Free magnetic energy and helicity in active and quiet solar regions and their role in solar dynamics

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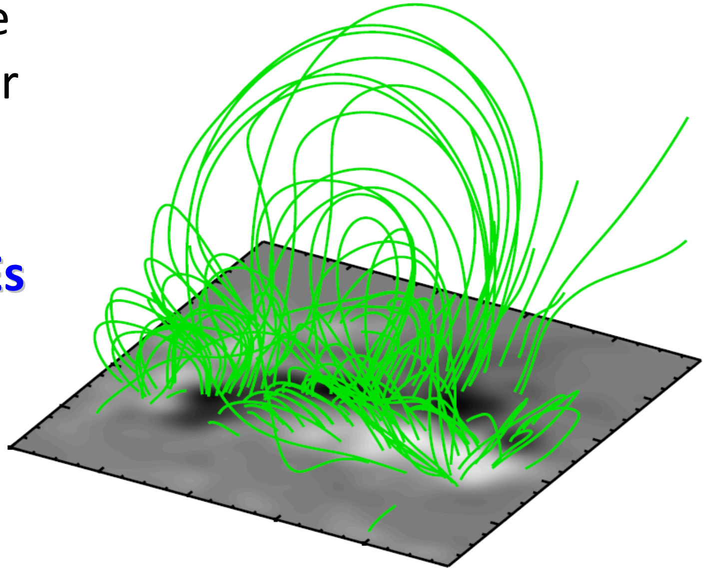
Magnetic helicity and free magnetic energy

Magnetic helicity:

- quantifies stress and distortion of magnetic field compared to its potential energy state; role in solar eruption under debate
- emerges via helical magnetic flux tubes and/or generated by photospheric proper motions
- **cannot be efficiently removed by magnetic reconnection; can be bodily expelled via CMEs**

$$H_m = \int_{\mathcal{V}} (\mathbf{A} \pm \mathbf{A_p}) \cdot (\mathbf{B} \mp \mathbf{B_p}) d\mathcal{V}$$



Free magnetic energy:

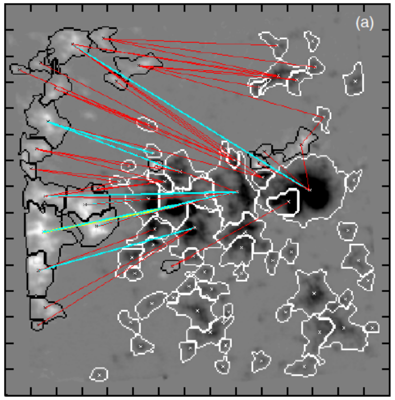
- fuels solar flares and/or coronal mass ejections (CMEs) that tend to relax the magnetic configuration

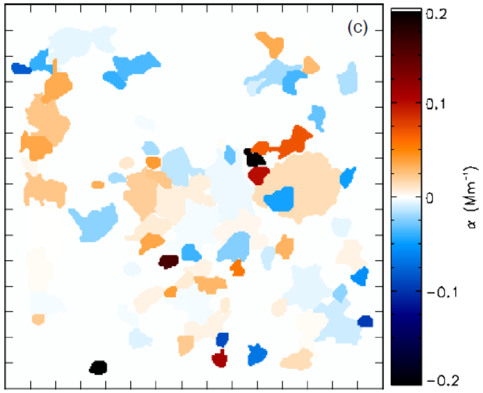
$$E_c = E_t - E_p = \frac{1}{8\pi}\int_V B^2_{NLFF} dV - \frac{1}{8\pi}\int_V B^2_p dV$$

New NLFF approach for energy/helicity calculations

Uses a continuous ***single vector magnetogram*** and translate it into a collection of discrete force-free flux tubes

AR 10254





- partition magnetic field configuration into ensemble of ***p*** positive and ***n*** negative "magnetic charges"

- Populate the ***p* × *n*** connectivity matrix, containing fluxes committed to each ***ij***-connection, using the simulated annealing method (Georgoulis & Rust 2007, that minimizes magnetic flux imbalance simultaneously with separation length of chosen partitions).

- assume that each connection is a slender flux tube with a force-free parameter α_{ij} (mean of α-parameters of connected partitions)

Free energy and helicity equations

For a magnetogram with a collection of *N* slender flux tubes:

$$H_m = H_{m_{\mathrm{self}}} + H_{m_{\mathrm{mut}}} = 8\pi d^2 A \sum_{l=1}^{N} \alpha_l \Phi_l^{2\delta} + \sum_{l=1}^{N} \sum_{m=1, l\neq m}^{N} \mathcal{L}_{lm}^{\mathrm{arch}} \Phi_l \Phi_m$$

$$E_c = E_{c_{\mathrm{self}}} + E_{c_{\mathrm{mut}}} = Ad^2 \sum_{l=1}^{N} \alpha_l^2 \Phi_l^{2\delta} + \frac{1}{8\pi} \sum_{l=1}^{N} \sum_{m=1, l\neq m}^{N} \alpha_l \mathcal{L}_{lm}^{\mathrm{arch}} \Phi_l \Phi_m$$

a_l : FF a-parameter
Φ_l : Flux
$A = 10^{-16.731\pm0.08}$
$\delta = 1.153\pm0.002$
d: pixel size

$\mathcal{L}_{lm}^{arch}$ describes "interaction" between flux tubes; value between [-1,1] calculated using trigonometric interior angles.

