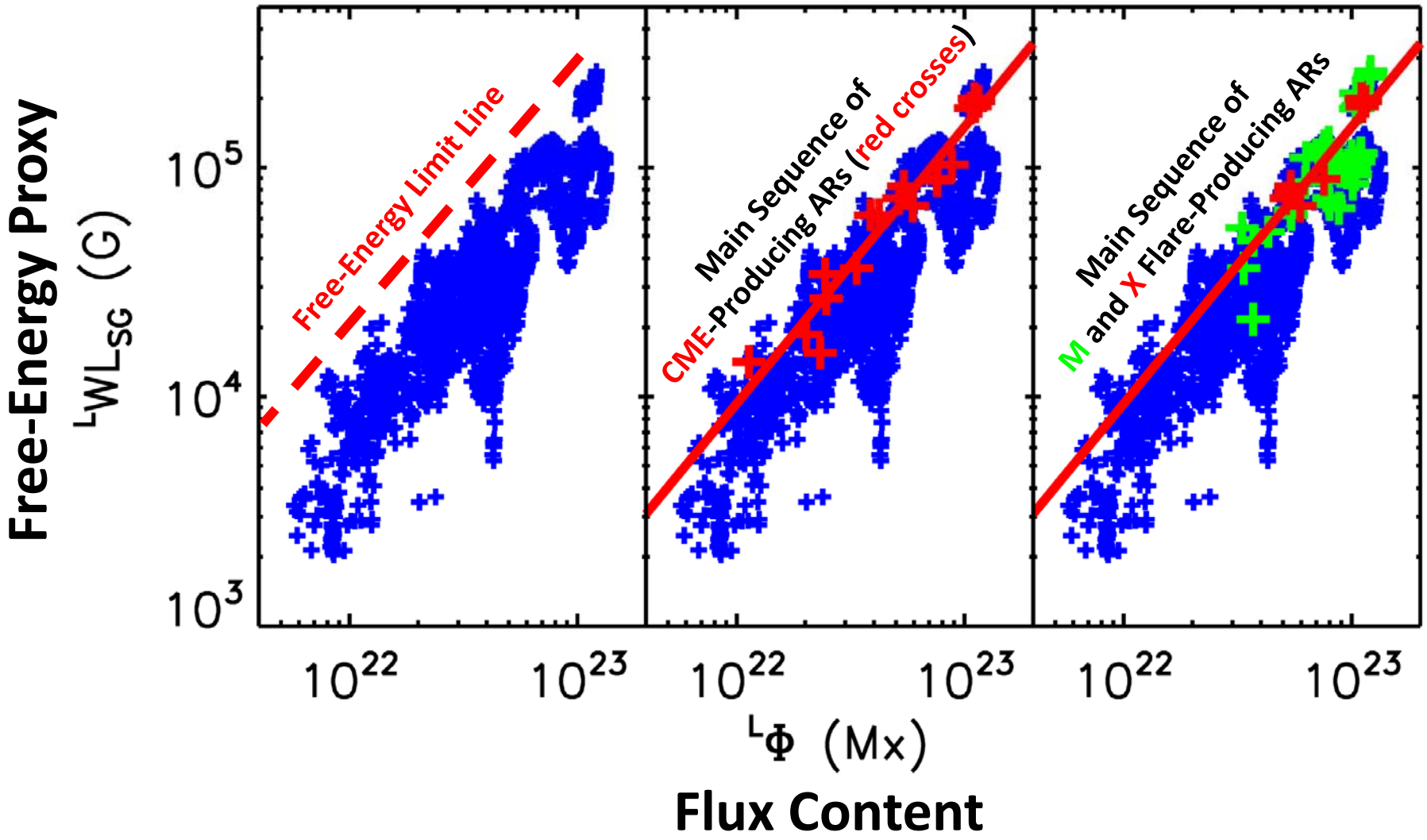
$$^{L}WL_{SG} \equiv \int |\nabla_{transverse} B_{LOS}| \, dl, \text{ integrated on active region's strong-field neutral lines.}$$

  - **$^{L}WL_{SG}$ is the active region's "gradient-weighted" length of strong-field neutral line.**

Free-Energy Limit and Explosive Main Sequence

(Falconer et al 2009, ApJ, 700, L166; Moore et al 2012, ApJ 750:24)

Blue crosses are AR locations in (flux content, free-energy proxy) phase space measured from 1800 MDI magnetograms of 44 active regions during their central-disk passage.



