The Main Sequence of Explosive Solar Active Regions: Comparison of Emerging and Mature Active Regions

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Summary

I. Previous Results (Falconer, Moore, Gary, & Adams 2009), from 44 mature active regions

- For mature active regions, an active region's magnetic flux content determines the maximum free energy the active region can have.
- Most Large flares and CMEs occur in active regions that are near their free-energy limit.
- Active-region flare power radiated in the GOES 1-8 Å band increases steeply as the free-energy limit is approached.
- We infer that the free-energy limit is set by the rate of release of an active region's free magnetic energy by flares, CMEs and coronal heating balancing the maximum rate the Sun can put free energy into the active region's magnetic field.
- This balance of maximum power results in explosive active regions residing in a "main-sequence" in active-region (flux content, free energy content) phase space, which sequence is analogous to the main sequence of hydrogen-burning stars in (mass, luminosity) phase space.

Have confirmed these results with a 10 times larger sample of mature active regions.

II. New Results from Expanded Sample

For Mature Active Regions (422 Active Regions)

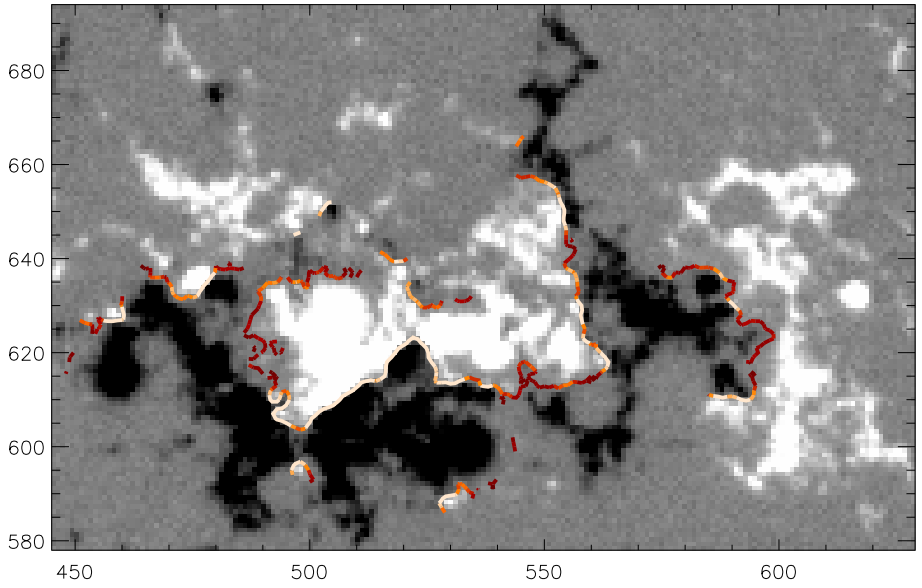
1.Most major flares and CMEs are produced near this upper limit, with rates increasing steeply as this limit is approached.

2.We have also shown that bulk of the flaring and CME production doesn't occur where the bulk of the active regions lie in flux-normalized free energy space but at larger free energy, nearer to the upper limit. This further indicates that the free-energy upper limit is set by flaring and CME production limiting the free energy a mature active region can reach.

For Emerging Active Regions (169 Active Regions)

1. Emerging active regions can exceed the free-energy upper limit of mature active regions.
2. They overlap the mature active region portion of phase space.
3. They tend to produce flares and CMEs for a given flux at larger free energy levels.

Active Region Magnetic Measures from MDI Line-of-Sight Magnetograms



Total Magnetic Flux (magnetic size)

$^{L}\Phi = \int |B_{LOS}|\, da$ (over areas having $|B_{LOS}| > 100G$)

Total Free Magnetic Energy Proxy

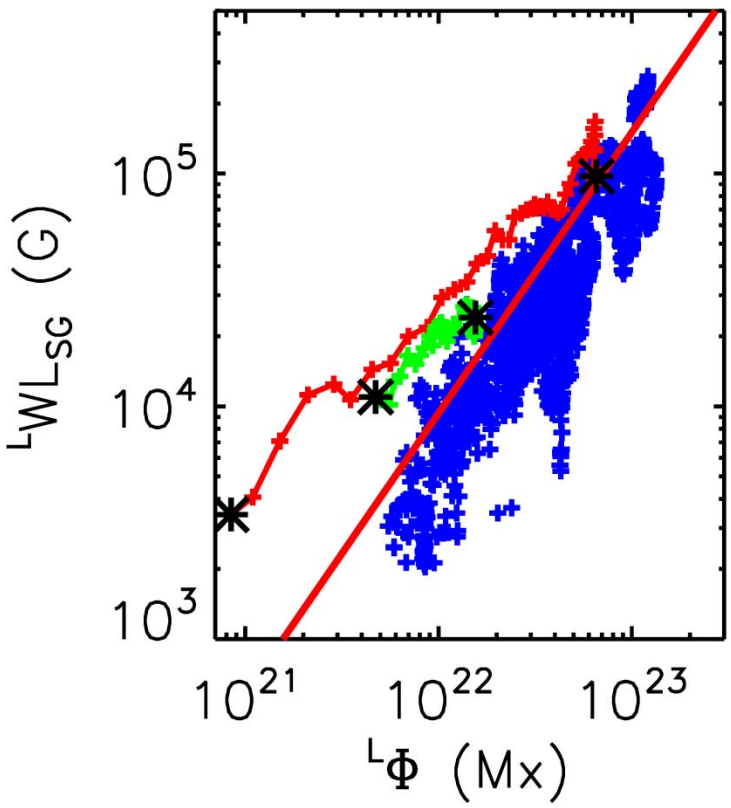
$^{L}WL_{SG} = \int (\nabla B_{LOS})\, dl$ (on neutral lines having potential $B_T > 150G$)

We limit our use of these measures from line-of-sight magnetograms to active regions within 30° of disk center.