- single value for non-intersecting flux tubes and flux tubes with a matching footpoint
- two possible values for intersecting flux tubes

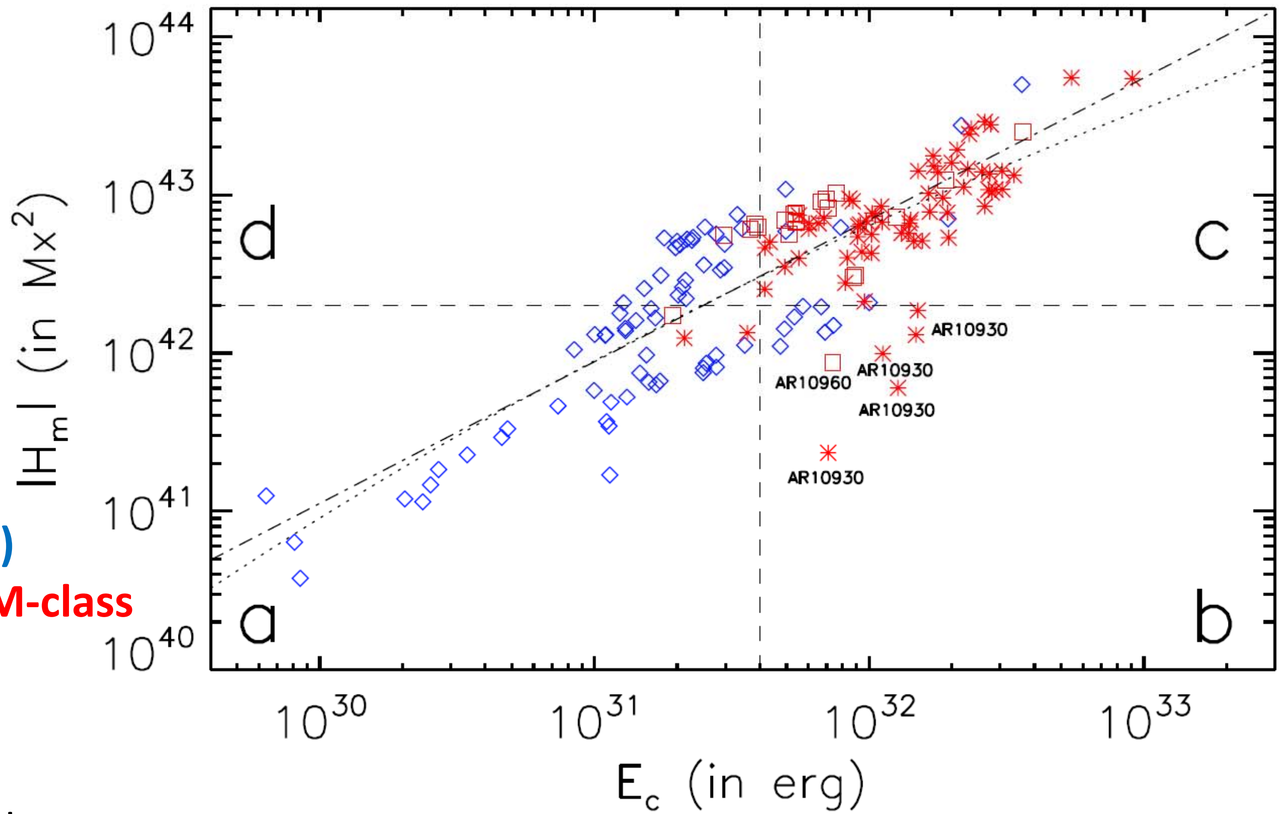
➢ Keep the value that gives positive contribution to energy $\alpha_l\ \mathcal{L}_{lm}^{arch} > 0$. Otherwise $\mathcal{L}_{lm}^{arch}$ is set to 0.

(See Georgoulis etal, 2012, ApJ, 759, 1 for validation and benchmarking of the method)

The energy – helicity diagram of solar ARs

Tziotziou, Georgoulis & Raouafi, 2012, ApJL, 759, 4

162 vector magnetograms of 42 ARs



Blue: non-flaring (≤ C-class)

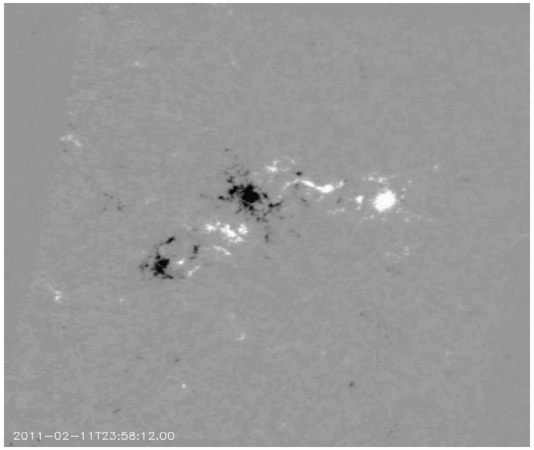
Red: flaring *: X-class ◘ : M-class

- nearly monotonic dependence
- flaring ARs show ***both*** large free energies and amplitudes of relative helicity
- flaring and non-flaring ARs well segregated; thresholds of ***~ 4 x 10^{31} erg*** in free magnetic energy and of ***~ 2 x 10^{42} Mx^2*** in relative magnetic helicity