General Reason for the Main Sequence:

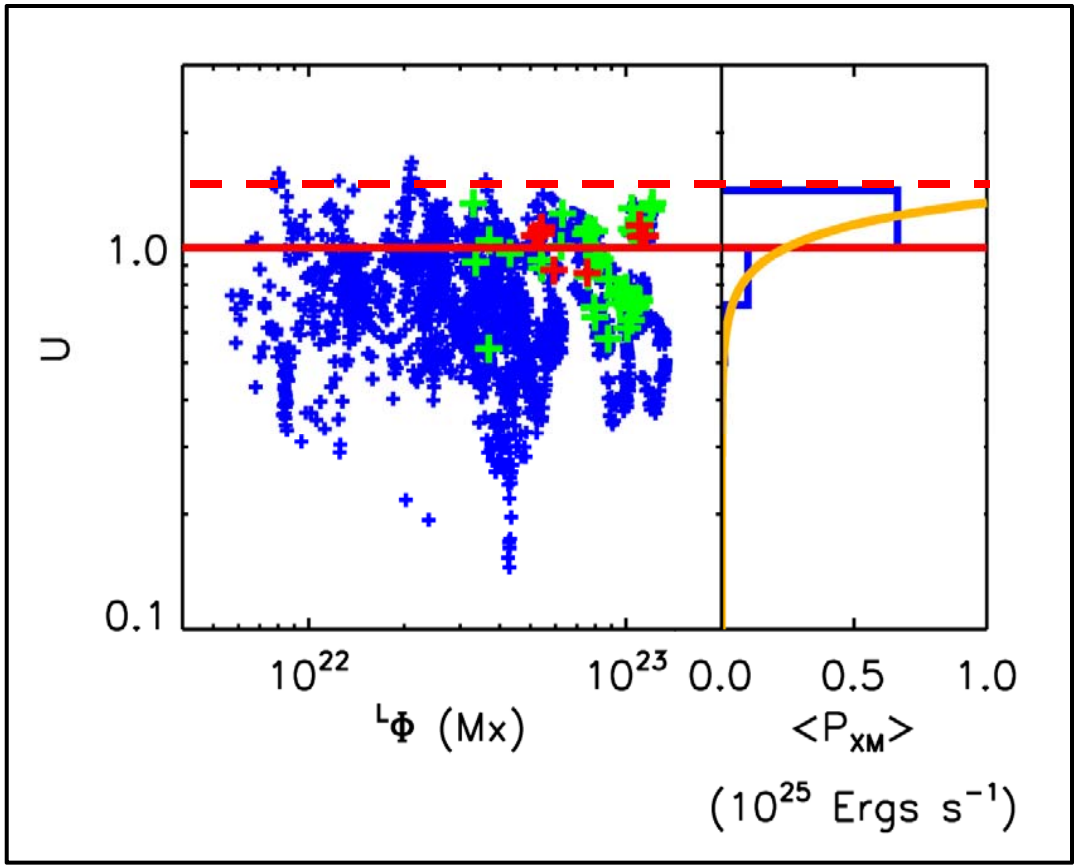
Balance

of

Buildup of Active-Region Free Energy (via Photospheric and Subphotospheric Flows)

by

Burndown of Active-Region Free Energy (via CMEs, Flares, and Coronal Heating) .

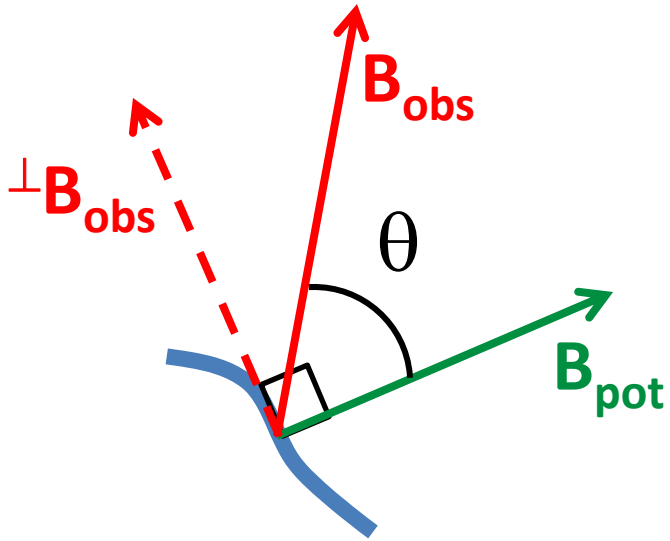


<P_{XM}> increases as U^5 as U increases across the main sequence and approaches the free-energy limit line.