From each magnetogram of each active region, we measure two quantities, $^{L}\Phi$ & $^{L}WL_{SG}$. $^{L}\Phi$ is the total magnetic flux, a measure of active region size. $^{L}WL_{SG}$ is the strong-field gradient-weighted neutral-line length, a proxy of the total free magnetic energy. The magnetogram is from AR 9077 on July 14 an hour before the active region produced the Bastille Day Flare/CME. Overlaid are neutral lines color coded with gradients ranging from 0 (red) to ≥75G/Mm (white). For each active region we have both $^{L}\Phi$ & $^{L}WL_{SG}$ as a function of time as it crosses the central disk region (within 30 heliocentric degrees from disk center).

Mature versus Emerging

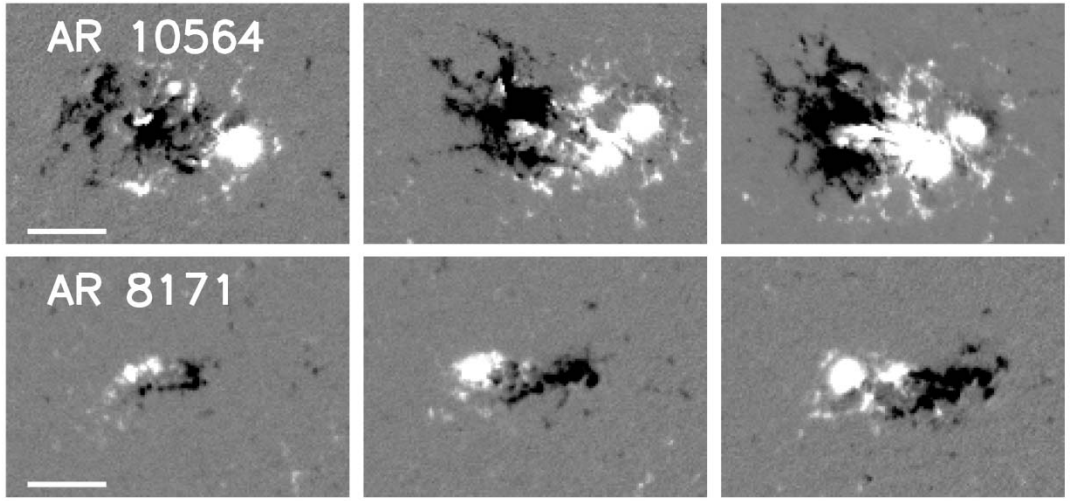
- Falconer et al 2009, studied a sample of 44 mature active regions, two emerging active regions were indentified, but excluded from sample due to their radical different behavior.
- The emerging active regions had a larger free energy than the mature active regions for their size, and were rapidly growing, just emerging as the active region was entering the central disk area.

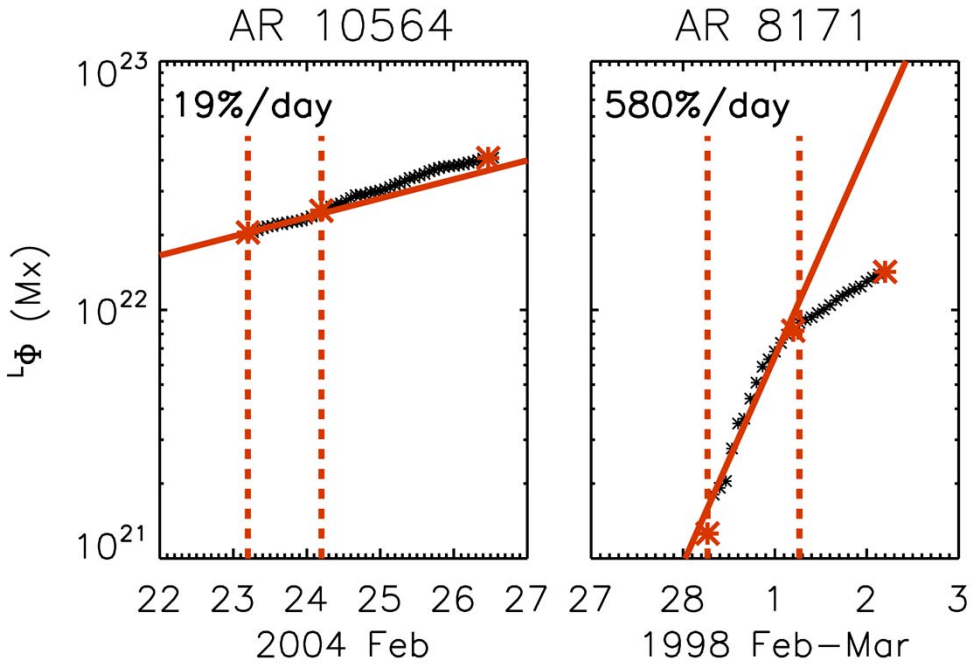


Red and Green data points give the tracks of two different emerging active regions. Blue +'s are from the 44 mature active regions.

Definition of Mature and Emerging Active Regions Categories

In the previous paper, we excluded two new rapidly emerging active regions, and defined the remaining 44 active regions as mature. From looking at a large set of active regions, we found that the rate of flux growth was a better way to separate mature and emerging than using when NOAA first numbered the active region. By our new definition, if an active region on entering the central disk has its is total magnetic flux growing by more than 50% a day, it is counted as emerging, and if its total flux is growing by less than 50% a day, the active region is counted as mature. Only mature active regions are included in this study. The red * indicate times of the three magnetograms, for each active region.





