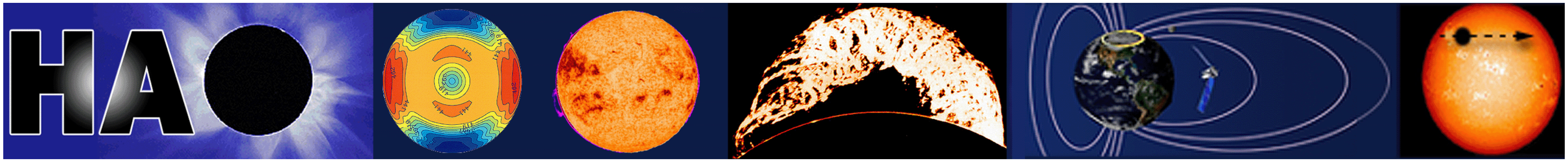


How Might the Structure and Evolution of the Photospheric Magnetic Field Influence the Chromosphere?

Bruce W. Lites

16 March 2016
NSO, Boulder, CO USA

The National Center for Atmospheric Research is operated by the University Corporation for Atmospheric Research under sponsorship of the National Science Foundation. An Equal Opportunity/Affirmative Action Employer.

Goal of this presentation:

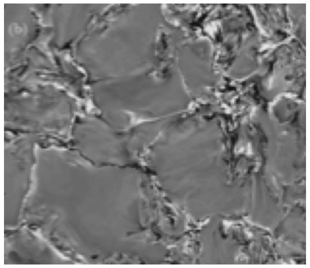
- Review a few observational findings regarding the photospheric magnetic field and its influence on chromospheric structure and dynamics

Overarching Theme: Flux Emergence

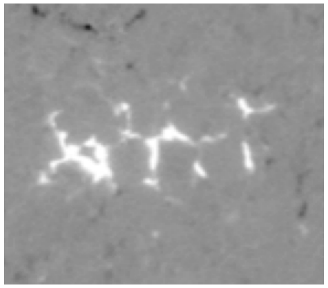
- Emergence fuels the dynamics of magnetic phenomena in the solar atmosphere
- Personal view: submergence on observable scales is very unlikely, but….
- Flux submergence may happen at scales that so far are unobservable

Structure of the Presentation: Increasing levels of Magnetic Influence

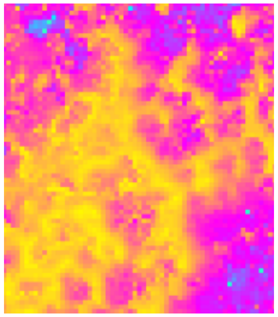
Quiet Sun Weak Internetwork:
(fields in equipartition with flows)



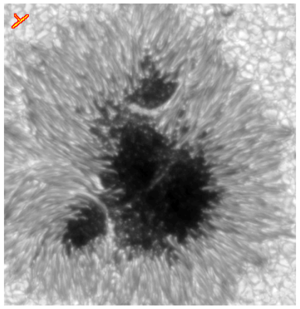
Quiet Sun Network:
(kiloGauss fields in photosphere that structure the atmosphere locally)



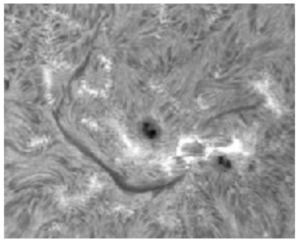
Plage:
(unipolar kiloGauss fields – larger scale ordering of chromosphere)



Sunspots:
(fields that dominate and strongly order atmospheric structure)



AR Filaments:
(fields that extend into the photosphere)



Overview: Magnetic Field Structure of the Quiet Photosphere

What Might Be the Chromospheric Field Structure Over the Quiet Sun?

1. **The observed structure of photospheric *internetwork* magnetic fields**
2. **The observed structure of photospheric *network* magnetic field**

The Astrophysical Journal, 614:L89–L91, 2004 October 10
© 2004. The American Astronomical Society. All rights reserved. Printed in U.S.A.

CONCERNING THE EXISTENCE OF A "TURBULENT" MAGNETIC FIELD IN THE QUIET SUN

Rafael Manso Sainz,[1,2] Egidio Landi Degl'Innocenti,[3] and Javier Trujillo Bueno[2,4]

Received 2004 June 2; accepted 2004 August 18; published 2004 September 15

ABSTRACT

We report on the $a\,^5F$–$y\,^5F^\circ$ multiplet of Ti I and its interest for the study of "turbulent" magnetic fields in the quiet solar photosphere. In particular, we argue that the sizable scattering polarization signal of the 4536 Å line (whose lower and upper levels have Landé factors equal to zero), relative to the rest of the lines in the multiplet, gives *direct* evidence for the existence of a ubiquitous, unresolved magnetic field. We cannot determine precisely the strength of the magnetic field, but its very existence is evidenced by the differential Hanle effect technique that this Ti I multiplet provides.

Subject headings: line: formation — polarization — scattering — Sun: atmosphere — Sun: magnetic fields

Magnetic fields in the solar atmosphere may be detected most clearly by the circular polarization pattern they induce in spectral lines. However, this Zeeman effect technique is not very suitable for investigating magnetic fields that have complex unresolved geometries because the contributions of opposite magnetic polarities within the spatiotemporal resolution element of the observation tend to cancel out. Consequently, extremely weak magnetic fields or even strong fields with a rather convoluted topology may remain virtually undetectable.

This is unfortunate since, according to our general picture of solar magnetism, most regions of the solar atmosphere are expected to be filled by magnetic fields whose geometries are complex and far from being spatially resolved. In particular, "turbulent" magnetic fields driven by highly chaotic fluid motions are supposed to pervade the "quiet" regions of the solar photosphere, with mixed magnetic polarities even below the photon mean free path (e.g., Cattaneo 1999). At higher chromospheric and coronal levels, the medium rarefies exponen-

The main problem of these analyses is that they require a reference zero-field polarization amplitude that, in turn, heavily relies on theoretical calculations. Only very recently such radiative transfer calculations have started to be sufficiently realistic, taking into account the three-dimensional and dynamic nature of the solar atmosphere (Trujillo Bueno et al. 2004). In any case, the question may always be raised of whether all the other relevant physical mechanisms that can produce depolarization have been accounted for and whether the observed depolarization can then be safely ascribed to the presence of a magnetic field. In order to achieve model independence, it is useful to consider various spectral lines with different sensitivities to the Hanle effect (Stenflo et al. 1998). Unfortunately, the particular combination of atomic lines used by Stenflo et al. (1998) is far from optimum, because they have different line formation properties and none of them is insensitive to magnetic fields. Here we present an analysis of the polarization pattern of the multiplet 42 of Ti I. We argue that the available lines to the linearly polarized spectrum cannot be simply added up, and the depolarization of the continuum by the presence of the spectral line cannot be neglected. Nevertheless, we can always assume a similar effect for all the lines in the multiplet and compare the Q/I signals between them, in particular, with the 4536 Å line.

A theoretical estimate for the Q/I structure of the multiplet is shown in Figure 2*b*. It has been calculated for a 90° observation of a layer of atomic titanium gas that is illuminated from below by a photospheric-like radiation field. Details on the atomic model and radiation field are given in Paper I. First, we have calculated the atomic polarization that optical pumping processes induce in all the levels of the atomic model in the absence of any depolarizing mechanism. Second, we have calculated the Q/I signal in each transition taking into account the emissivity as well as dichroism effects (see eq. [14] of Paper I). As demonstrated in Paper I, this method is able to reproduce (at least qualitatively) the structure of the whole second solar spectrum of Ti I.

In order to model the depolarization due to a weak microturbulent magnetic field, we assume one and the same depolarizing rate for all the atomic levels, except for the levels $a\,^5F_1$ and $y\,^5F_1^o$, which have Landé factors equal to zero (Sugar & Corliss 1985).[5] We point out that all the ^5F terms of titanium are well described by the *LS* coupling. Therefore, according to the well-known formula for the Landé factor, we can assume that all the $^5F_1$ and $^5F_1^o$ levels are completely insensitive to the magnetic field. Figures 2*c* and 2*d* show the Q/I structure of the $a\,^5F$–$y\,^5F^o$ multiplet assuming depolarizing rates D of 10^8 and 5×10^8 s^{-1}, respectively, for all except the $^5F_1$ and $^5F_1^o$ levels (*thick lines*). If we roughly estimate an "equivalent" magnetic field intensity through the equation $2\pi\nu_L g = 8.79 \times 10^6 Bg \approx D$ (ν_L and g being the Larmor frequency and Landé factor, respectively), then, taking $g \approx 1$, a depolarizing rate $D = 10^8$ s^{-1} corresponds to a magnetic field of the order of 12 G, while $D = 5 \times 10^8$ s^{-1} implies 60 G. For comparison, the dotted lines show the Q/I values when all the levels are depolarized without exception. Only the transitions involving at least one level with a zero Landé factor (λλ4527, 4536, and 4544) change their behavior, as expected.