<P_{XM}> is the 48-hour average power output per active region by X and M flares in GOES 1-8 Å X-ray flux.

U is the normalized coordinate in the direction of increasing $^{L}WL_{SG}$ orthogonal to the main sequence in (Log $^{L}\Phi$, Log $^{L}WL_{SG}$) phase space.

Shear Angle and Shear Component of the Observed Field on Neutral Lines



$$\perp B_{obs} = B_{obs} \sin \theta$$

- Observed field B_{obs} and potential field B_{pot} are horizontal on neutral lines.
- $\theta \equiv$ shear angle $\equiv$ angle between B_{obs} and B_{pot}.
- $\perp B_{obs} \equiv$ component of B_{obs} perpendicular to B_{pot},
  $\equiv$ shear component of observed field on neutral lines.

Ratio of Free to Non-Free Energy in Active Region's Core Field
(Measured from a Vector Magnetogram)

- **Free-Energy Proxy WL_{SSED}**
  - WL_{SSED} is the AR's "shear-energy-density-weighted" length of strong-field neutral line.
  - $WL_{SSED} \equiv \int[(B_{obs} \sin\theta)^2/8\pi]\, dl$, integrated on AR's strong-field neutral lines.

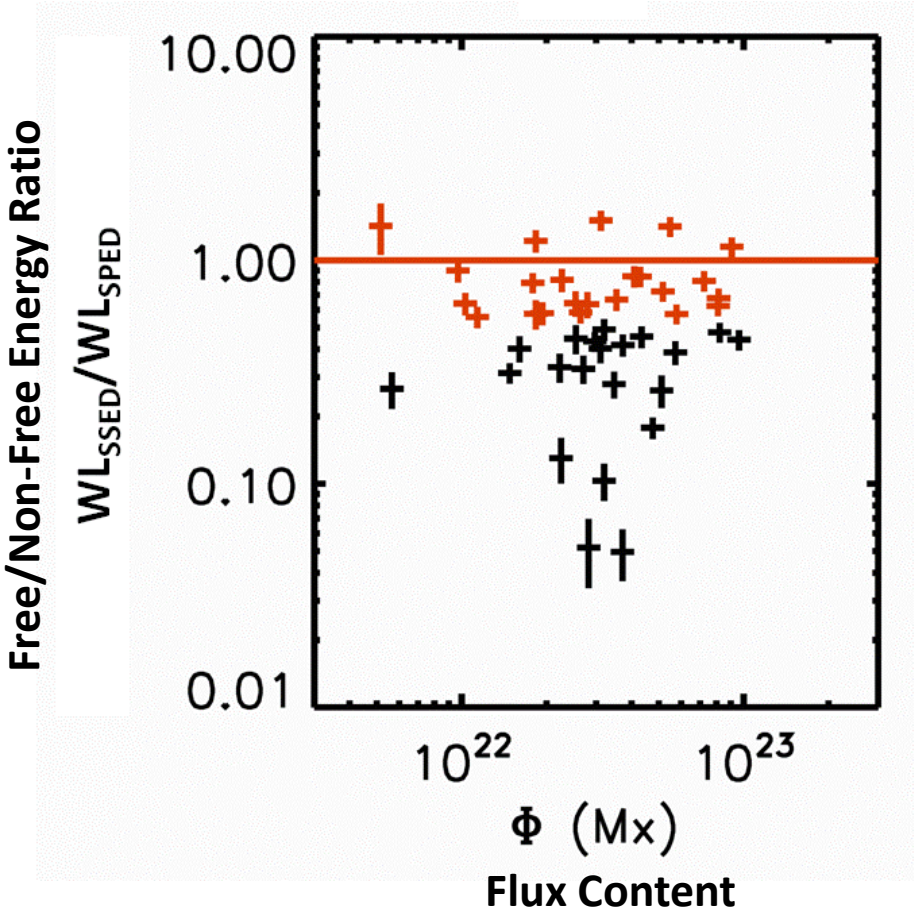
- **Non-Free-Energy Proxy WL_{SPED}**
  - WL_{SPED} is the AR's "potential-field-energy-density-weighted" length of strong-field neutral line.
  - $WL_{SPED} \equiv \int[(B_{pot})^2/8\pi]\, dl$, integrated on AR's strong-field neutral lines.

