Magnetic energy and helicity budgets of solar quiet regions and their role in fine structure dynamics

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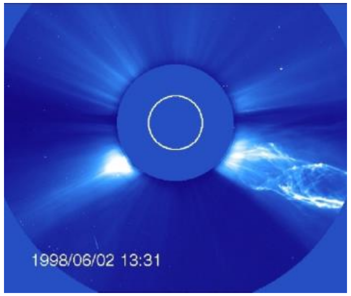
INTRODUCTION

Magnetic helicity and free magnetic energy

Magnetic helicity: quantifies distortion (twist and writhe) and linkage of magnetic field lines compared to their current-free potential state

Free magnetic energy: quantifies the excess energy on top of "ground" potential energy

While free energy is released via reconnection, helicity in plasmas with high Reynolds numbers is mostly conserved during reconnection; hence, if not transferred to other solar areas, has to be bodily removed

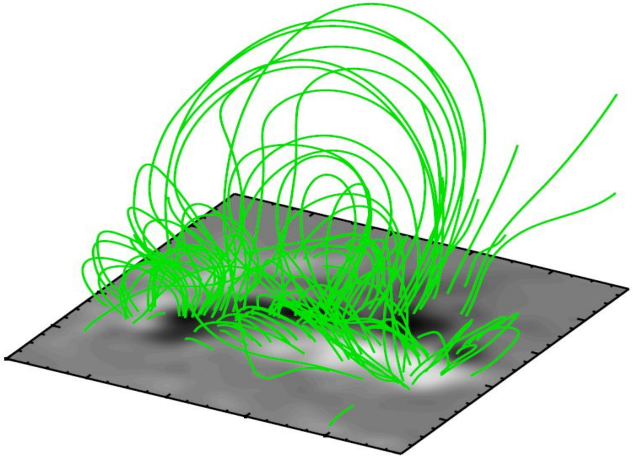


Helicity/Energy derivation

Volume calculations

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

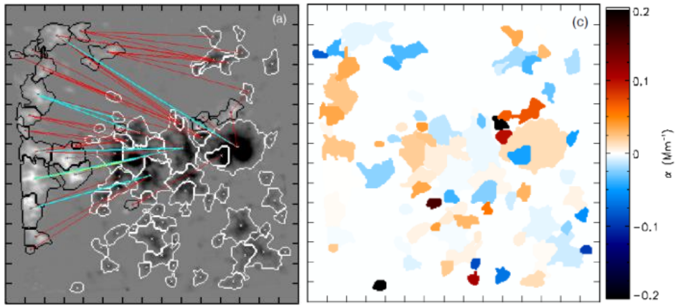
$$E_{\rm c} = E_{\rm t} - E_{\rm p} = \frac{1}{8\pi} \int_{\mathcal{V}} {\rm d}V\, \mathbf{B}^2 - \frac{1}{8\pi} \int_{\mathcal{V}} {\rm d}V\, \mathbf{B}_{\rm p}^2$$



1st method: New NLFF approach for energy/helicity calculations

The method translates a ***single vector magnetogram*** into a collection of ***N*** slender flux tubes by:

- ✓ *partitioning the magnetic field configuration into an ensemble of **p** positive and **n** negative "magnetic charges"*
- ✓ *populating the **p** × **n** connectivity matrix that contains fluxes committed to each ij-connection, using the simulated annealing method*
- ✓ *assuming each connection to be a slender flux tube with a force-free parameter α_{ij} (mean of α-parameters of connected partitions)*



Free magnetic energy (lower limit)