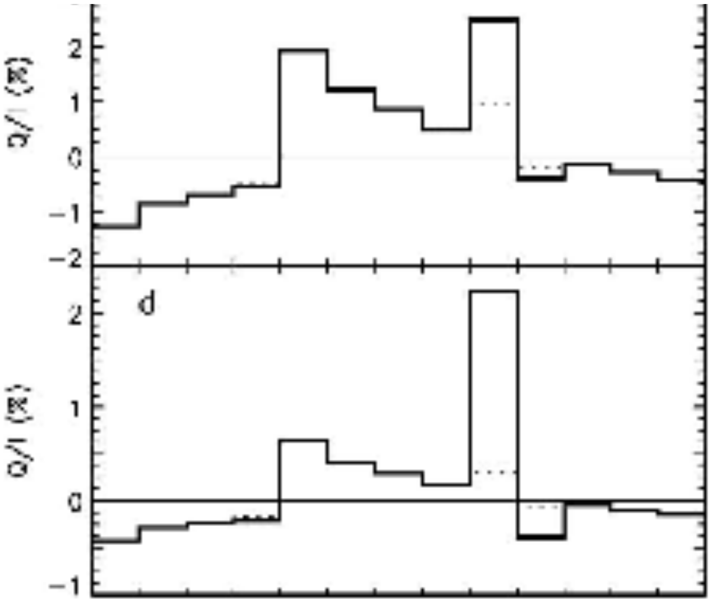


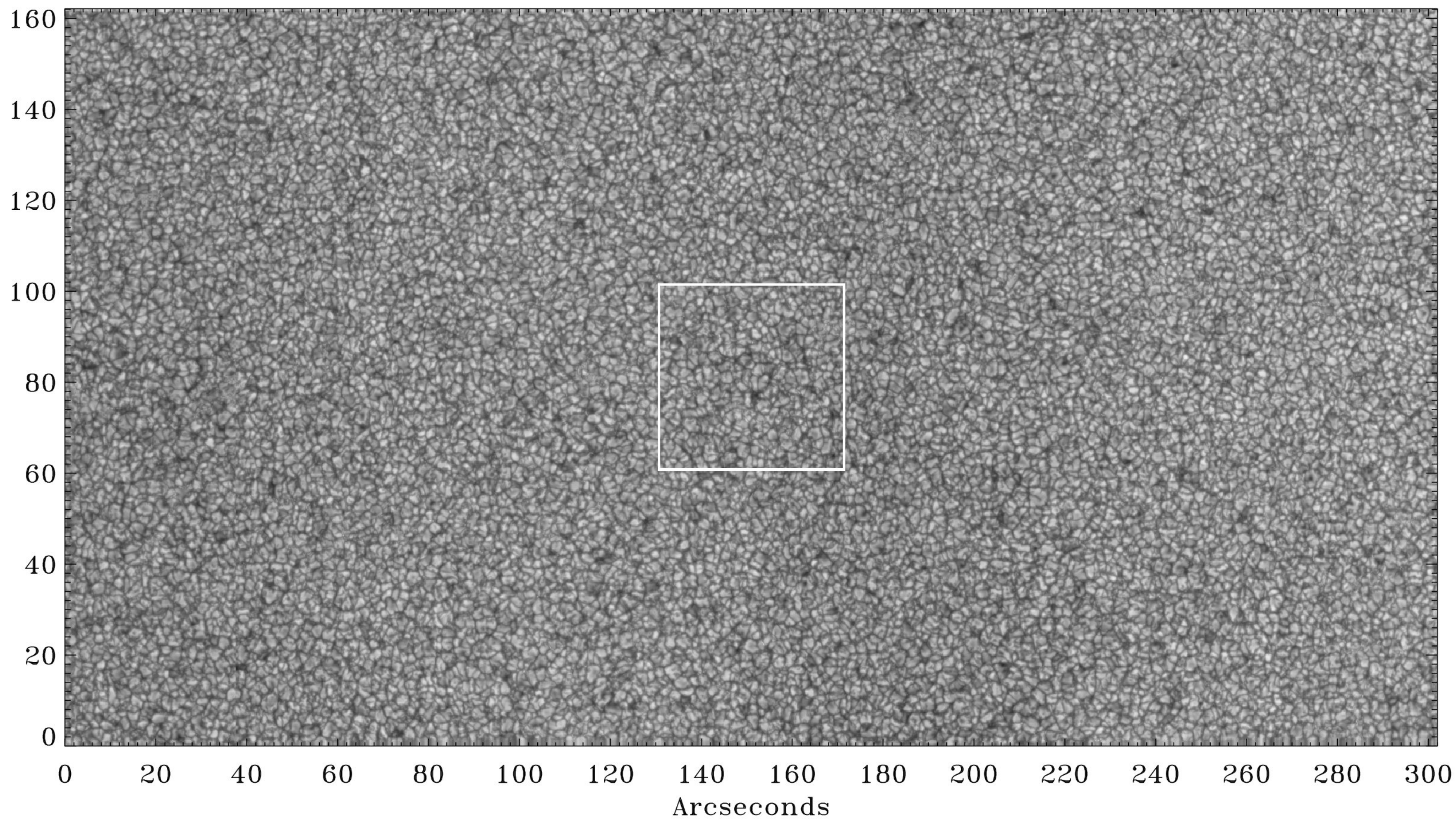
FIG. 2.—Fractional polarization Q/I in the 13 spectral lines allowed between the $a\,^5F$ and $y\,^5F^o$ terms of Ti I. (*a*) Observations near the solar limb as reported in Gandorfer (2002). (*b*) Theoretical Q/I calculated as explained in the text. (*c*, *d*) Same as (*b*), but assuming depolarizing rates 10^8 and 5×10^8 s^{-1}, respectively, for all Ti I levels except the $a\,^5F_1$ and $y\,^5F_1^o$ ones. Note the change of the Q/I scale between panels. The meaning of the dotted lines is explained in the text, while the asterisk indicates a Ti I line that we do not consider in our analysis because it is heavily blended.

It is of interest to note that this $D = 5 \times 10^8$ s^{-1} case produces a relatively good agreement with the Q/I observations of Gandorfer (2002) and that Trujillo Bueno et al. (2004) concluded that when one assumes a volume-filling and single-valued microturbulent field. then the best theoretical fit to the observed scattering polarization in the Sr I λ4607 line is obtained for $B_{\rm microturbulent} \approx 60$ G.

Since we are considering transitions belonging to the same multiplet, we can assume that they "form" in the same atmospheric region and, hence, under similar environmental con-

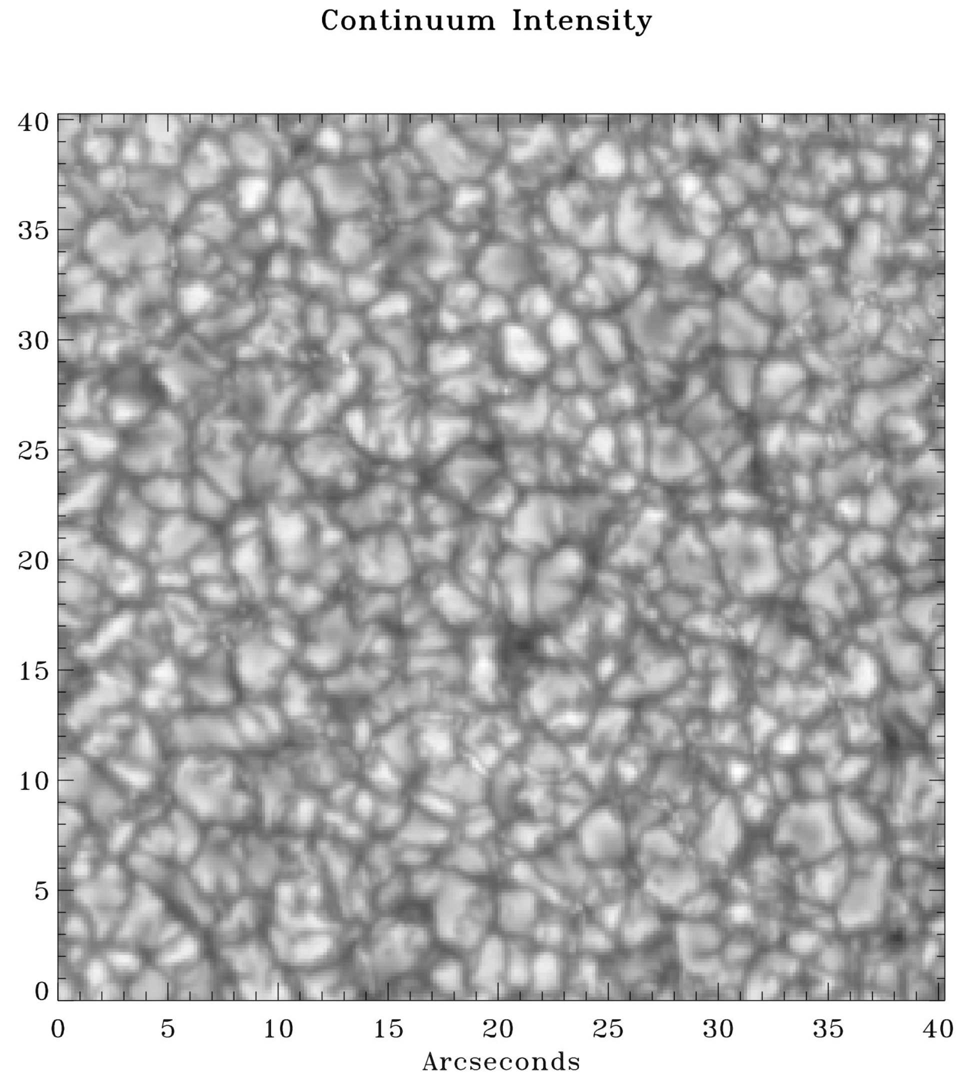
---

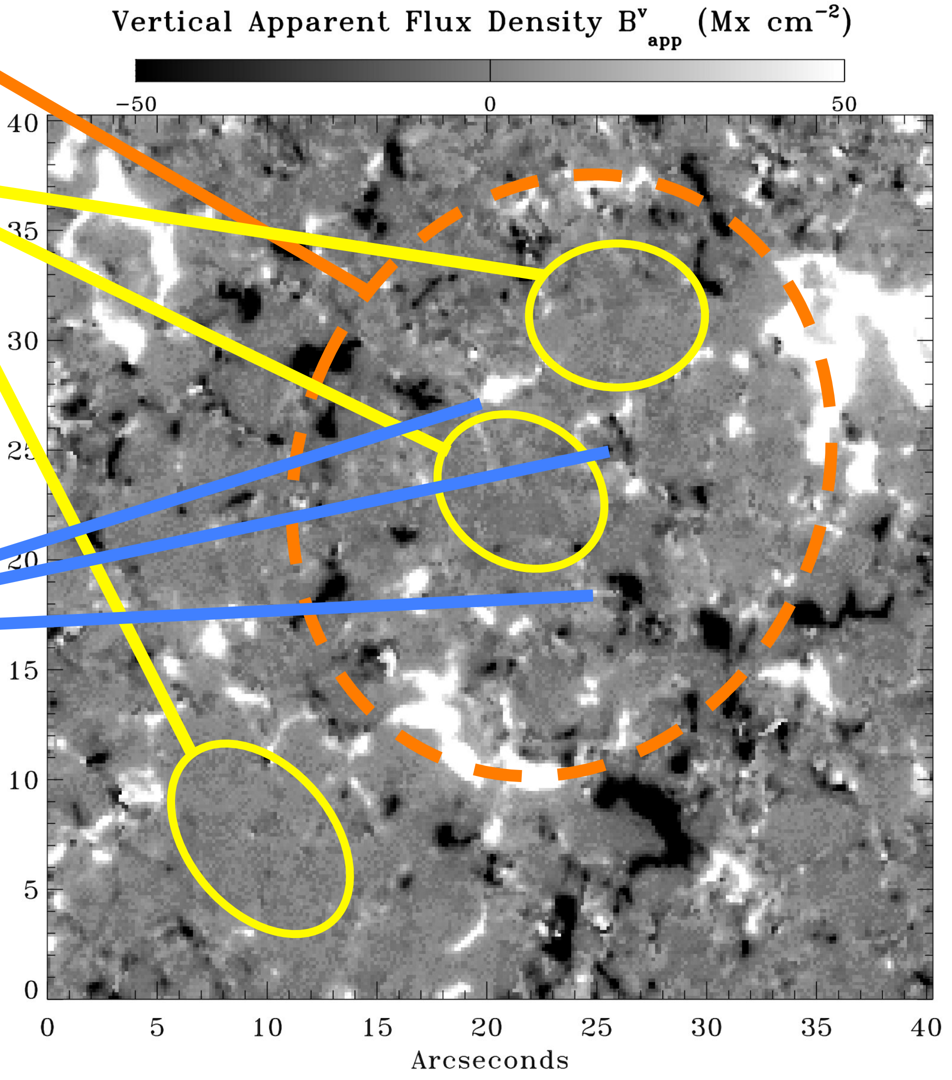
[5] See http://physics.nist.gov.