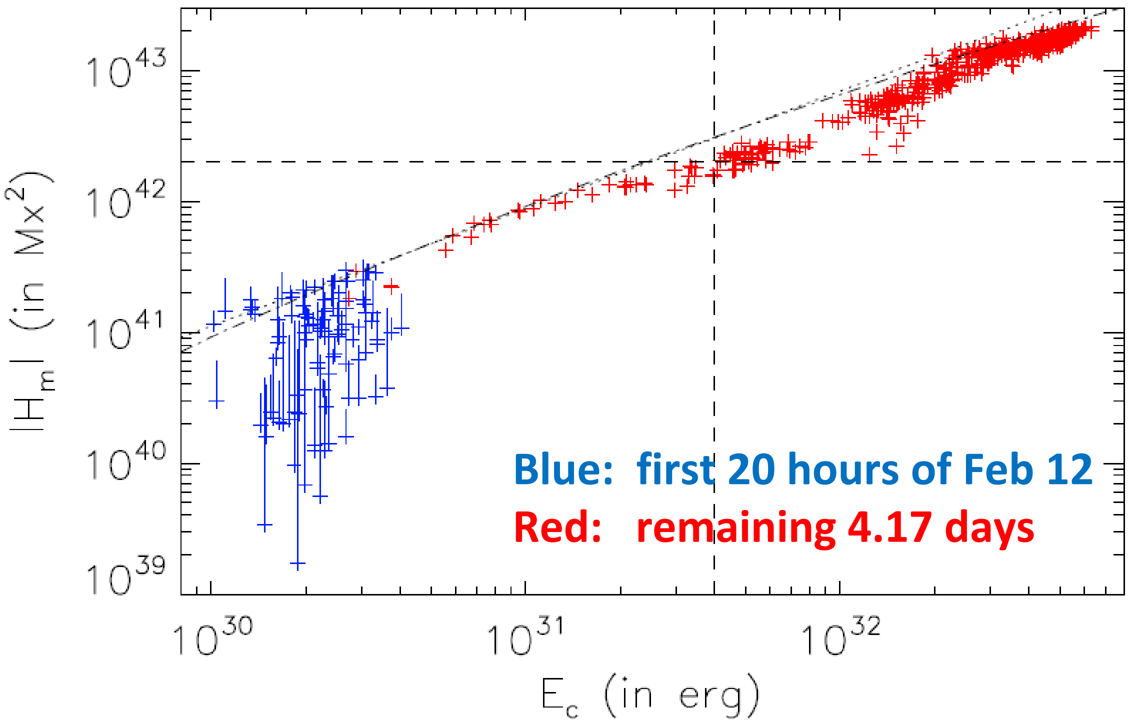
The energy – helicity diagram of AR 11158