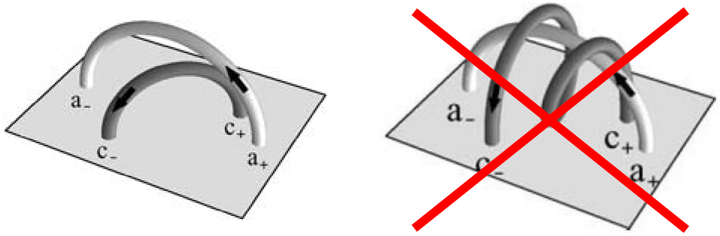
$$E_c = \underbrace{A\lambda^2 \sum_{l=1}^{N} \alpha_l^2 \Phi_l^{2\delta}}_{\text{Self term}} + \frac{1}{8\pi} \underbrace{\sum_{l=1}^{N} \sum_{m=1,l\neq m}^{N} \alpha_l \mathcal{L}_{lm}^{\text{arch}} \Phi_l \Phi_m}_{\text{Mutual term}}$$

$$H = \overbrace{8\pi\lambda^2 A \sum_{l=1}^{N} \alpha_l \Phi_l^{2\delta}}^{\text{Self term}} + \overbrace{\sum_{l=1}^{N} \sum_{m=1,l\neq m}^{N} \mathcal{L}_{lm}^{\text{arch}} \Phi_l \Phi_m}^{\text{Mutual term}}$$

Relative magnetic helicity

λ: pixel size
A, δ: known scaling constants
l,*m*: different flux tubes with known flux Φ and FF parameter α

$\mathcal{L}_{lm}^{arch}$ describes "interaction" between flux tubes (derived from trigonometric interior angles)



(Georgoulis etal, 2012, ApJ, 759, 1)

2nd method: Helicity and energy injection rate calculations

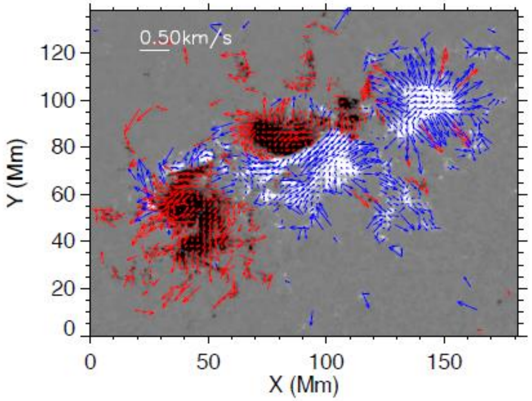
$$\left.\frac{dH}{dt}\right|_S = 2\int_S (\mathbf{A}_p\cdot\mathbf{B}_h)\upsilon_{\perp n}dS - 2\int_S(\mathbf{A}_p\cdot\boldsymbol{\upsilon}_{\perp t})B_z dS$$

Berger & Field (1984)

$$\left.\frac{dE}{dt}\right|_S = \frac{1}{4\pi}\int_S B_h^2 \upsilon_{\perp n}dS - \frac{1}{4\pi}\int_S(\mathbf{B}_h\cdot\boldsymbol{\upsilon}_{\perp t})B_z dS$$

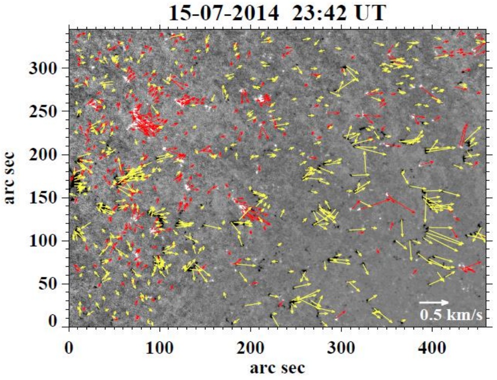
emergence ***shuffling***

Kusano *etal.* (2002)