Hinode **Spectro-Polarimeter map of the quiet Sun**

RMS **Granular Contrast = 7.5%**


Continuum Intensity
40
35
30
25
20
15
10
5
0
0
5
10
15
20
25
30
35
40
Arcseconds



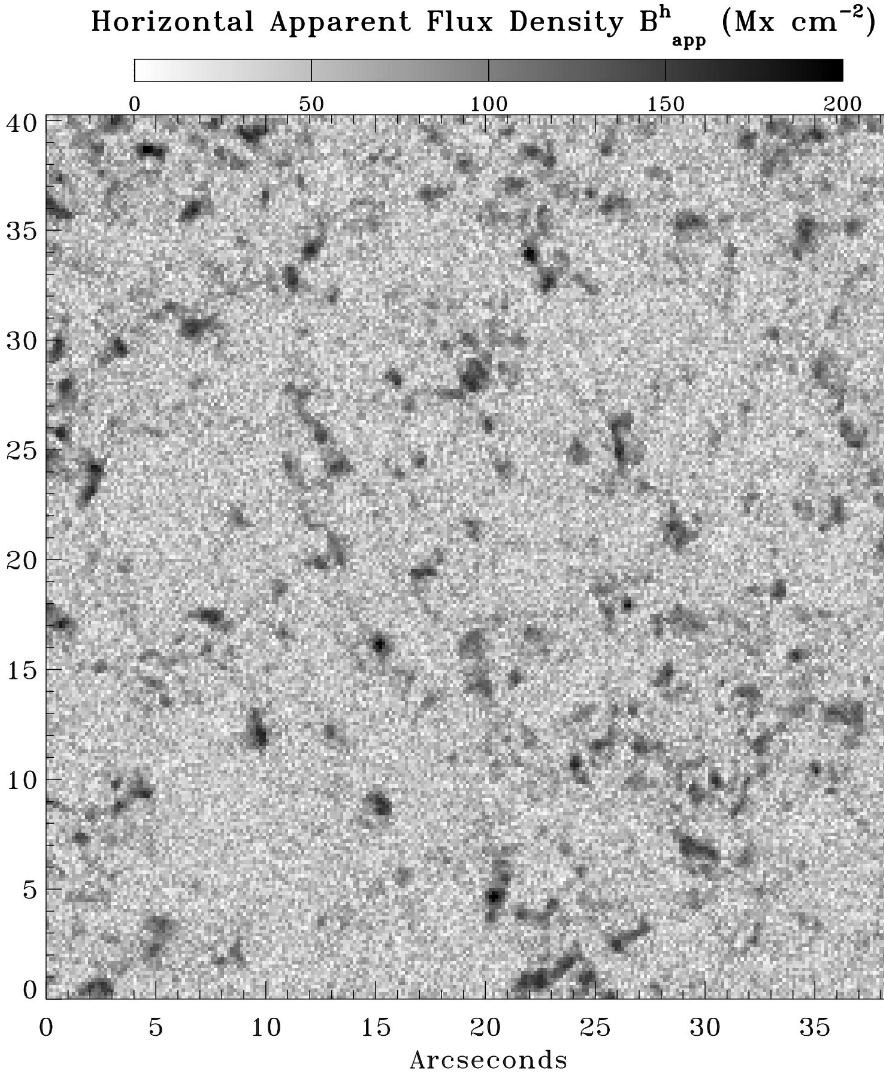
Network Boundary

Mesogranular scale “voids” or “dead calm” regions

Internetwork kilo-Gauss flux elements

Transient, strong (100's of Gauss) horizontal flux

- Vertical flux concentrated in intergranular lanes
- Horizontal flux is over granules themselves

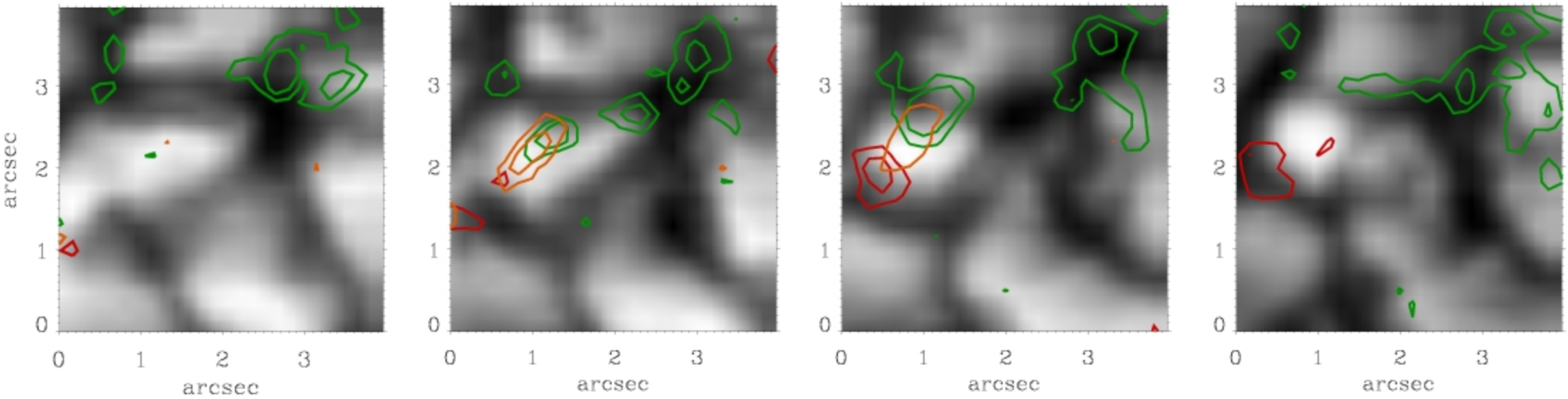


What are the Horizontal Internetwork Flux Elements?

Most Likely, Emerging Flux in Granules

Time Sequence of Internetwork Flux Emergence

R. Centeno et al. 2007



- Emergence begins as horizontal field in middle of granule (amber contour)

- As emergence proceeds, vertical components strengthen at both ends of the horizontal field structure (red and green contours)

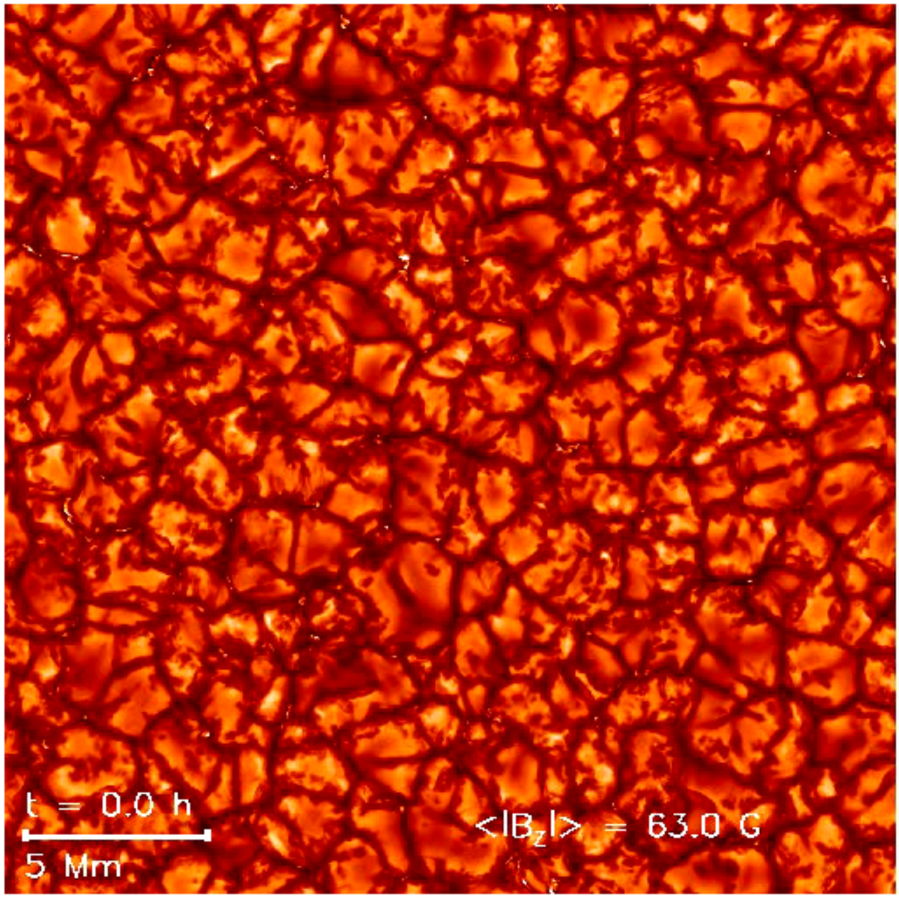
- Horizontal component disappears, vertical components rapidly migrate to surrounding dark lanes

- Sequence very similar to small-scale emergence events in active regions described by (Ishikawa et al. 2007)

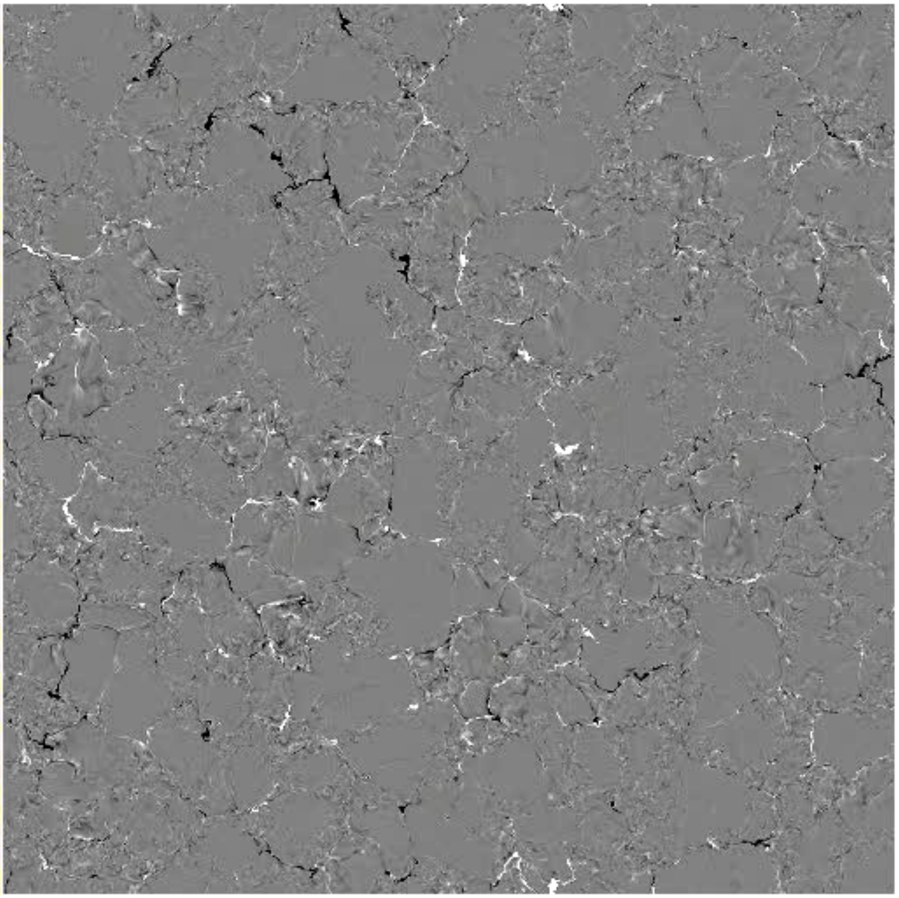
Numerical MHD Simulations Help Us to Understand the Internetwork Photospheric Magnetic Field