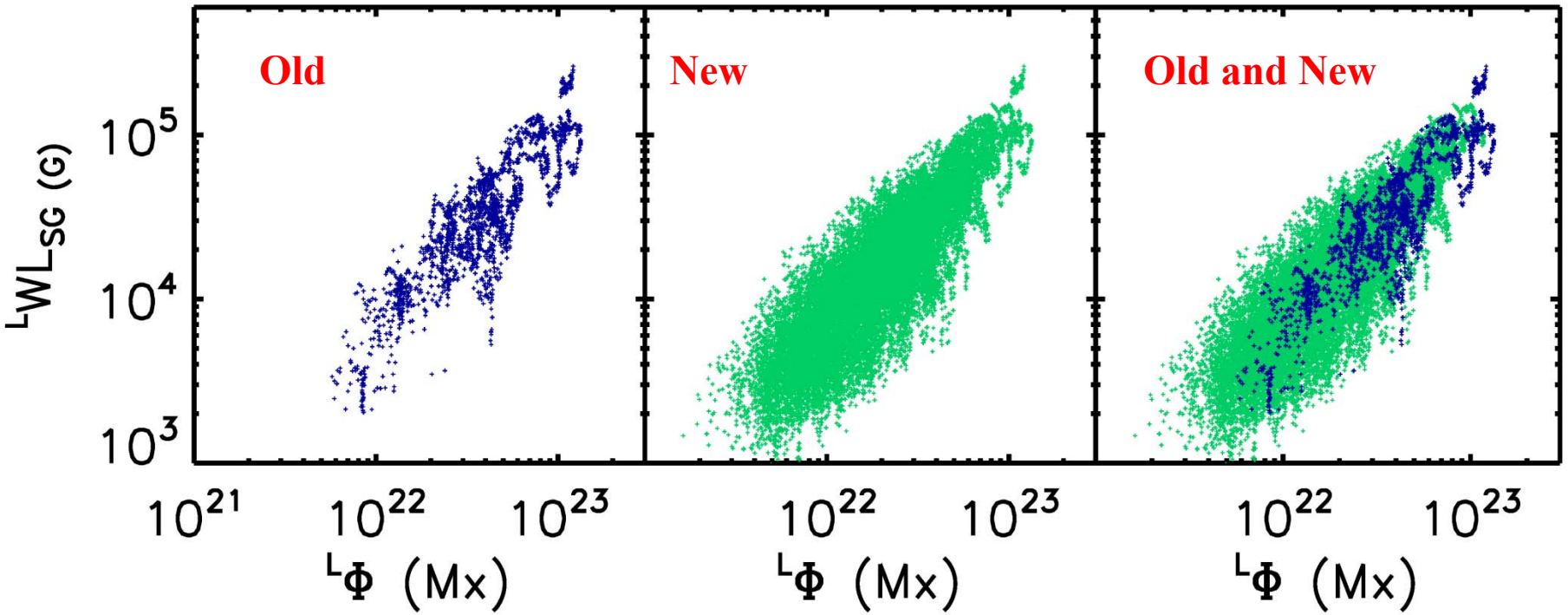
Our Three Samples of MDI Active Regions

	Old Mature	**Expanded Mature[1]**	**Emerging[1]**
# of AR	44	422	160
# of Magnetograms	1,865	18,833	6,982
Selection criterion	AR was 3 days old when entering central disk	Flux Growth less than 50%/day when entering central disk	Flux Growth greater than 50%/day when entering central disk

[1] From the ~1,300 AR observed between 1996 and 2004.

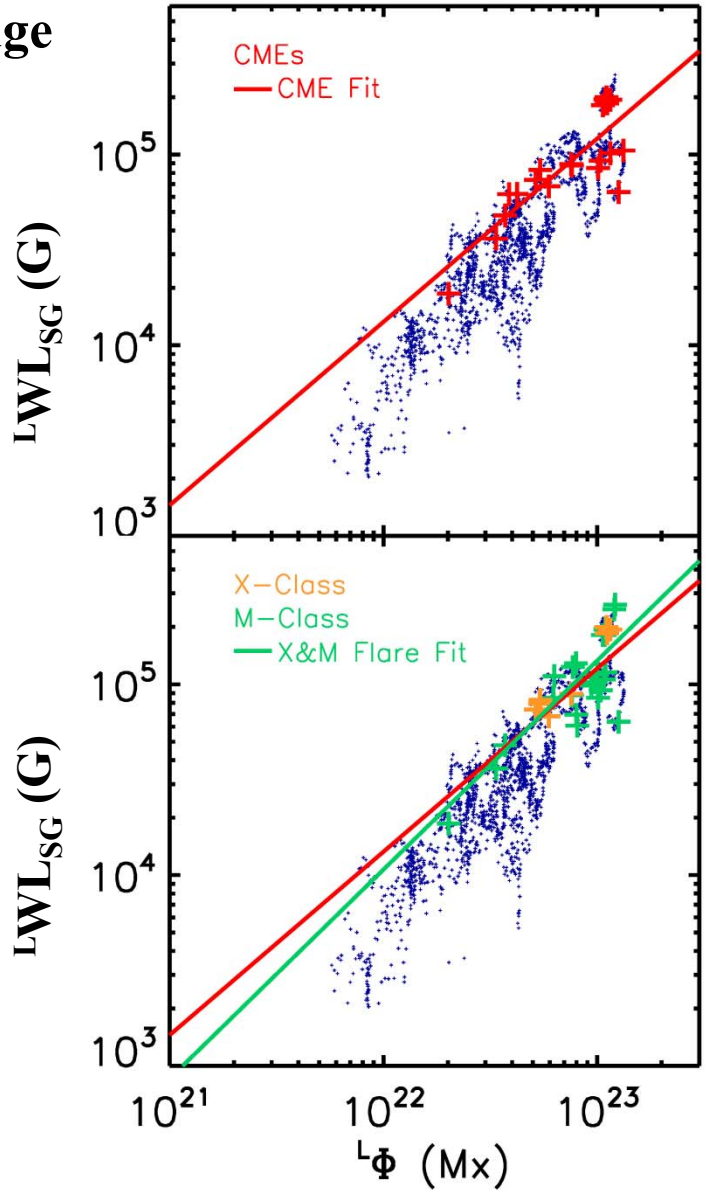
Upper Bound on Free Energy of Mature Active Regions of any Given Flux Content

Plot of log $^{L}WL_{SG}$ versus Log $^{L}\Phi$ for our old sample (left), new sample (middle) and both samples (right). For either sample, the cloud of points has an upper edge that is sharper than its lower edge. The increase in the upper limit on log $^{L}WL_{SG}$ with increasing Log $^{L}\Phi$ is better defined by the expanded sample than by the original smaller sample.