Tziotziou, Georgoulis & Liu, 2013, ApJ, 772, 115

600 vector magnetograms of AR11158



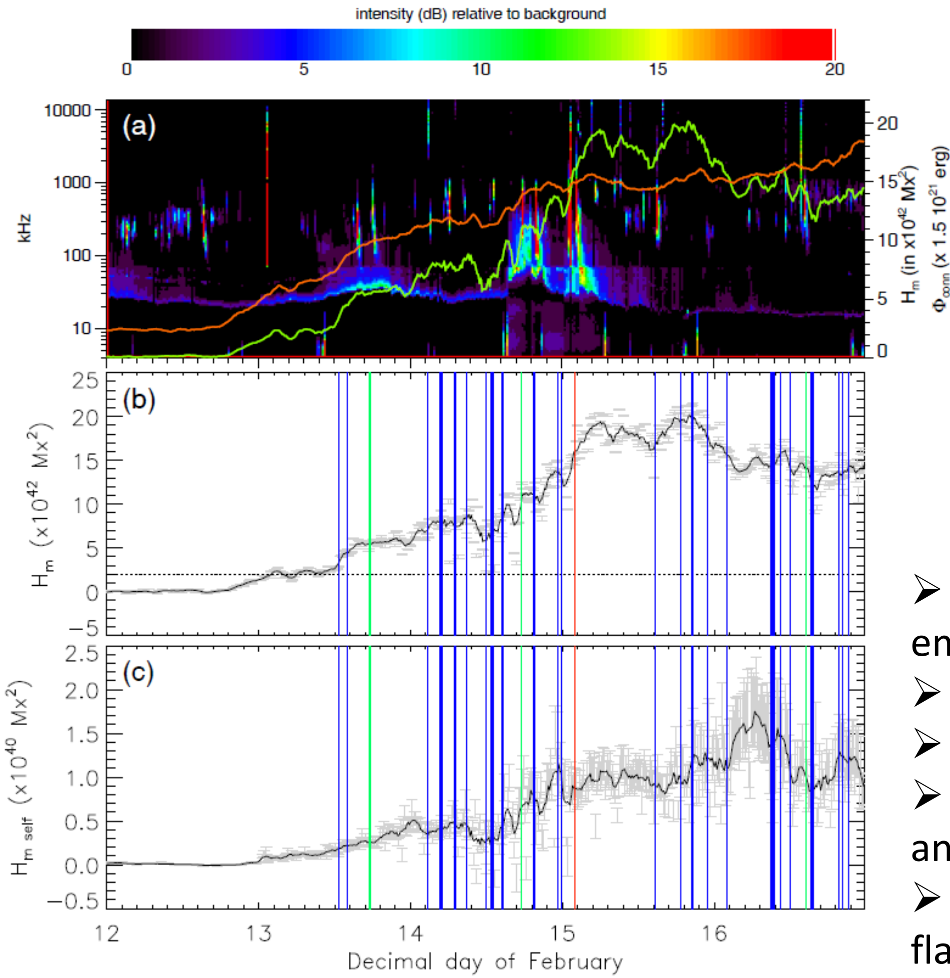
12-16 February 2012

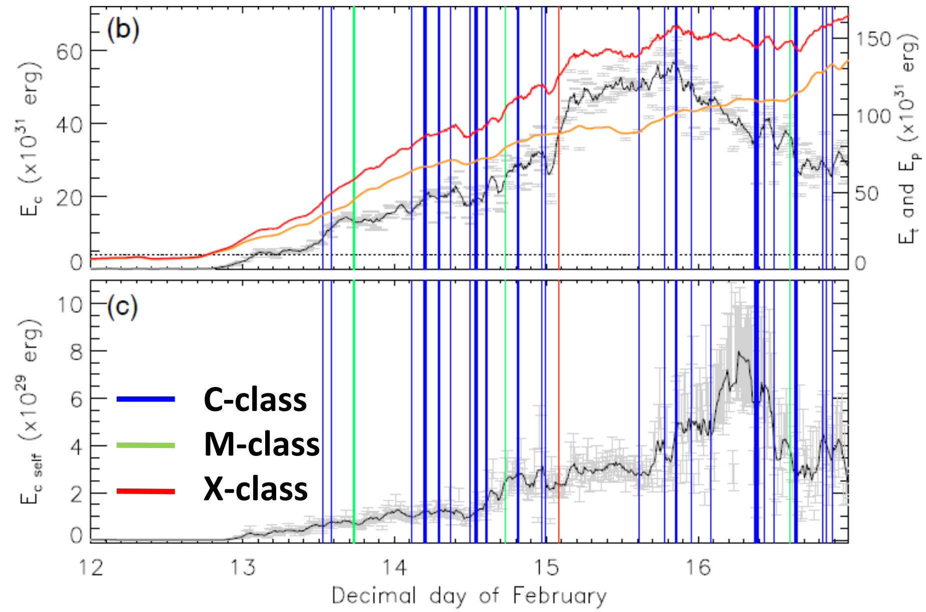


- ➢ first 20 hours: accumulation of helicity in ARs at higher rate than energy
- ➢ monotonic dependence for a large range of helicities and energies, attesting the validity of previously derived E-H diagram
- ➢ no major flare (≥ M-class) occurs before ***both*** thresholds are crossed

Energy and helicity budgets in AR 11158

1 X-class, 3 M-class and 25 C-class



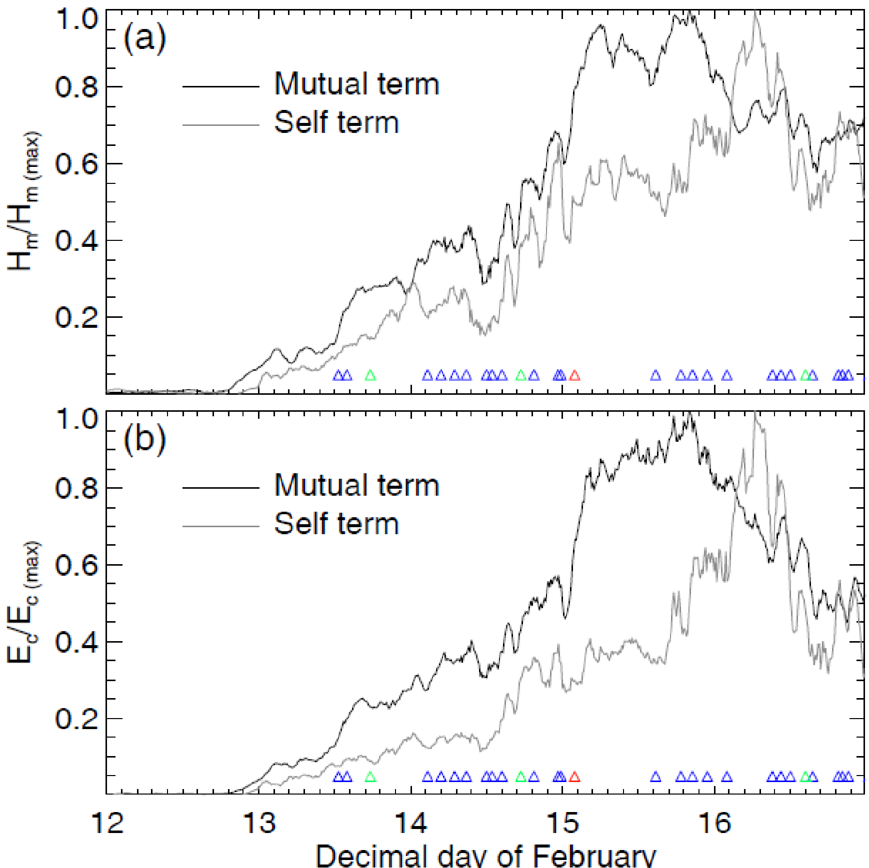


- ➢ significant energy/helicity budgets by continuous flux emergence, enough to power several eruptive flares
- ➢ all 3 M-class and the X-class flare are eruptive
- ➢ dominant sense of positive (right handed) helicity
- ➢ no major flare before thresholds of ***~ 2 x 10^{42} Mx^2*** and of ***~ 4 x 10^{31} erg*** are exceeded
- ➢ increases/decreases agree with dynamical evolution, flaring/erupting behavior and large re-organizations of the magnetic field

For detailed description see Tziotziou, Georgoulis & Liu, 2013, ApJ, 772, 115

Relative timing between mutual and self helicity/energy terms

Hysteresis in the build-up of self helicity/energy with respect to mutual terms



- qualitative features of mutual terms are reproduced in self terms with a delay of several to ~ 24 hours
- mutual terms peak ~ 12 hours earlier than self terms