- **Simulations by Rempel (2014) attain a self-sustaining small-scale dynamo**
- **Higher resolution, larger computational box lead to good quantitative agreement with many aspects of observations**
- **Allow investigation of role played by very small scale flux elements**

Continuum Intensity



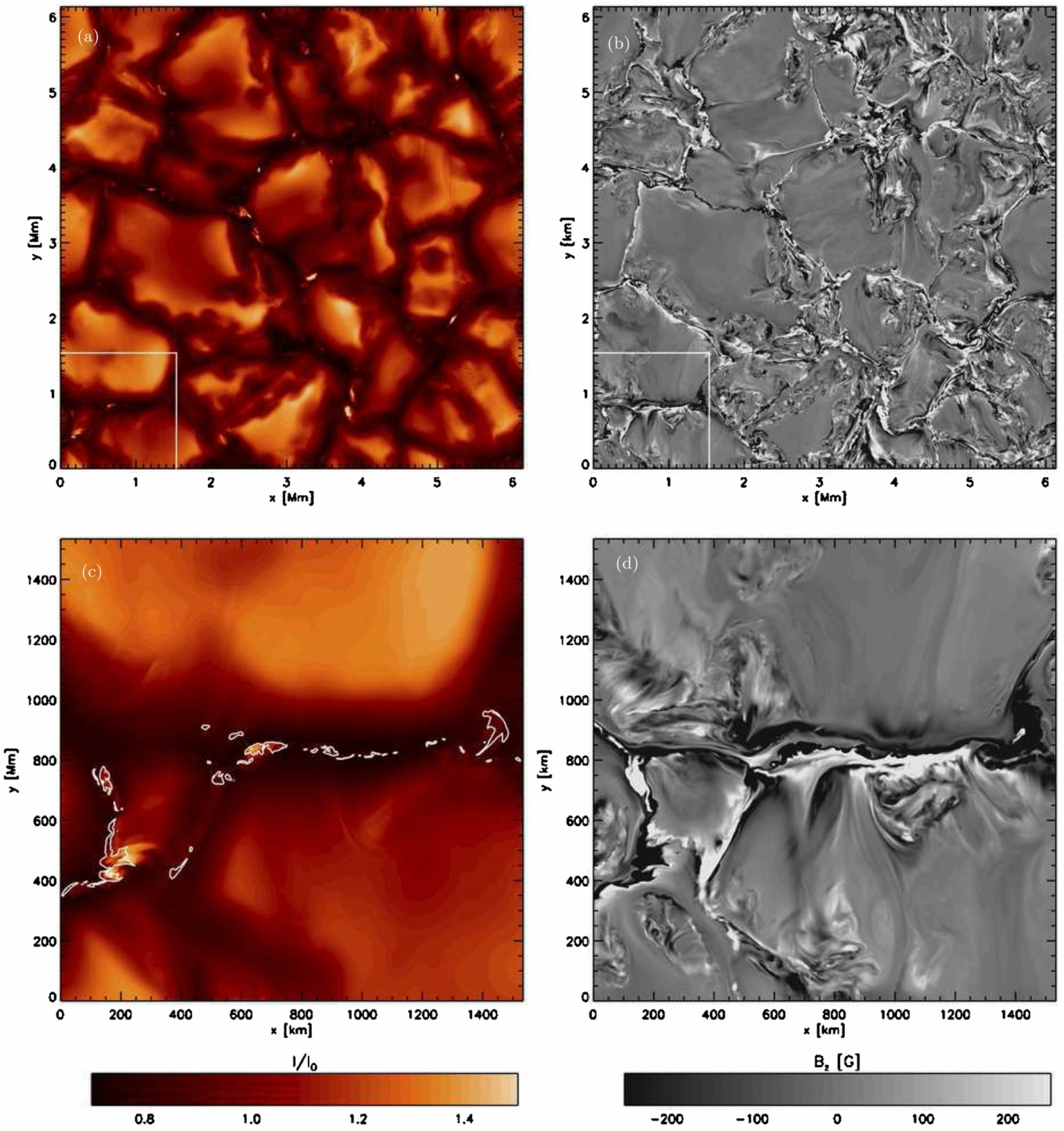
B_Z at τ=1



<|B_Z|> ~ 60 Gauss

Simulation by Rempel 2014 (*ApJ* **789**, p 132)

Expanded view of simulation:



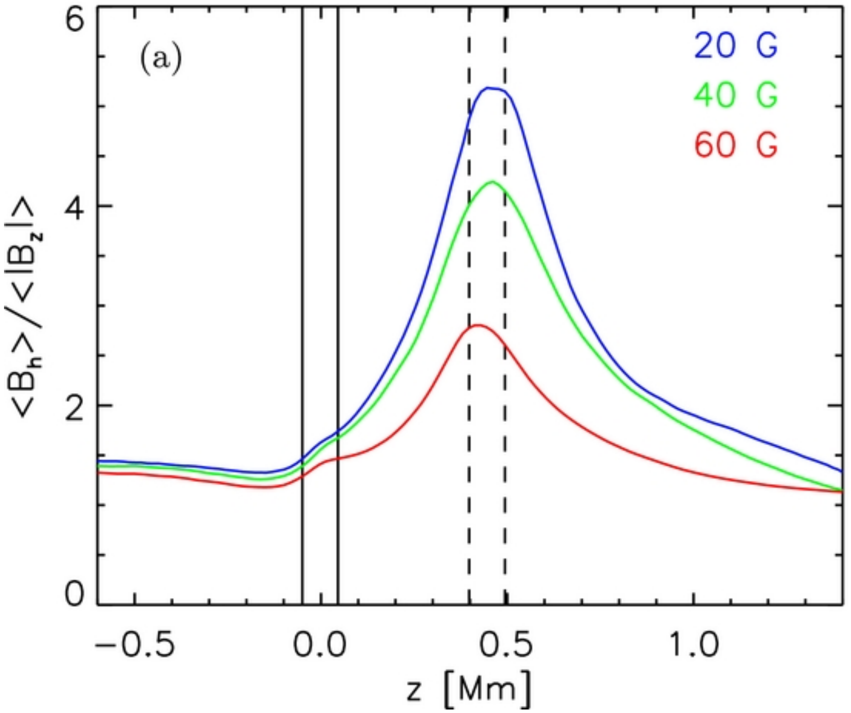
Continuum Intensity

B_Z at τ=1

(Contours outline 1 kG regions)

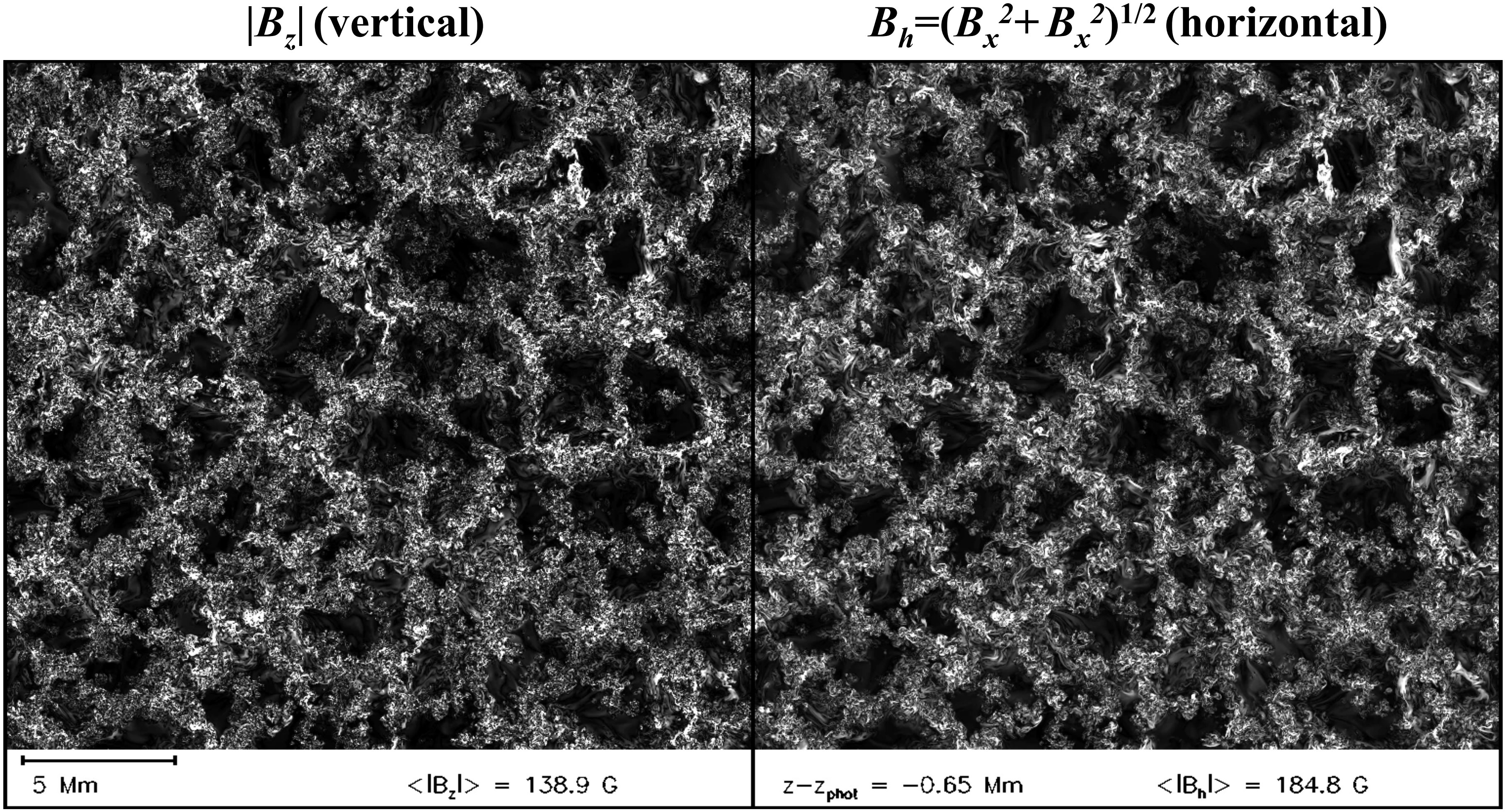
Simulation by Rempel 2014
(*ApJ* **789**, p 132)