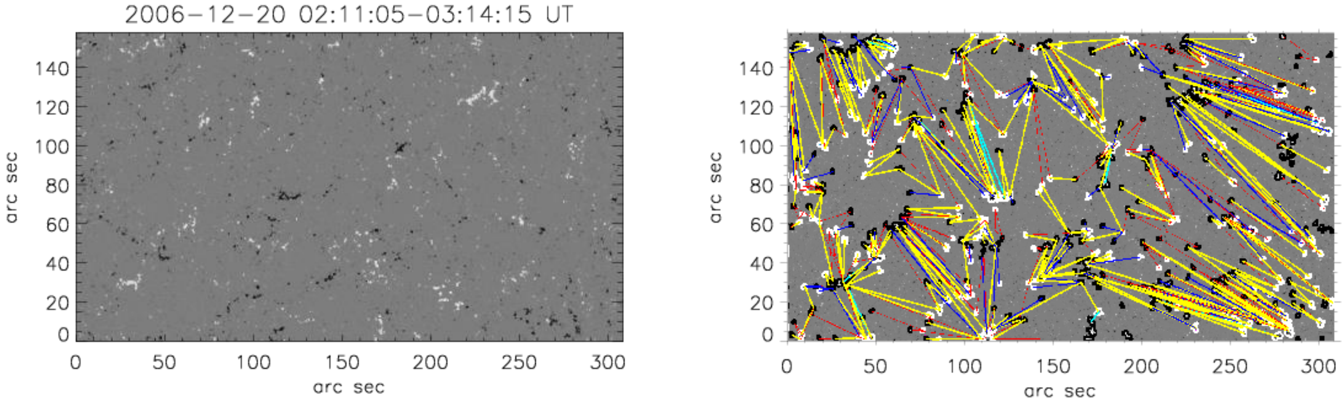
Best method for velocity field calculation:
DAVE4VM **(Schuck 2008)**
Finds the velocity by using the normal component of the ideal induction equation

$$\partial_t B_z + \nabla_h\cdot\left(B_z\boldsymbol{\upsilon}_h - \upsilon_z\mathbf{B}_h\right) = 0$$