Magnetic reconnection

Helicity roughly conserved in reconnection

Energy dissipates in reconnection

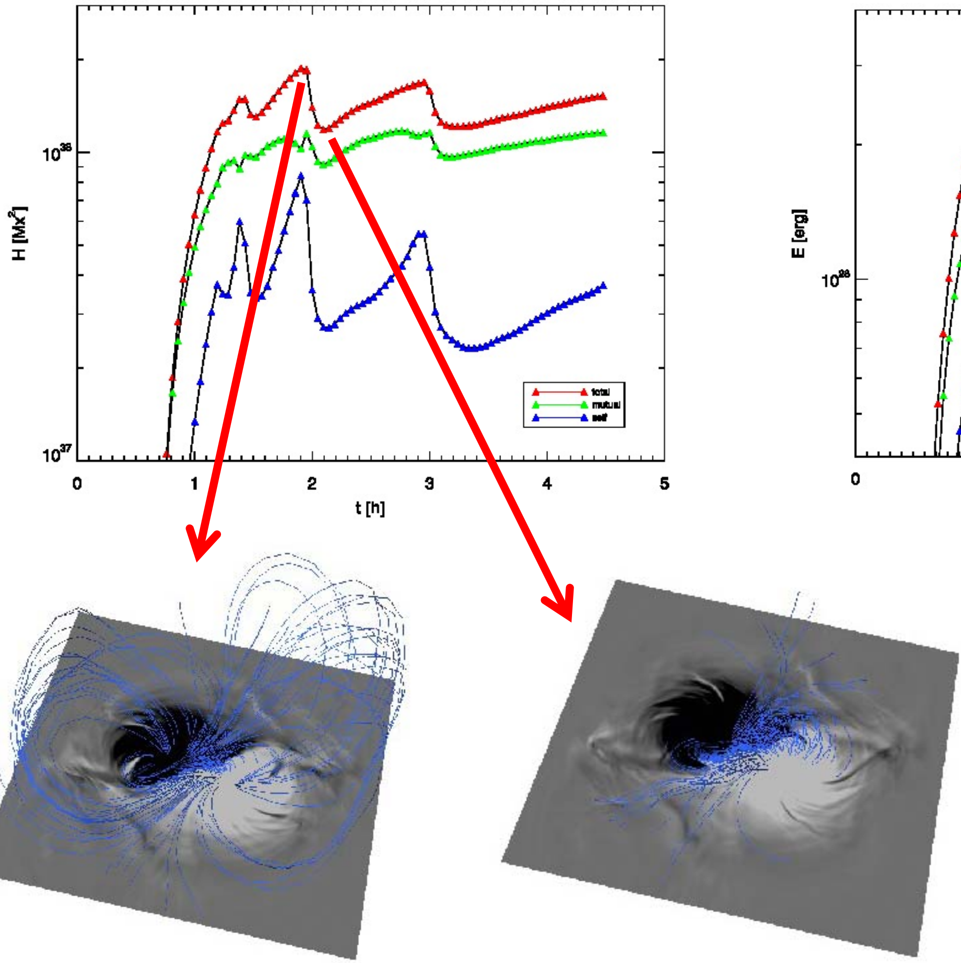
Increasingly twisted individual flux tubes (flux rope)

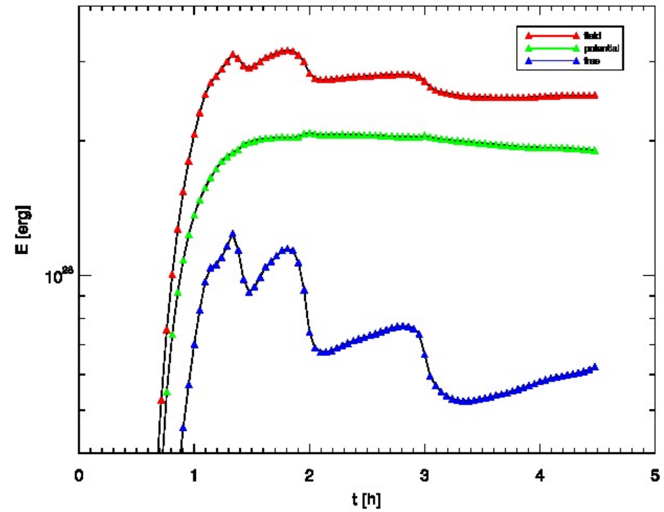
Interacting pre-reconnection flux tubes more helical after because they interact less

Lower build-up rate of free energy compared to helicity

Relative timing between mutual and self helicity/energy terms

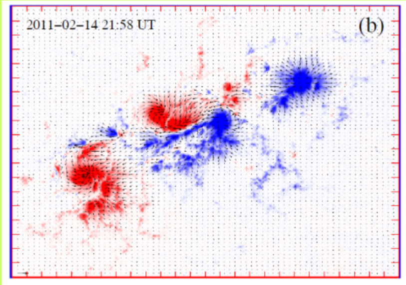
Hysteresis supported by analytical derivation of helicity and energy terms from 3D eruption simulations (V. Archontis)



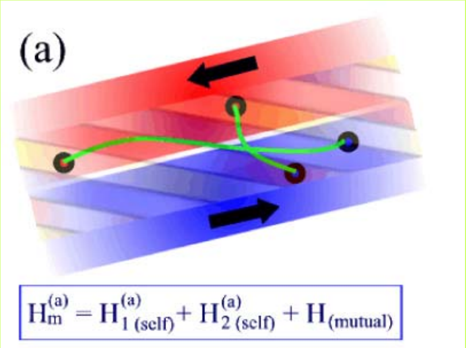


See poster S1-29, Moraitis etal.

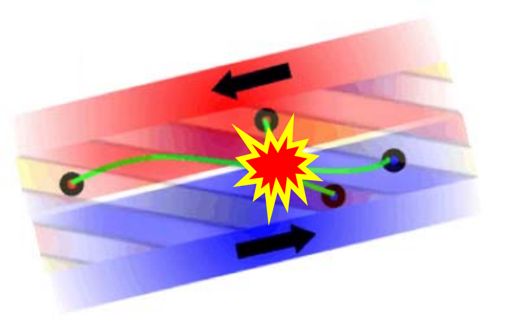
An eruption scenario (see poster S1-12, Georgoulis etal.)