Ratio of horizontal to vertical field strength in small-scale dynamo simulation



(Figure from Rempel 2014, *ApJ,* **789**, 132)

Scan upward into atmosphere

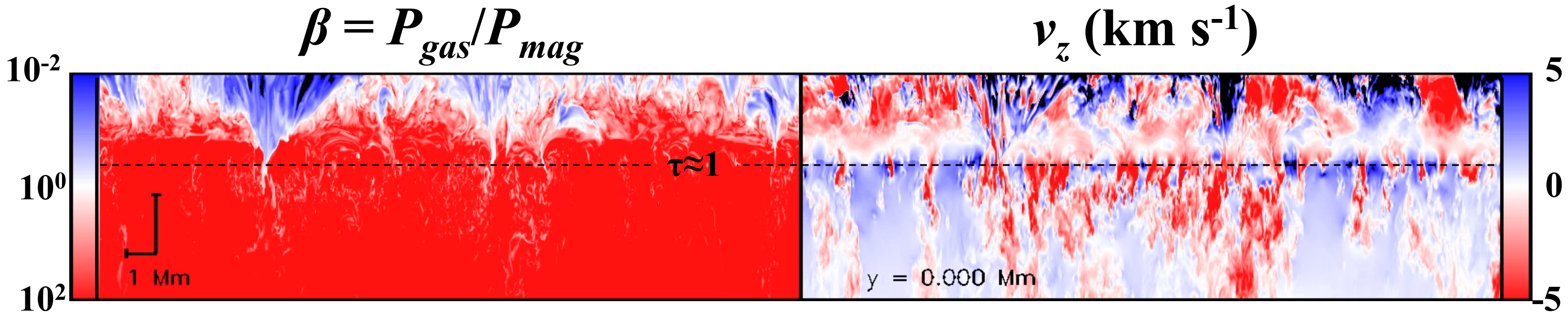


$|B_z|$ (vertical)

$B_h=(B_x^2+B_x^2)^{1/2}$ (horizontal)

Small-scale dynamo simulations, M. Rempel

Vertical slice showing plasma β, vertical velocity v_z
Scan horizontally through atmosphere



(white ➔ $\beta = 1$)

- **Internetwork is high beta plasma through photosphere into chromosphere**
- **Punctuated by occasional intense flux tubes**

Small-scale dynamo simulations, M. Rempel

SST/CRISP Movies of Quiet Sun (Coronal Hole)

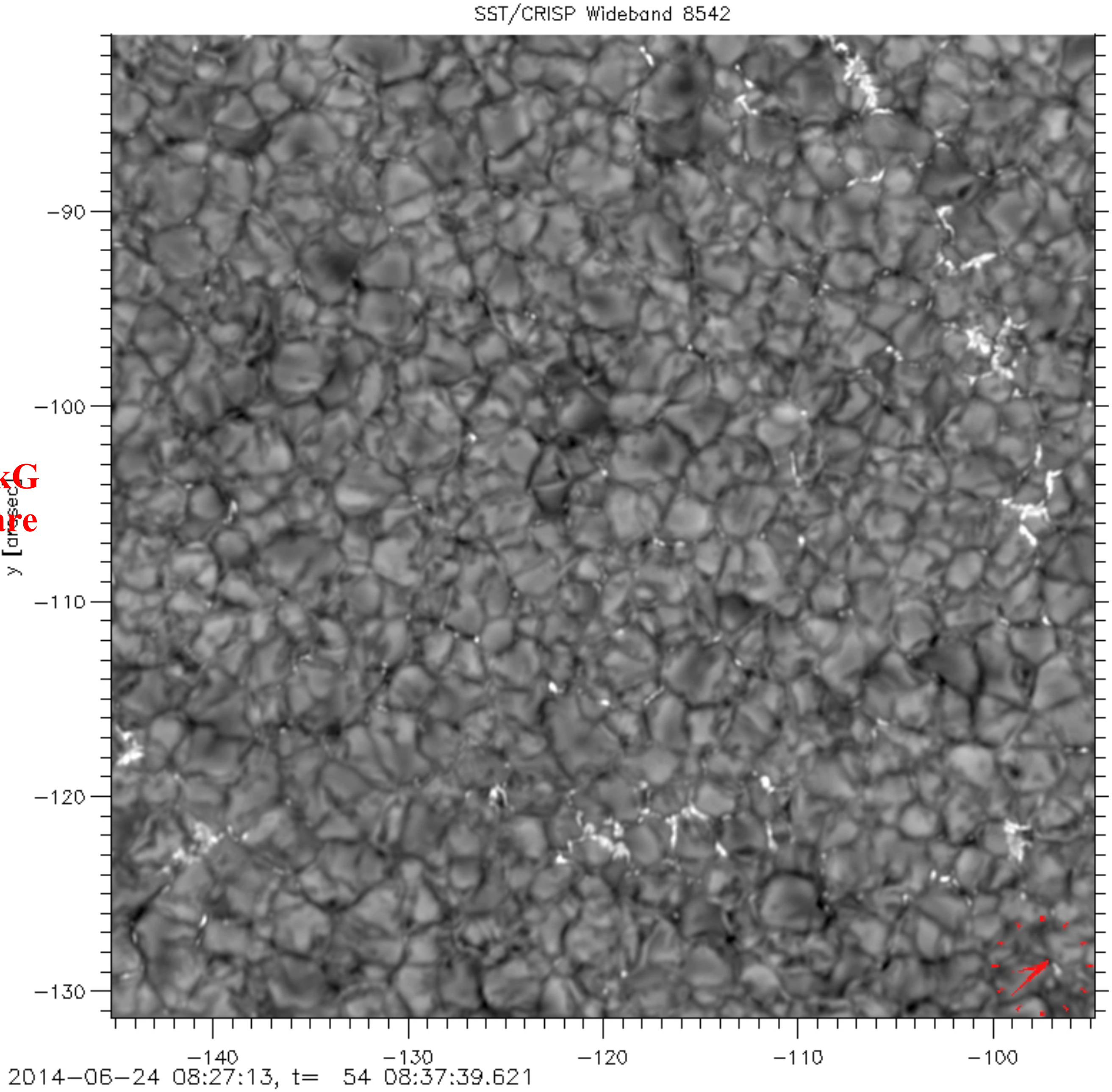
CRISP, Swedish Solar Telescope, One Supergranule

L. Rouppe Van Der Voort

Coronal Hole

Broadband
8542 Å

- **Photospheric Evolution**
- **Internetwork kG flux elements are bright**



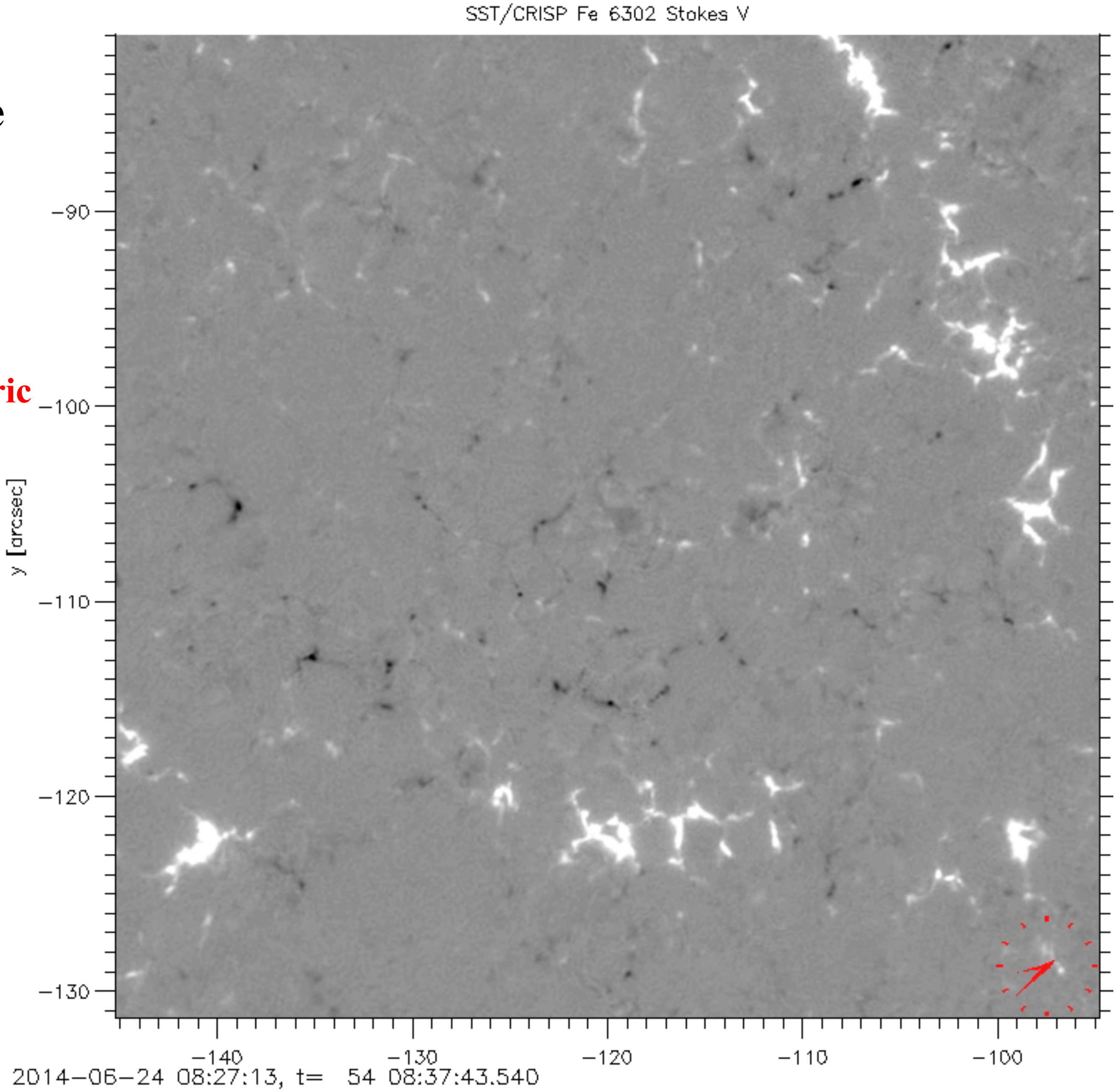
CRISP, Swedish Solar Telescope, One Supergranule