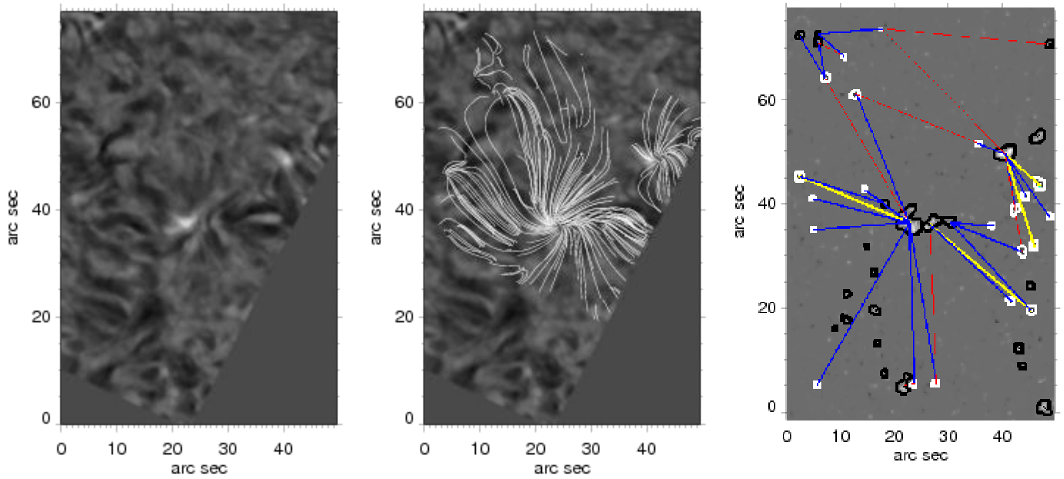


Applying the first method to quiet Sun regions

Example of quiet Sun connectivity



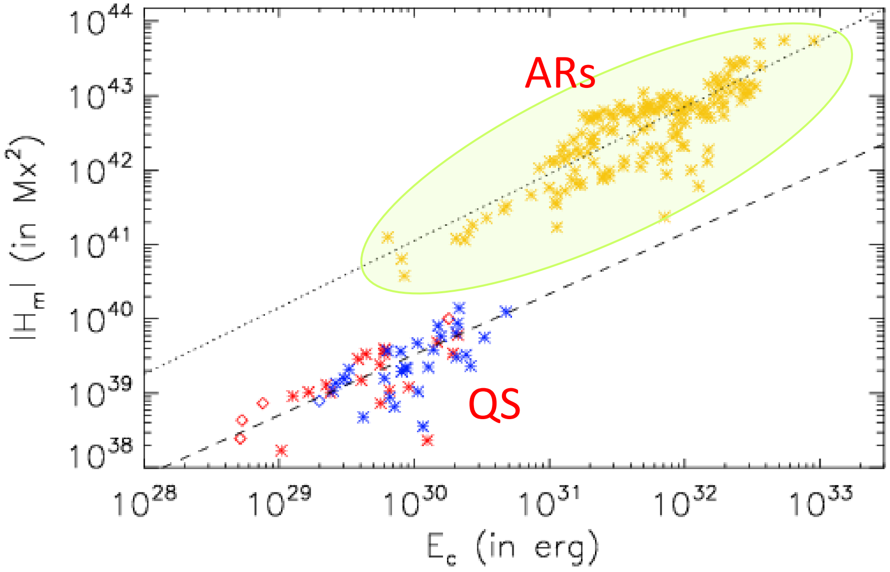
Validity of the method

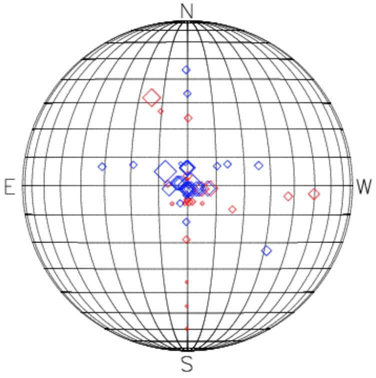


The NLFF method reproduces the general configuration inferred from Hα observations and extrapolations

The energy – helicity diagram of quiet Sun

See also poster S1.05 by Georgoulis etal.





55 Hinode QS regions

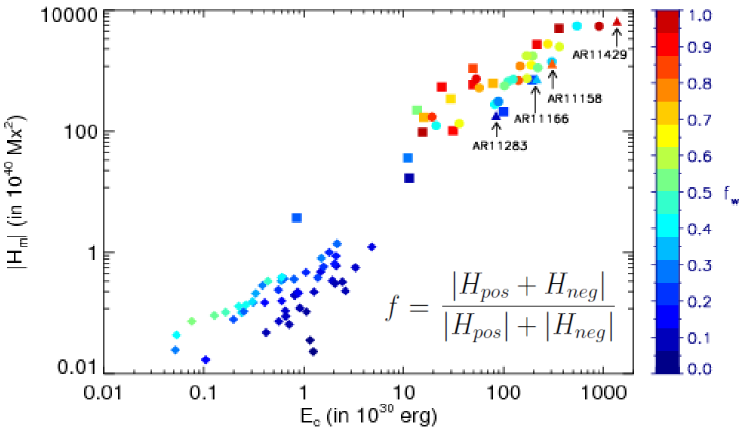
Scaling law:

$$|H_m| \propto E_c^{0.84 \pm 0.05}$$

Tziotziou *etal.* 2014, A&A, 570, L1,

Tziotziou *etal.* 2014, A&A, 564, A86

Tziotziou *etal.* 2012, ApJL, 759, 4)



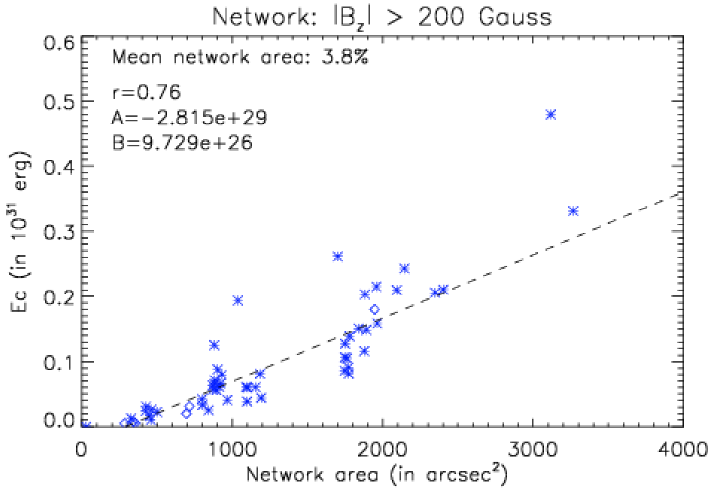
Helicity behaviour:

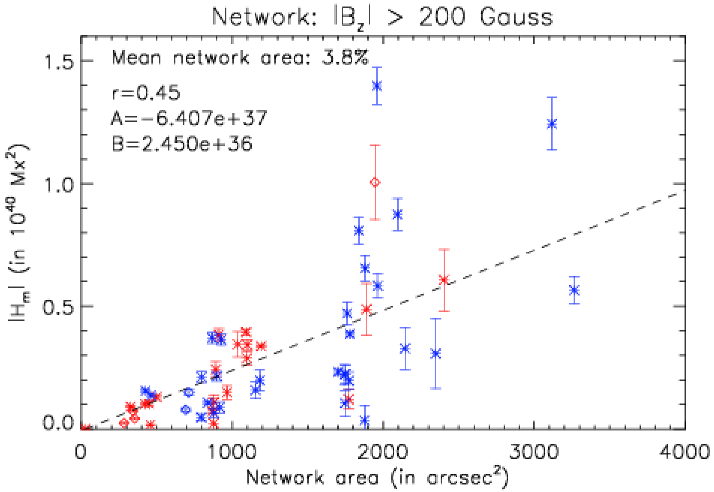
- eruptive ARs have a dominant sense of helicity f = 0.58 ± 0.27 (on average ~ 4:1 dominance)
- QS regions incoherent in terms of helicity sense f = 0.2 ± 0.17 (on average ~ 1.5:1 dominance)

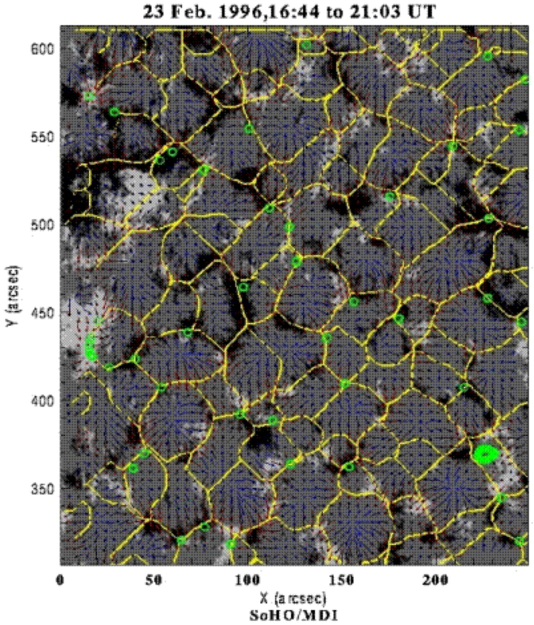
Majority of ARs formed deep inside the convection zone while QS structures formed by shallow, near-surface, convection-powered dynamo

RESULTS OF FIRST METHOD

Energy and helicity as function of network area







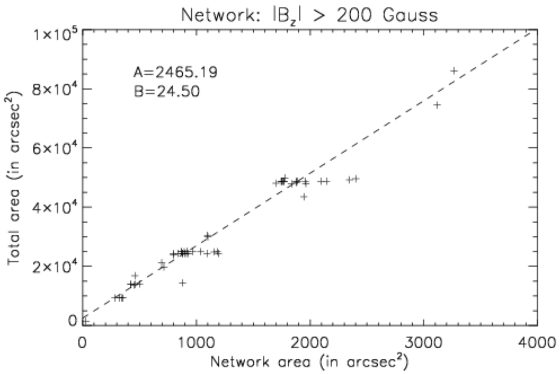
Dependence stems from the hierarchical structure of the magnetic field in QS: supergranular cells/network with rather similar physical characteristics (sizes, magnetic flux concentrations)

structure:

dgets scale roughly with number

in an area

ger the derived network areas

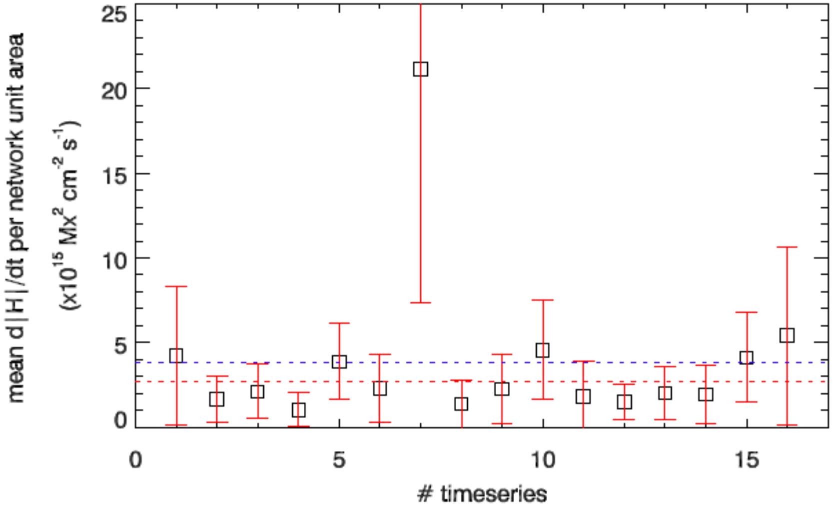


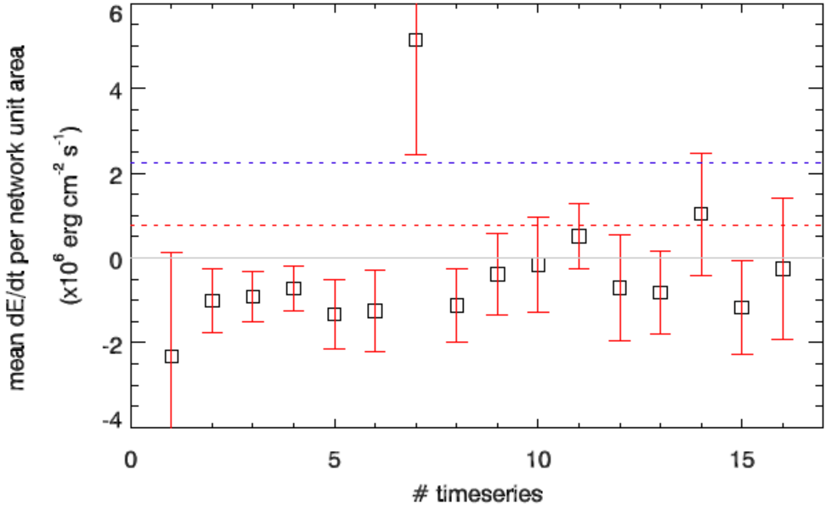
Energy and helicity injection rates

16 SDO/HMI daily timeseries, each comprising 120 magnetograms

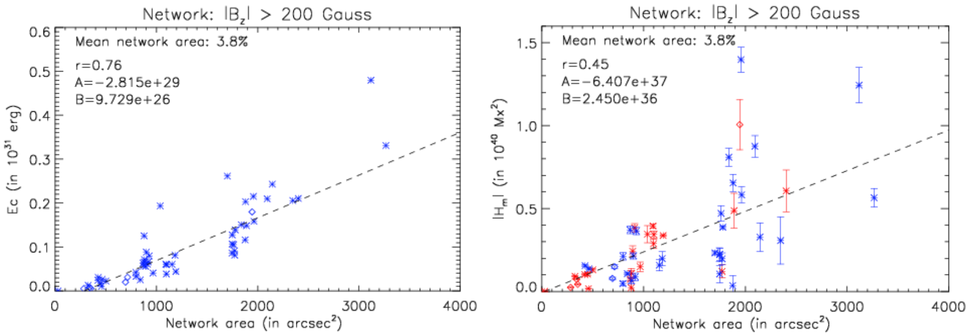
$$2.70 \pm 1.37 \times 10^{15}\ \mathrm{Mx}^2\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$$