The Main Sequence of Explosive Mature Active Regions: Old Sample Active Regions Producing CMEs and Major Flares are Concentrated Near the Cloud's Upper Edge

- The blue dots in each panel represent the flux and free energy of the active region from a single MDI magnetograms in the old sample.
- In the upper panel, the state of an active region, when it is producing a CME is designated by +.
- A log-log fit through these CME producing data points is shown in red.
- In the lower panel, the state of an active region when it is producing a M or X-class flares is designated by + or + respectively.
- A log-log fit through the X and M class flare producing data points is shown in green. The red line shows the CME fit from the upper panel.
- Both fits have similar slopes. Both roughly match the slope of the maximum attainable-free-energy upper edge of the cloud of active-region points.

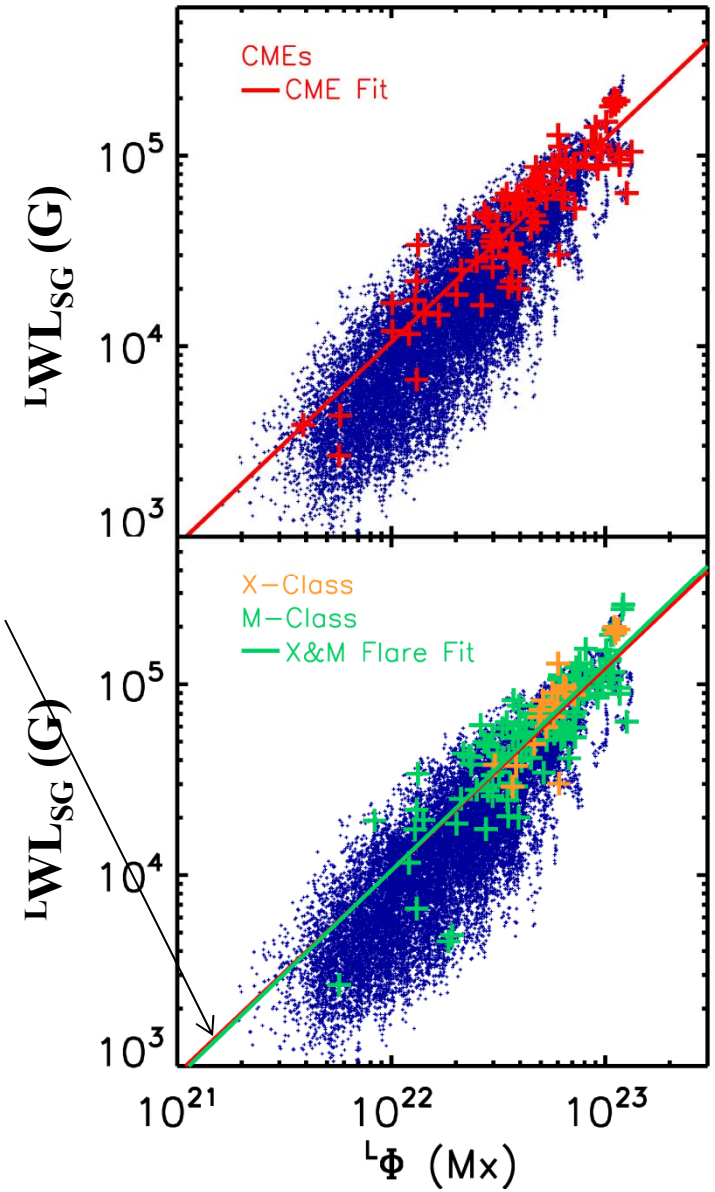


The Main Sequence of Mature Explosive Active Regions: Expanded Sample

Active Regions Producing CMEs and Major Flares are Concentrated Near the Cloud's Upper Edge

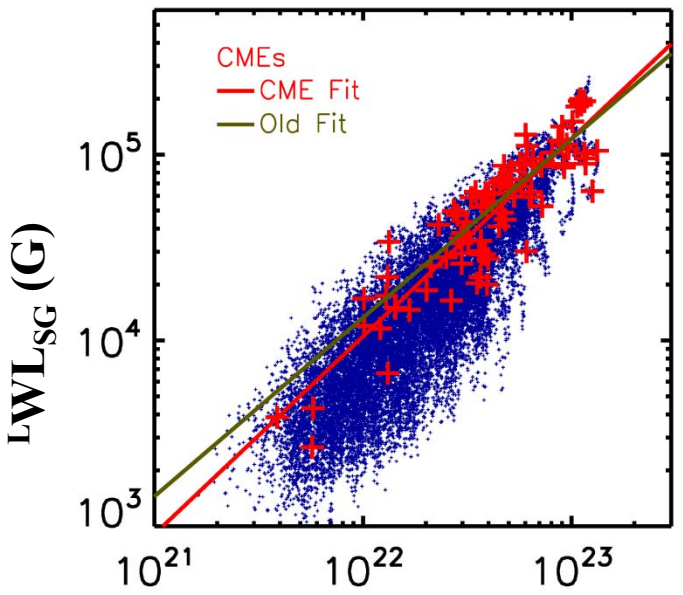
- The plots are similar to the last panel, but with the new expanded sample, which is a factor of 10 larger. Due to using an automated active region identification program, there is less selection bias and there are more small flux active regions in the sample. There is also a factor of 4 more flares and CMEs. The increase is less, because small active regions are less productive of major flares and CMEs.
- The log-log fits through the CME and through the X&M class flares are essentially identical, with the green line, almost covering the red.
- The fits run parallel to the cloud's upper edge.