L. Rouppe Van Der Voort

Coronal Hole

Photospheric Stokes V

- **IN Photospheric Field evolves slowly with granulation**



CRISP, Swedish Solar Telescope, One Supergranule

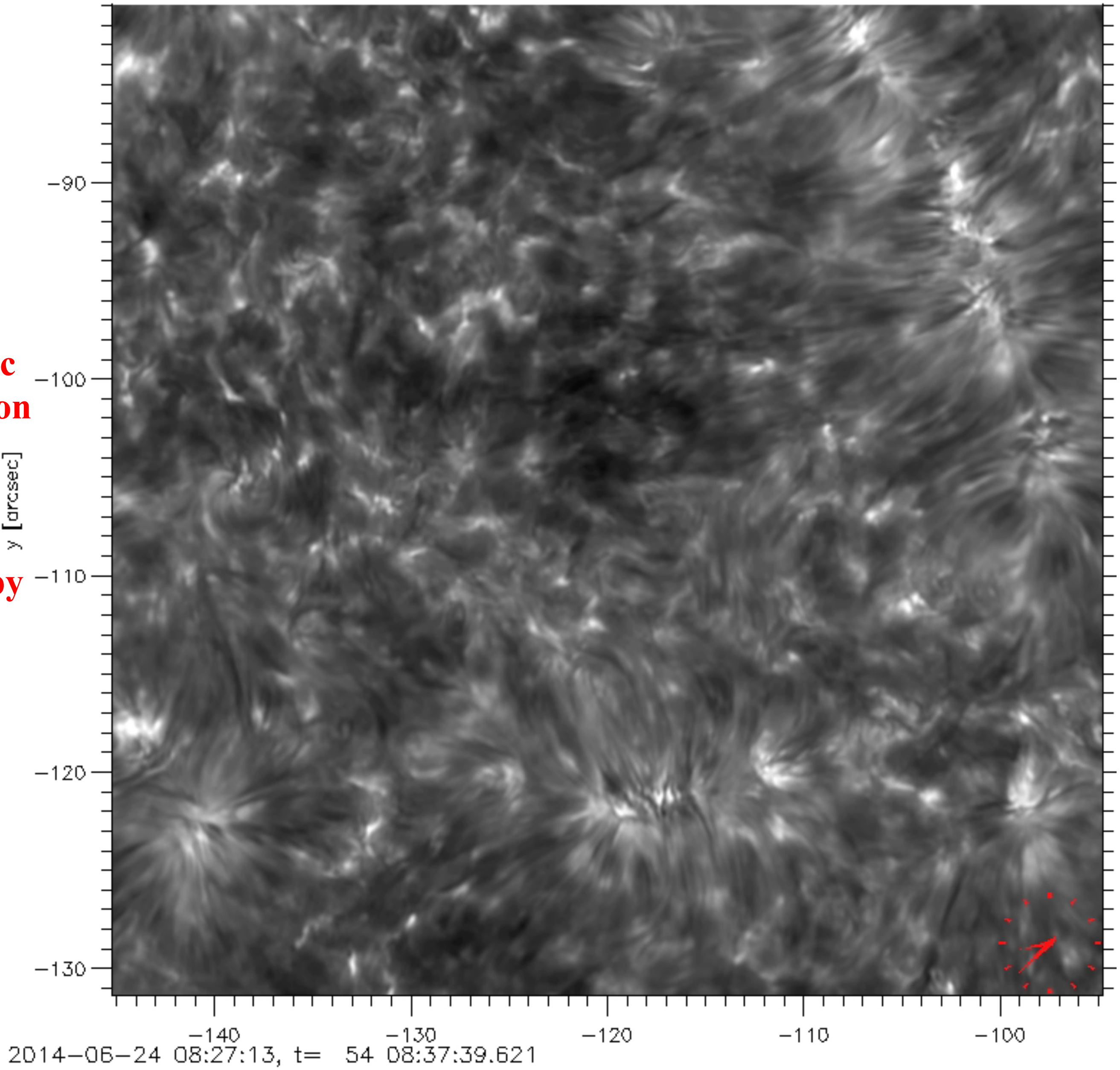
L. Rouppe Van Der Voort

Coronal Hole

Ca II 8542 Å Line Center

- Chromospheric 3-min oscillation is apparent in internetwork
- Dynamic network canopy is visible

SST/CRISP Ca II 8542 line center



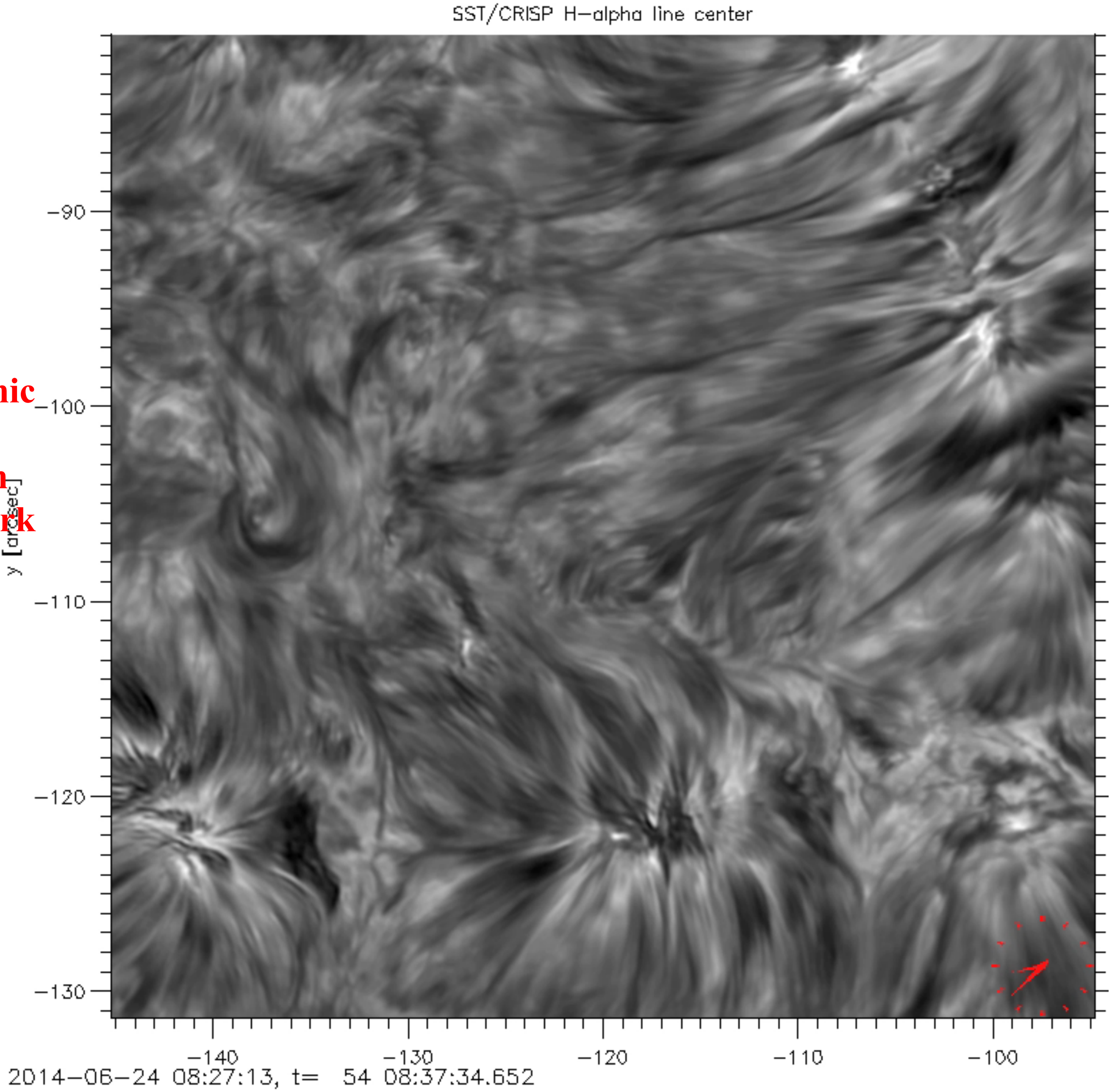
CRISP, Swedish Solar Telescope, One Supergranule

L. Rouppe Van Der Voort

Coronal Hole

Hα
Line Center

- **Reveals dynamic mesogranular scale canopy in the internetwork**



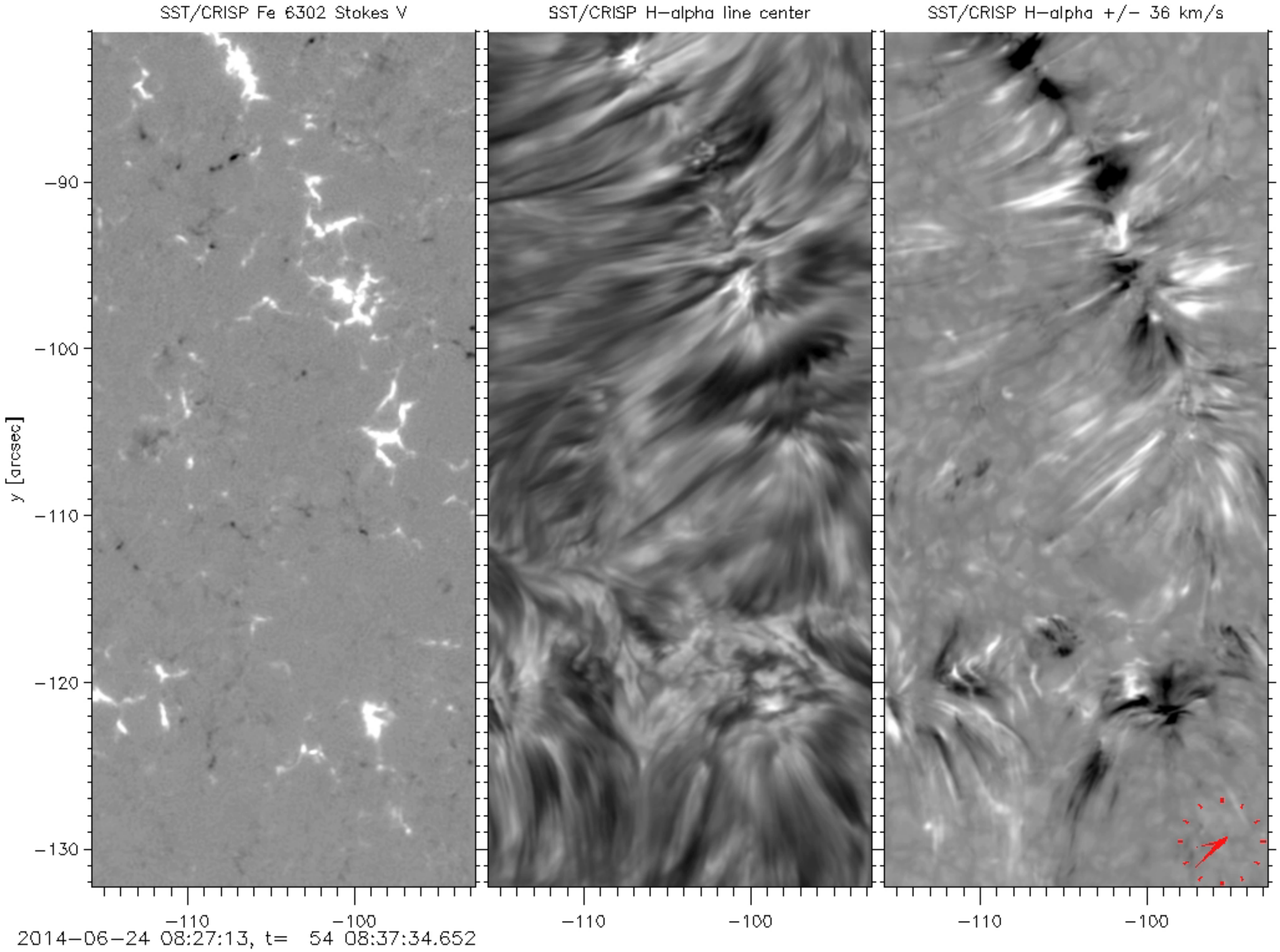
What Might Be the Chromospheric Field Structure Over the Quiet Sun?