- **$WL_{SSED}/WL_{SPED} \approx$ ratio of free to non-free energy in the core field.**

- **Maybe $WL_{SSED}/WL_{SPED} \sim$ ratio of free to non-free energy in the active region's entire field.**

Energy-Ratio Limit

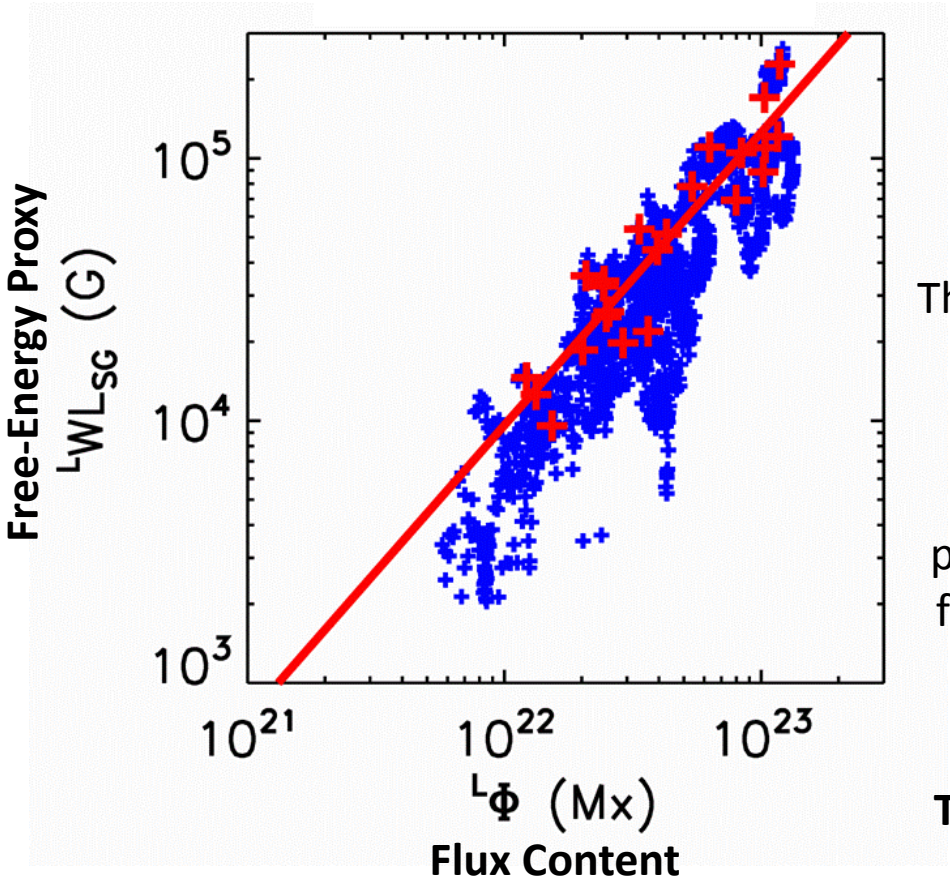
This Log-Log plot shows:
(1) ARs have an upper limit to the energy ratio they can attain.
(2) The limit is independent of AR magnetic size (flux content).
(3) The limit is of the order of 1.



The cloud of 44 crosses is for the same 44 ARs measured for the main-sequence plots in panel 8. The cross for each AR is the (flux content, energy ratio) point and its 1-σ uncertainties measured from an MSFC vector magnetogram.

The energy ratio is 1 on the horizontal red line.
The 23 red crosses are the points within a factor of 2 of the unity line.