$$7.73 \pm 3.67 \times 10^{5}\ \mathrm{erg\ cm}^{-2}\ \mathrm{s}^{-1}$$

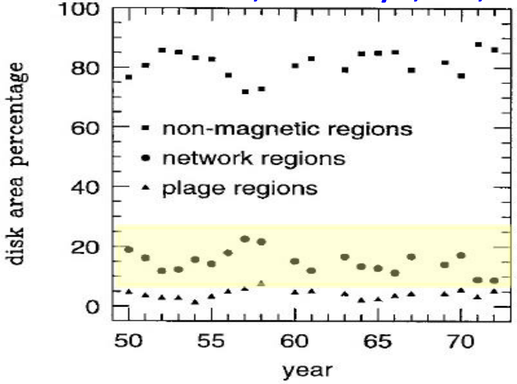




Instantaneous energy and helicity budgets



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



Instantaneous budgets for network with $|B_z| > 200$ G			
Relative helicity (**Mx²**)		Free energy (erg)	
Maximum	*Minimum*	*Maximum*	*Minimum*
$1.42 \pm 0.05 \times 10^{42}$	$3.54 \pm 0.13 \times 10^{42}$	$5.62 \pm 0.21 \times 10^{32}$	$1.41 \pm 0.05 \times 10^{33}$

helicity lags respective AR helicity due to incoherence

~ a sizeable (X-class eruptive) AR

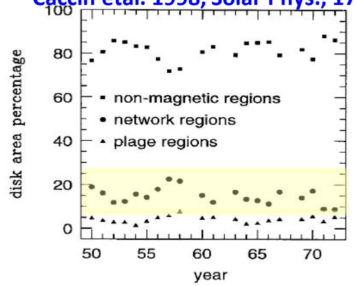
RESULTS

Energy and helicity budgets in a solar cycle

First method

Instantaneous budgets for network with $\|B_z\|$ > 200 G			
Relative helicity (Mx²)		**Free energy (erg)**	
Maximum	*Minimum*	*Maximum*	*Minimum*
$1.42 \pm 0.05 \times 10^{42}$	$3.54 \pm 0.13 \times 10^{42}$	$5.62 \pm 0.21 \times 10^{32}$	$1.41 \pm 0.05 \times 10^{33}$

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



Energy and helicity replenishes within 1.8±0.9 d

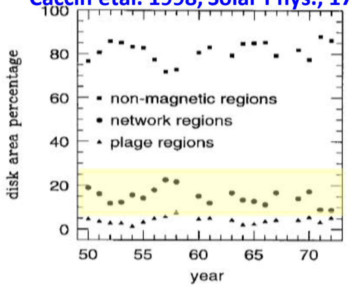
(Rieutord & Rincon 2010)

Second method

$$2.70 \pm 1.37 \times 10^{15}\ \mathrm{Mx}^2\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$$

$$7.73 \pm 3.67 \times 10^{5}\ \mathrm{erg}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$$

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



Total within a solar cycle	
Relative helicity (Mx²)	**Free energy (erg)**
$5.02 \pm 2.52 \times 10^{45}$	$1.99 \pm 1.0 \times 10^{36}$
$9.1 \pm 4.56 \times 10^{45}$	$2.6 \pm 1.2 \times 10^{36}$

Higher than previous studies:

~10^{43} Mx² (Welch & Longcope 2003) **~1.5 ×10^{44}** Mx² (Georgoulis etal. 2009)