1. The observed structure of photospheric *internetwork* magnetic fields
2. The observed structure of photospheric *network* magnetic field

CRISP, Swedish Solar Telescope, Network Elements

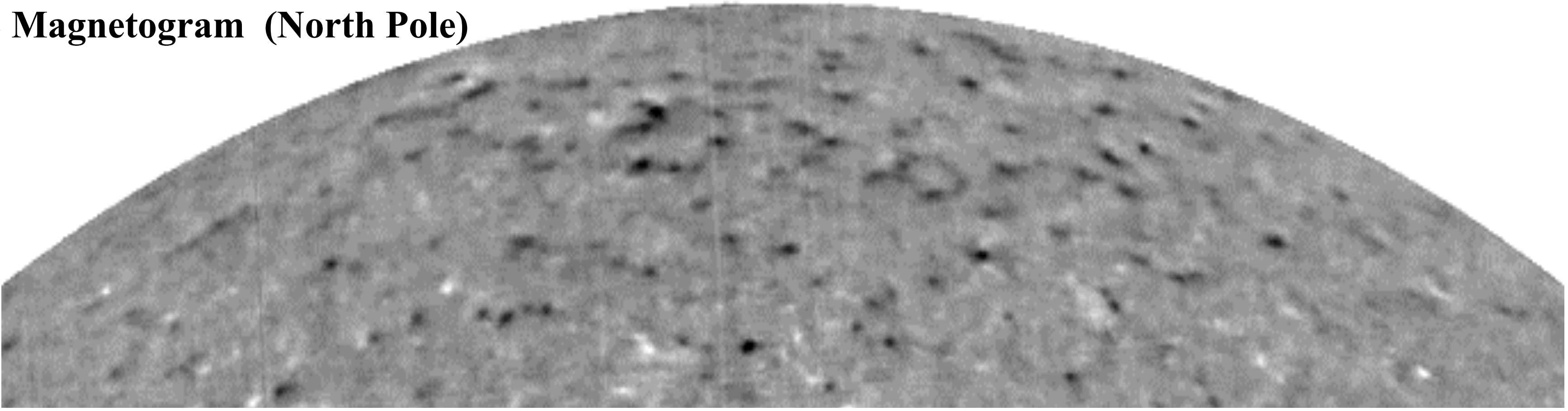
L. Rouppe Van Der Voort

Photospheric Stokes V **Hα Line Center** **Hα Doppler**

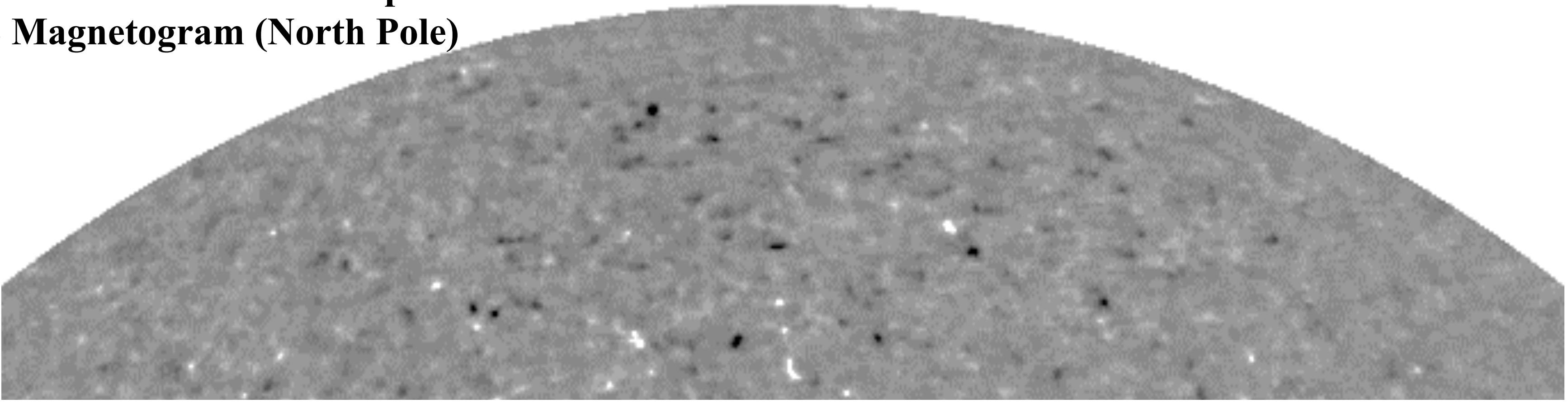


Chromospheric Canopy From Polar Magnetic Network

SOLIS Ca II 854.2nm Chromospheric
LOS Magnetogram (North Pole)



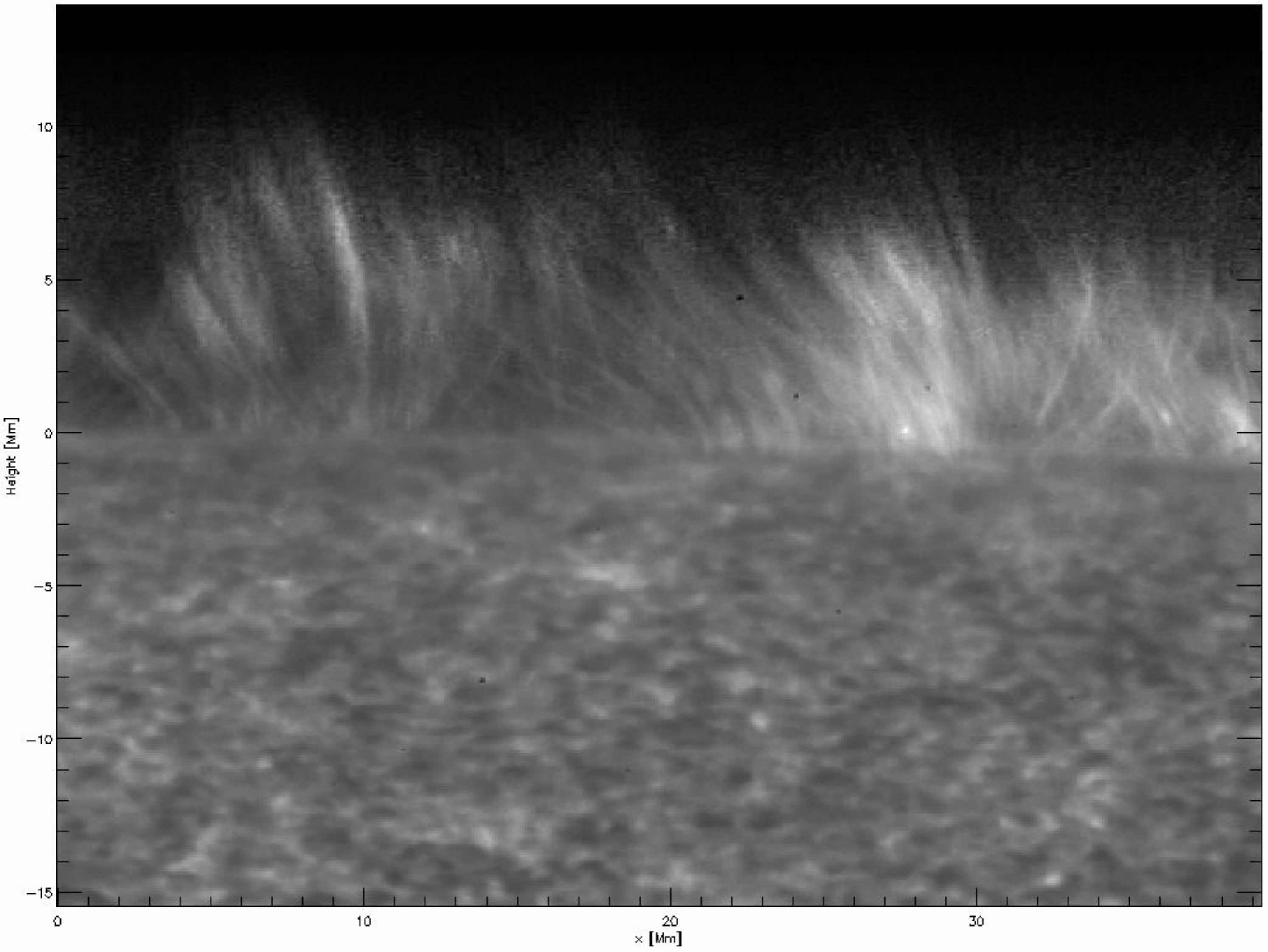
SOLIS Fe I 630.1nm Photospheric
LOS Magnetogram (North Pole)