Log-log fits in this poster, are least-squares, straight-line fits through the logarithmic values of the data points.



Comparison of Mature Active Region Main-Sequence Fits for Old and New Samples

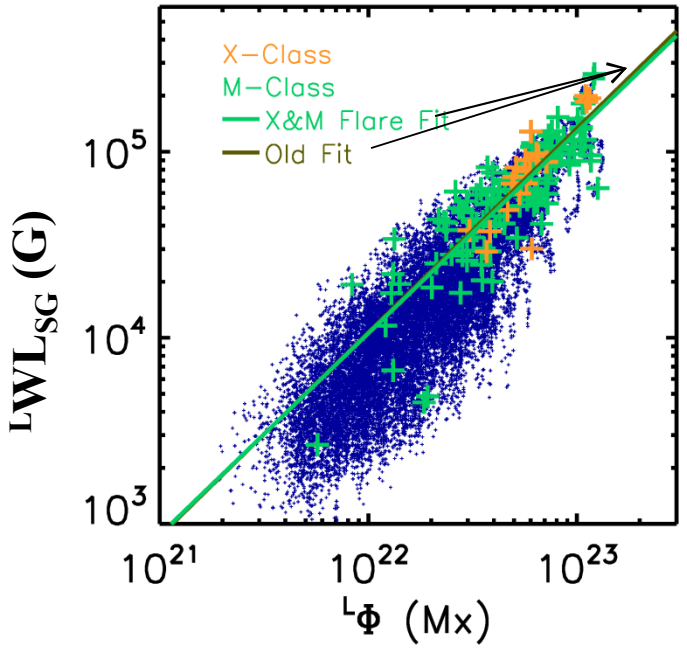
The old flare fit is essentially identical to the new flare fit, and the slope of the old CME fit is within 1σ of the slopes of the other fits. The new sample certifies that the CME main-sequence line is roughly parallel to the cloud's upper edge and close below it.



Fits are of the form

$^{L}WL_{SG}=10^{A}x(^{L}\Phi/(5x10^{22}))^{B}$ G

The value of $^{L}\Phi$ is divided by $5x10^{22}$ Mx, which is in the middle of the range of values for flares and CME producing active regions.



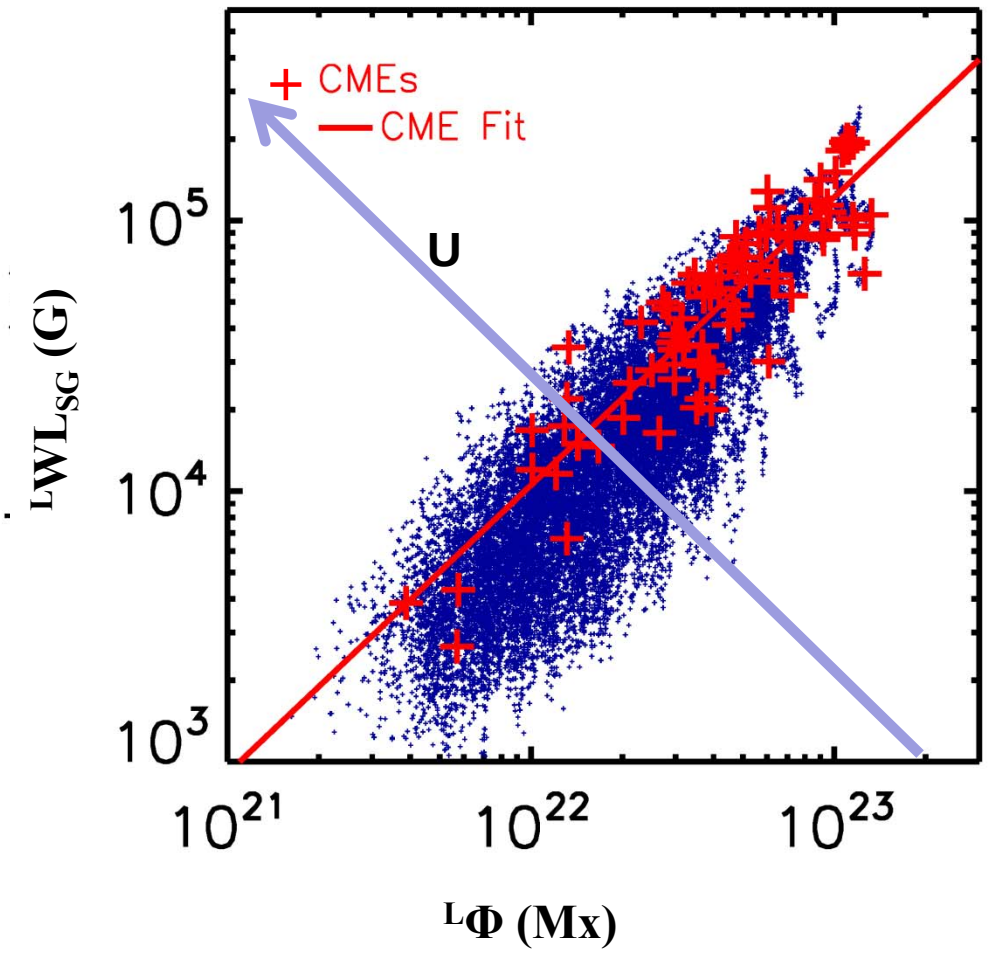
	A	B
Old X&M flares	4.79±0.04	1.10±0.13
New X&M flares	4.78±0.01	1.08±0.06
Old CMEs	4.79±0.04	0.96±0.15
New CMEs	4.77±0.02	1.06±0.05

New coordinate U Orthogonal to Main Sequence

In Log $^{L}WL_{SG}$, Log $^{L}\Phi$ phase space, U is the coordinate of increasing $^{L}WL_{SG}$ orthogonal to the CME main-sequence least-squares line.