RESULTS OF FIRST METHOD

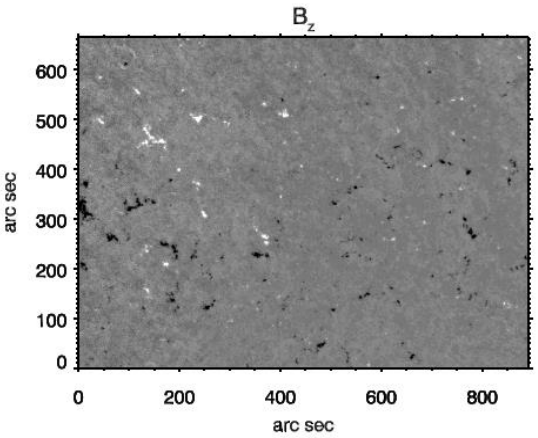
Energy dissipation and small-scale dynamics

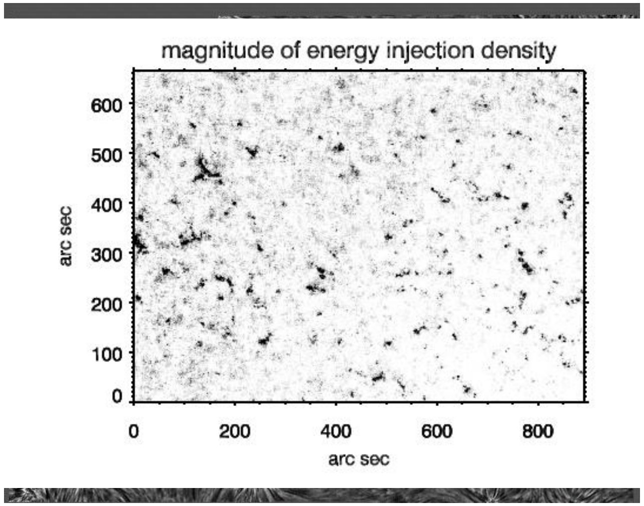
Free energy rate	
First method	Second method
5.4 ×10^5 erg cm^2 s^{-1}	7.73 ×10^5 erg cm^2 s^{-1}

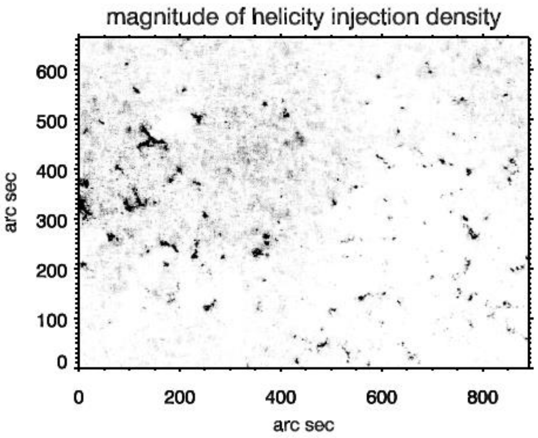
Energy dissipated by fine structures:

1.2 ×10^5 erg cm^2 s^{-1} (Tsiropoula & Tziotziou 2004)

7 ×10^5 erg cm^2 s^{-1} (Moore *et al.* 2011)







Conclusions

- Investigated energy and helicity in quiet Sun region with two different methods

- Just like in ARs, there exists a monotonic relation between free magnetic energy and relative magnetic helicity in quiet-Sun regions $|H_m| \propto E_c^{0.81}$

- Contrary to ARs quiet-Sun regions have no dominant sense of helicity (near-surface dynamo?)

- There exists a monotonic relation between helicity/energy and network area

- Considerable amounts of free energy and helicity present on the quiet-Sun solar surface (similar to a moderate X-class producing AR)

- Helicity/energy budgets during an entire solar cycle higher than previously reported values

- **Free energy budgets considerable and enough to power the dynamics of quiet Sun fine structures (mottles, spicules etc)**

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, Tsiropoula, Georgoulis & Kontogiannis, 2014, A&A, 564, A86 *"Energy and helicity budgets of solar quiet regions"*
- Tziotziou, Moraitis, Georgoulis & Archontis, 2014, A&A, 570, L1 *"Validation of the magnetic energy vs. helicity scaling in solar magnetic structures"*
- Tziotziou, Park, Tsiropoula & Kontogiannis, 2015, A&A, submitted *"Energy and helicity injection in solar quiet regions"*