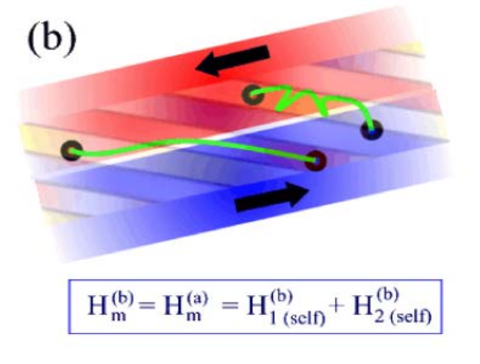
Most eruptive ARs characterized by intense PIL



Lorentz-force tension causes shear adding stresses to already complex magnetic configuration



Reconnection events along PIL

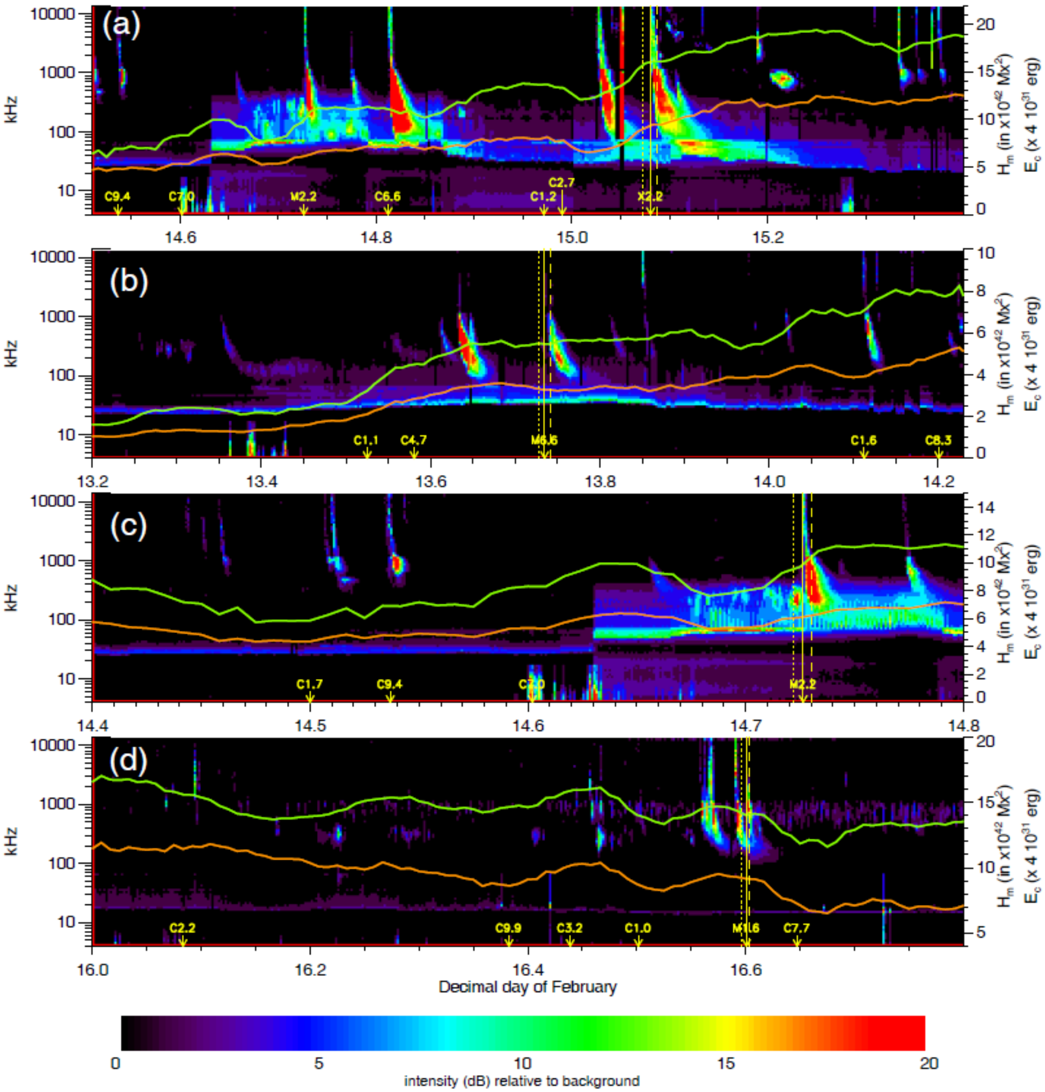


Shear-induced mutual helicity transforms into self helicity

Helical structures along PILs

Formation of pre-eruption flux ropes

Flare – CME causal connection



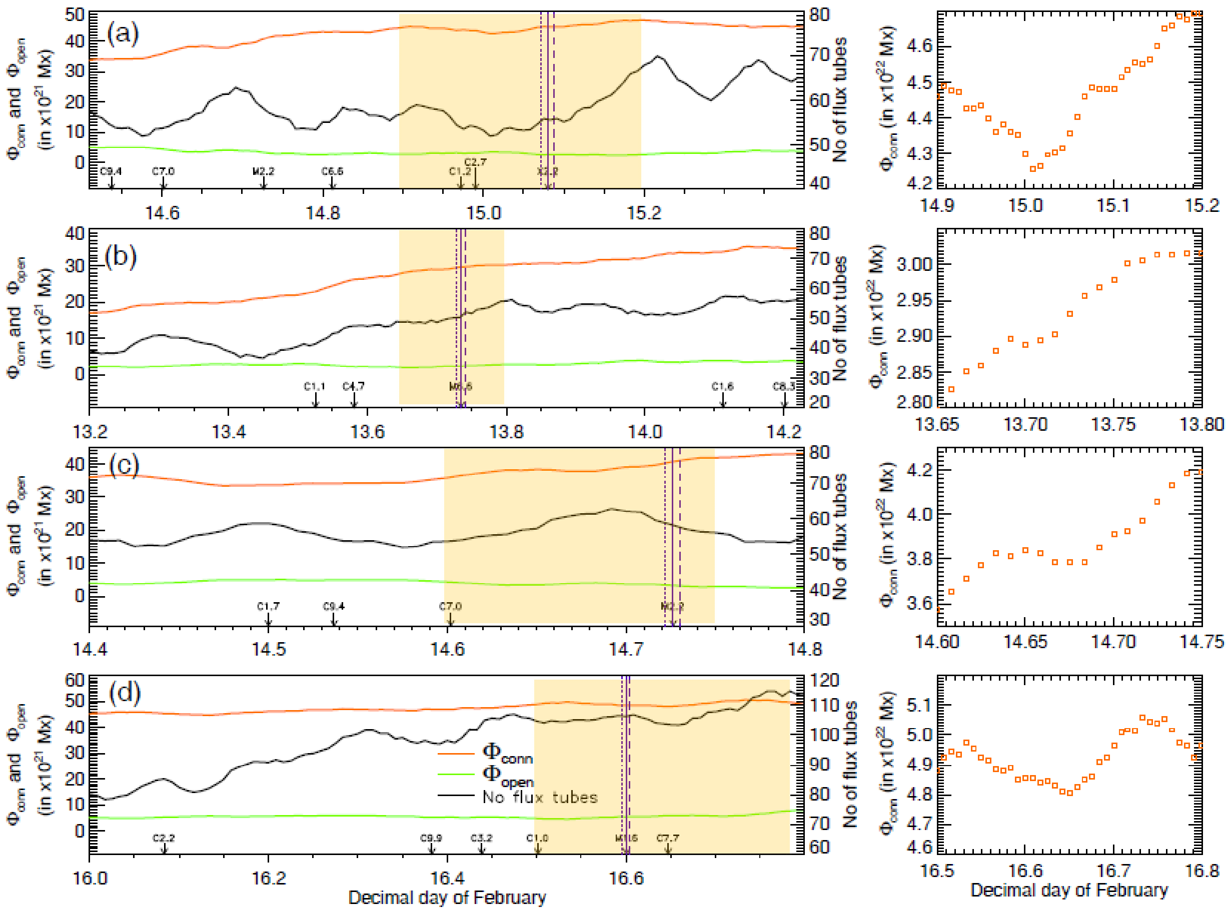
Four largest eruptive flares indicate:

- significant decreases of helicity and energy, lasting 2-3 hours, ***well before*** the onset of flare and launch time of CME
- Flares and CMEs occur 15-30 min before the end of dips; helicity/energy follows the general trend afterwards