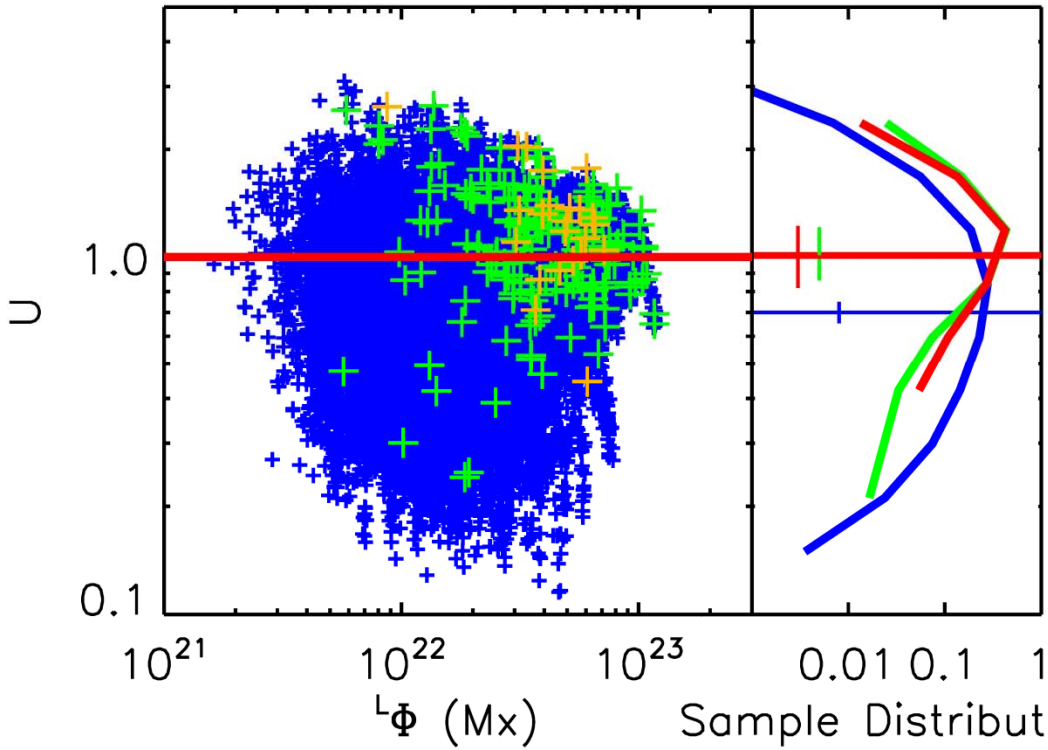
$U \equiv WL_{SG}/((10^{A})*(\Phi/5x10^{22})^{B})$

U is a proxy measure of the active region's free energy per a unit of flux (B~1).



The Main Sequence of Explosive Active Regions is Centered on the Large-U side of the Cloud, near the Free-Energy Limit

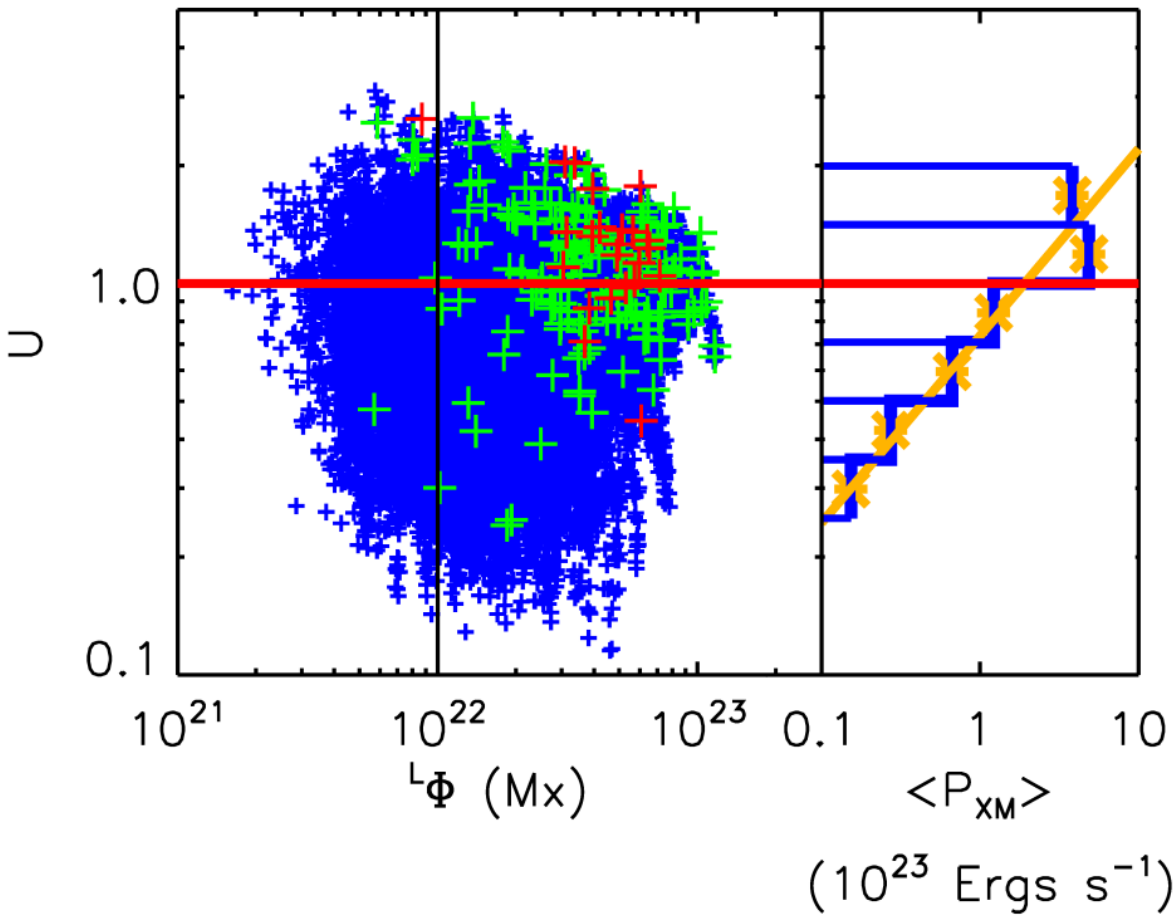
	Average Log(U)
M & X Flares	0.01±0.01
CME	0.00±0.02
Magnetograms	-0.15±0.01