Correspondence of Energy-Ratio Limit to Free-Energy Limit



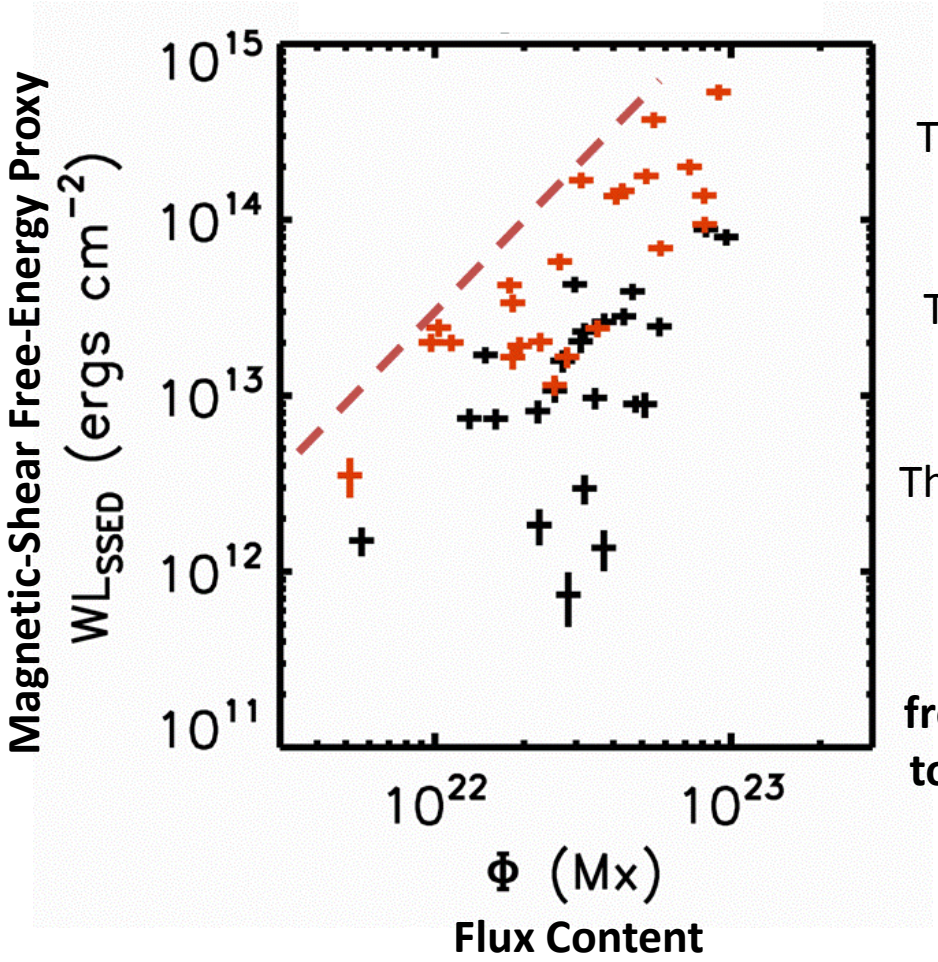
This Log-Log plot shows that the top 23 ARs in energy ratio (red crosses) are scattered along the main sequence of explosive ARs.

The cloud of blue crosses is the previous (panel 8) MDI plot of the 44 ARs in (flux content, free-energy proxy) phase space.

Each red cross marks, for one of the previous panel's top 23 ARs in energy ratio, the blue cross from the AR's MDI magnetogram closest in time ($\Delta t < 1$ hr) to the AR's measured MSFC vector magnetogram.

The red line is the least-squares linear fit to the 23 red crosses. It runs close below the blue cloud's free-energy-limit upper edge.

Free-Energy Limit in (Flux Content, Magnetic-Shear Free-Energy Proxy) Phase Space



The cloud of 44 crosses is for the same 44 ARs as in the (Flux Content, Energy Ratio) plot.

The crosses for the top 23 ARs in energy ratio are red.

The dashed red line is the free-energy limit line in this phase space.

This plot confirms that ARs near their free-energy limit have free energy comparable to the non-free energy of their potential field.

Conclusion

When the free energy in an active region's magnetic field rises to the level of the potential-field energy, the field sheds free energy by exploding.