- Helicity budgets of respective CMEs for X2.2, M2.2 and M1.6 in excellent agreement with estimated typical contents of CMEs

Flare class	ΔE_c (erg)	ΔH_m (Mx^2)
X2.2	8.4×10^{31}	2.6×10^{42}
M6.6	1×10^{31}	2.9×10^{42}
M2.2	4.9×10^{31}	2.8×10^{42}
M1.6	6.5×10^{31}	2×10^{42}

- M6.6 appears weak in radio spectra and registered as “Poor” and “Partial Halo” in the LASCO CME catalogue

Flare – CME causal connection



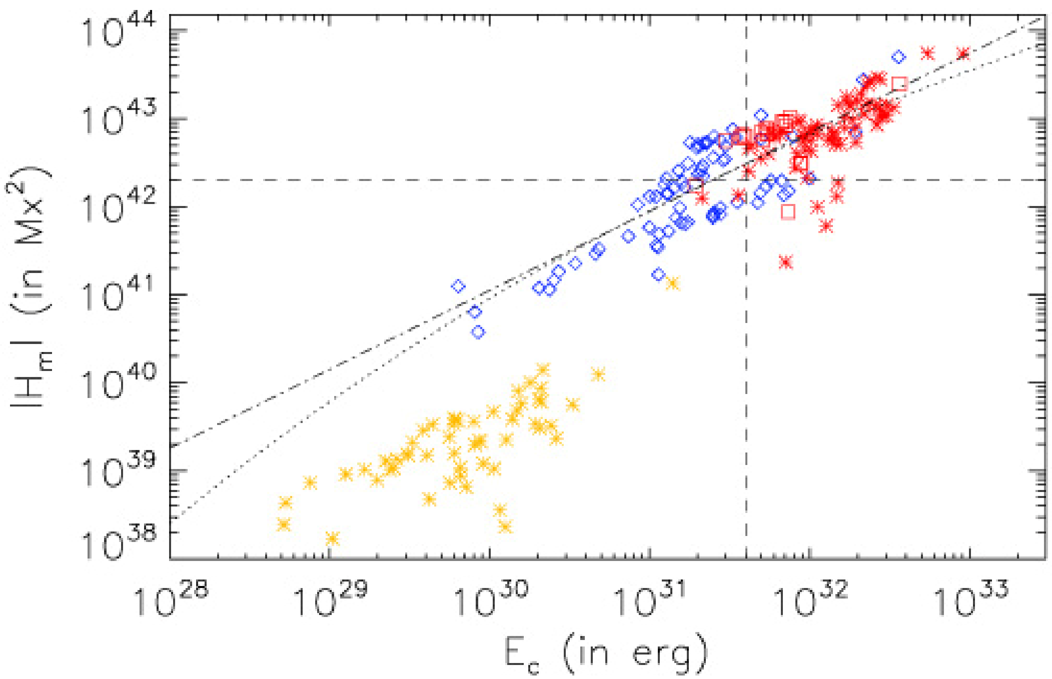
- co-temporal slight decreases in connected flux (largest for X2.2 smaller for M6.6)
- no associated increases in "open" flux

Normal B_z component becomes weaker prior to eruptions

The CME progenitor precedes flares which are the result of a drastic perturbation caused by the progenitor's ascension