Left: When plotted as a function of U versus Φ, X&M flares (as well as CMEs not shown) are seen to occur in active regions which at the time of the event have both larger average total magnetic flux and larger average U, than the entire cloud.

RightThe distribution in U of all magnetograms (blue) is significantly different than either CMEs (Red) or X&M flares (Green). The average Log U values of magnetograms and X&M flares are plotted as the vertical blue and green lines. The 5σ uncertainty of these values are shown by the horizontal bars. The vertical red line in both panels, is the average value for CMEs, and by definition of U is at U=1.

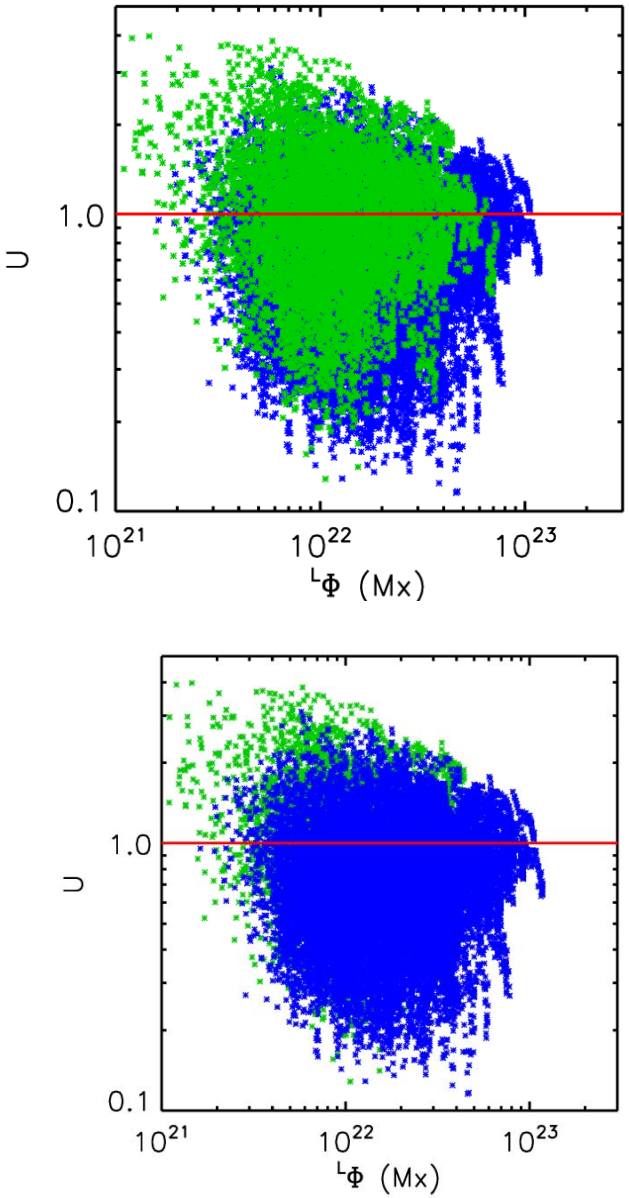
Average Flare Power Increase Steeply as U Approaches Free-energy Limit



Left-panel: Same as slide 12. **Right-Panel:** The sample is divided into bins of U, with 5 bins per a decade. For each bin an average X&M flare power is determined (the average power emitted in the GOES 1-8 A band of all flares in a 48 hour window). For all bins with at least 500 data points, and at least 1 flare, a data is plotted and a log-log linear fit is done through the data, and plotted. The slope of the fit (the power-law index) is ~2.

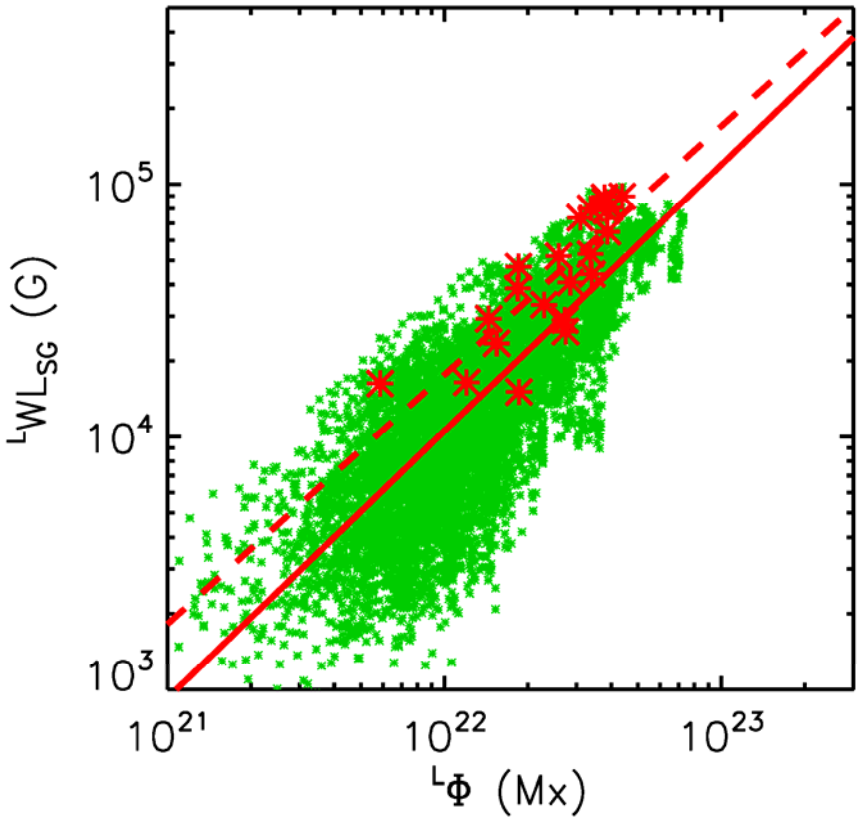
Emerging Active Regions is shifted to larger U than Mature Active Regions

- The * in each panel represent the flux and U of the active region from single MDI magnetograms.
  - Blue Mature active region
  - Green Emerging active region
- The red line is the U=1.
- The two populations overlap, but emerging active regions tend to have larger U and smaller flux, and mature active regions tend to have smaller U and larger flux.
- The difference is most significant for small flux, large U, and for large flux small U portion of phase space.
- There though is a large region of overlap.
- Emerging active regions have a different upper edge than mature active region, especially for small flux active regions.

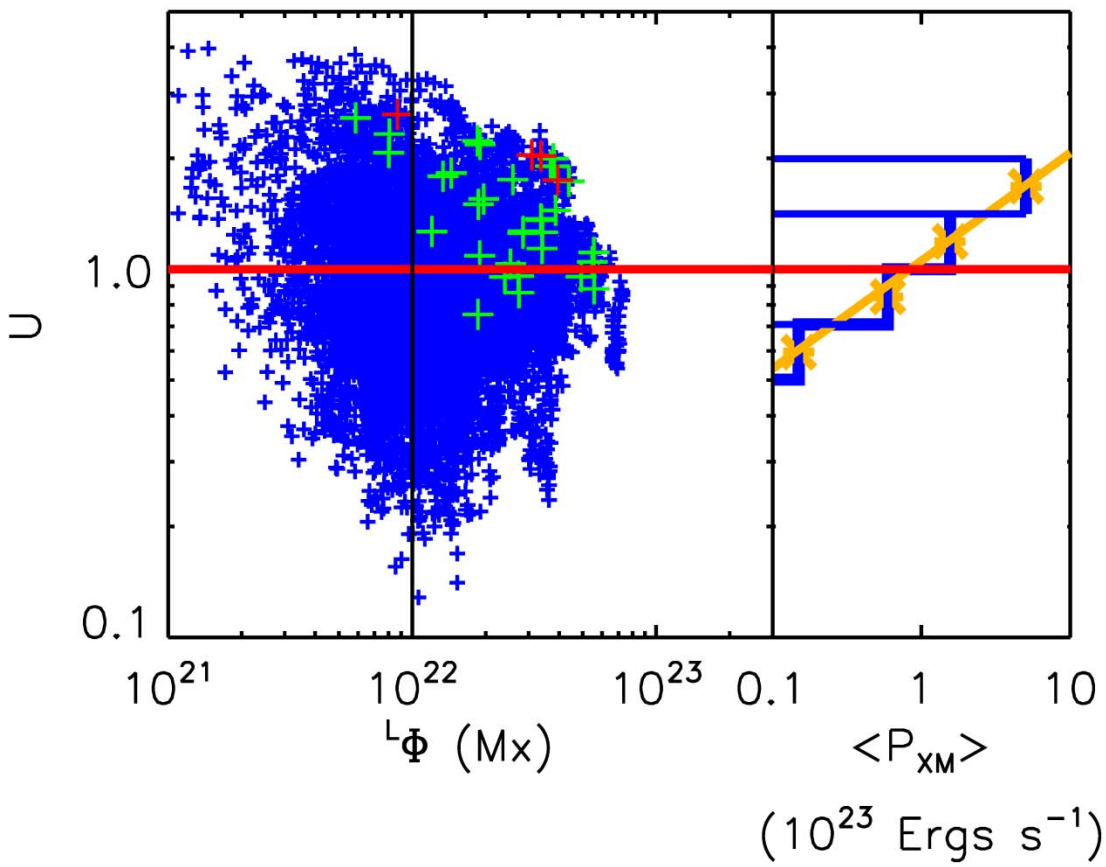


Emerging active region "Main Sequence" is shifted upward relative to mature active regions.

- Each small green * represents one emerging active region magnetogram free-energy proxy and flux.
- The red * indicate state of emerging active regions when it producing is a a CME.
- The dashed red line is the fit through the emerging active regions CMEs.
- The solid red line, is the fit through the mature active regions CMEs.
- The emerging active regions "Main Sequence" is shifted to higher values of $^{L}WL_{SG}$, and possibly has a different slope, that is more parallel to the emerging active region upper edge, but is not statistically significant different, for rather small sample size of CMEs.
- Slope Mature 1.06±0.06; Emerging 0.99±0.15



The steep increase of Flare Power for Emerging ARs as U increase above 1



- Same format as Slide 13, except for Emerging AR's.
- Emerging active regions like mature active regions show flare power increases strongly with U near 1.