The energy – helicity diagram of solar quiet regions

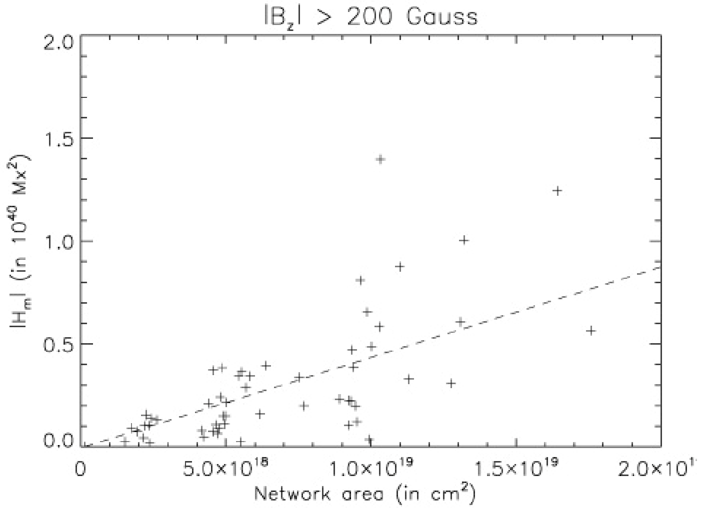
Calculated energy/helicity in 56 flux-balanced (within 15%) quiet Sun regions

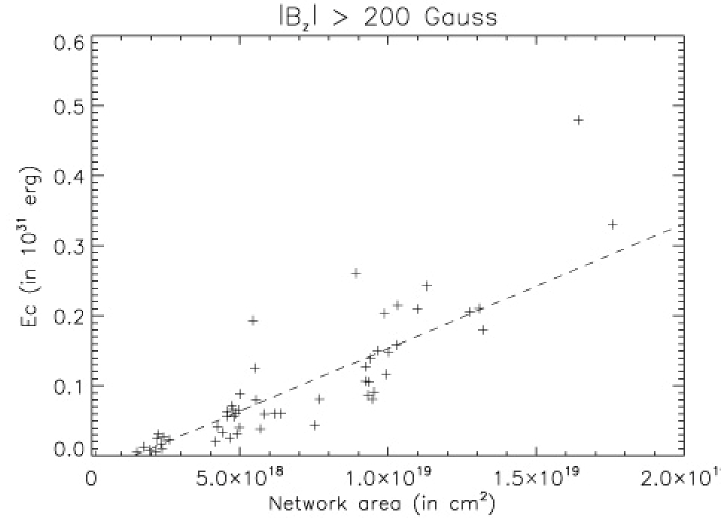


E-H diagram of quiet Sun regions results from combined effect of:

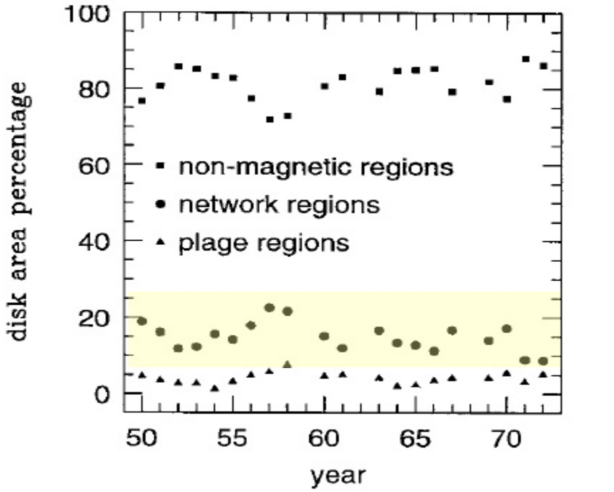
- presence of hierarchical structures (chromospheric network)
- non-dominant sense of helicity in quiet Sun regions

Energy and helicity in quiet solar regions





Caccin etal. 1998, Solar Phys., 177, 295



Quiet Sun helicity variations within solar cycle:

6.68×10^{41} Mx^2 – 1.67×10^{42} Mx^2

Quiet Sun helicity free energy variations within solar cycle:

2.71×10^{32} erg – 6.78×10^{32} erg

Within 1 solar cycle		
Quantity	**Our calculation**	**Previous studies**
Helicity	**1.34×10^{43} Mx^2**	**~10^{43}** (Welch & Longcope 2003) **~10^{45}** (Georgoulis etal. 2009)
Free energy	**5.42×10^{33} erg**	**-**

Conclusions

- New method for estimating magnetic energy and helicity budgets **using single vector magnetograms**

- Both magnetic free energy and helicity seem to play an important role in AR evolution and quiet Sun dynamics

- There exist **thresholds** of ***4×10^{31} erg*** *and* ***2×10^{42} Mx^2*** for free energy and helicity, respectively, for ARs to host major, typically eruptive, flares

- Eruption-related decreases before flare/CME launch times, suggest that CME progenitors precede flares

- progressive mutual-to-self helicity/energy conversion, stemming from magnetic reconnection along the PIL, seems to build increasingly helical pre-eruption structures that will eventually erupt. Support from analytical calculations using a MHD model of an eruptive region.

- E-H diagram of quiet Sun regions shows also monotonic dependence; considerable amounts of free energy and helicity present (similar to a moderate X-class flare)

Thank you!

Relevant papers:

- Georgoulis, Tziotziou & Raouafi, 2012, ApJ, 759, 1, *“Magnetic Energy and Helicity Budgets in the Active-region Solar Corona. II. Nonlinear Force-free Approximation”*
- Tziotziou, Georgoulis & Raouafi, 2012, ApJL, 759, 4 *“The Magnetic Energy-Helicity Diagram of Solar Active Regions”*
- Georgoulis, Titov, & Mikić, 2012, ApJ, 761, 61, *“Non-neutralized Electric Current Patterns in Solar Active Regions: Origin of the Shear-generating Lorentz Force”*
- Tziotziou, Georgoulis & Liu, 2013, ApJ, 772, 115 *“Interpreting Eruptive Behavior in NOAA AR 11158 via the Region's Magnetic Energy and Relative-helicity Budgets”*