29-June-2009 SOLIS/VSM

(See Jin, C. L. et al. 2013, *ApJ*, 765, 79**)**

Spicule dynamics observed in Ca II H with *Hinode*/SOT

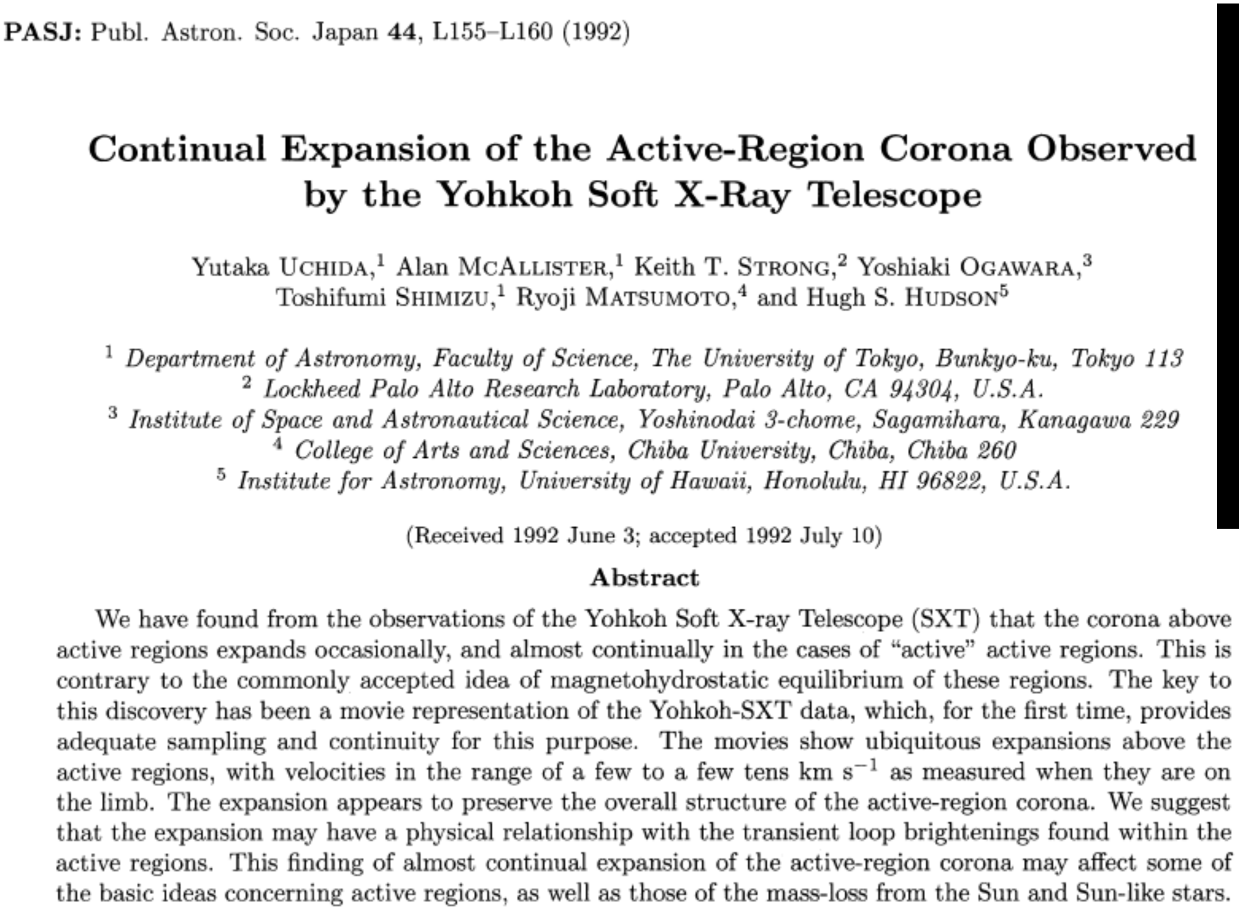


Implications of Network Fields for Chromospheric Field Structure

- Network fields are kiloGauss, and unipolar on mesogranular scales
- Network fields extend outward over internetwork forming a canopy in the chromosphere
- Internetwork flux of opposite polarity is swept to network by supergranular flows ➔ reconnection and chromospheric activity
- Small-scale dynamics at the photosphere ➔ reconnection ➔ large-scale rearrangement of network field connectivity ("Magnetic Carpet": Title & Schrijver 1998)
- Spicules are likely a chromospheric manifestation of network fields and stronger internetwork flux elements

What Might Be the Chromospheric Field Structure Over Active Regions?

1. **The ever-expanding corona over active regions**
2. **Plage: the source of most active region chromospheric emission**
3. **Sunspots: strong, ordered fields in the chromosphere**
4. **Filaments/Prominences: flux rope structure in the photosphere/chromosphere**



PASJ: Publ. Astron. Soc. Japan **44**, L155–L160 (1992)

Continual Expansion of the Active-Region Corona Observed by the Yohkoh Soft X-Ray Telescope

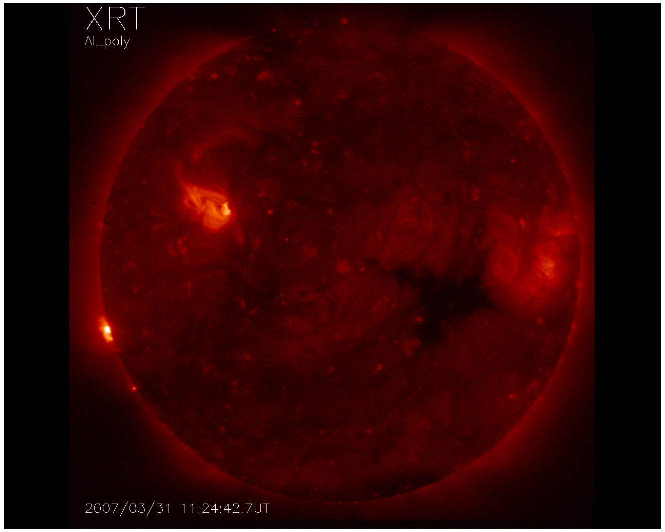
Yutaka Uchida,[1] Alan McAllister,[1] Keith T. Strong,[2] Yoshiaki Ogawara,[3]
Toshifumi Shimizu,[1] Ryoji Matsumoto,[4] and Hugh S. Hudson[5]

[1] *Department of Astronomy, Faculty of Science, The University of Tokyo, Bunkyo-ku, Tokyo 113*
[2] *Lockheed Palo Alto Research Laboratory, Palo Alto, CA 94304, U.S.A.*
[3] *Institute of Space and Astronautical Science, Yoshinodai 3-chome, Sagamihara, Kanagawa 229*
[4] *College of Arts and Sciences, Chiba University, Chiba, Chiba 260*
[5] *Institute for Astronomy, University of Hawaii, Honolulu, HI 96822, U.S.A.*

(Received 1992 June 3; accepted 1992 July 10)

Abstract

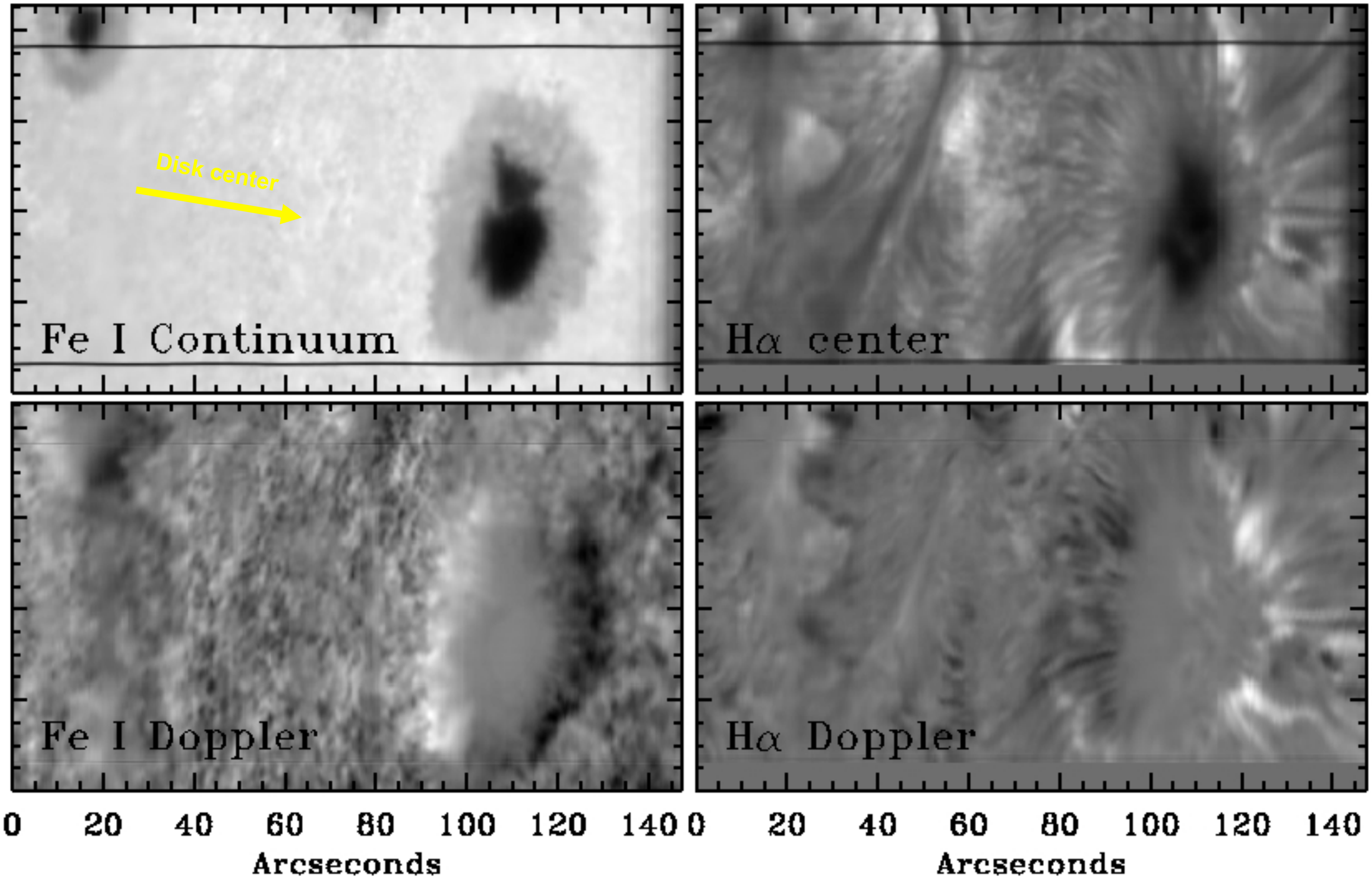
We have found from the observations of the Yohkoh Soft X-ray Telescope (SXT) that the corona above active regions expands occasionally, and almost continually in the cases of “active” active regions. This is contrary to the commonly accepted idea of magnetohydrostatic equilibrium of these regions. The key to this discovery has been a movie representation of the Yohkoh-SXT data, which, for the first time, provides adequate sampling and continuity for this purpose. The movies show ubiquitous expansions above the active regions, with velocities in the range of a few to a few tens km s^{-1} as measured when they are on the limb. The expansion appears to preserve the overall structure of the active-region corona. We suggest that the expansion may have a physical relationship with the transient loop brightenings found within the active regions. This finding of almost continual expansion of the active-region corona may affect some of the basic ideas concerning active regions, as well as those of the mass-loss from the Sun and Sun-like stars.



Hinode XRT movie, CR2055 April 2007

- **Flux submergence is difficult via magnetic tension: field curvature must be comparable to a scale height**
- **Consequence: active region field evolution dominated by flux emergence and expansion into the chromosphere/corona**

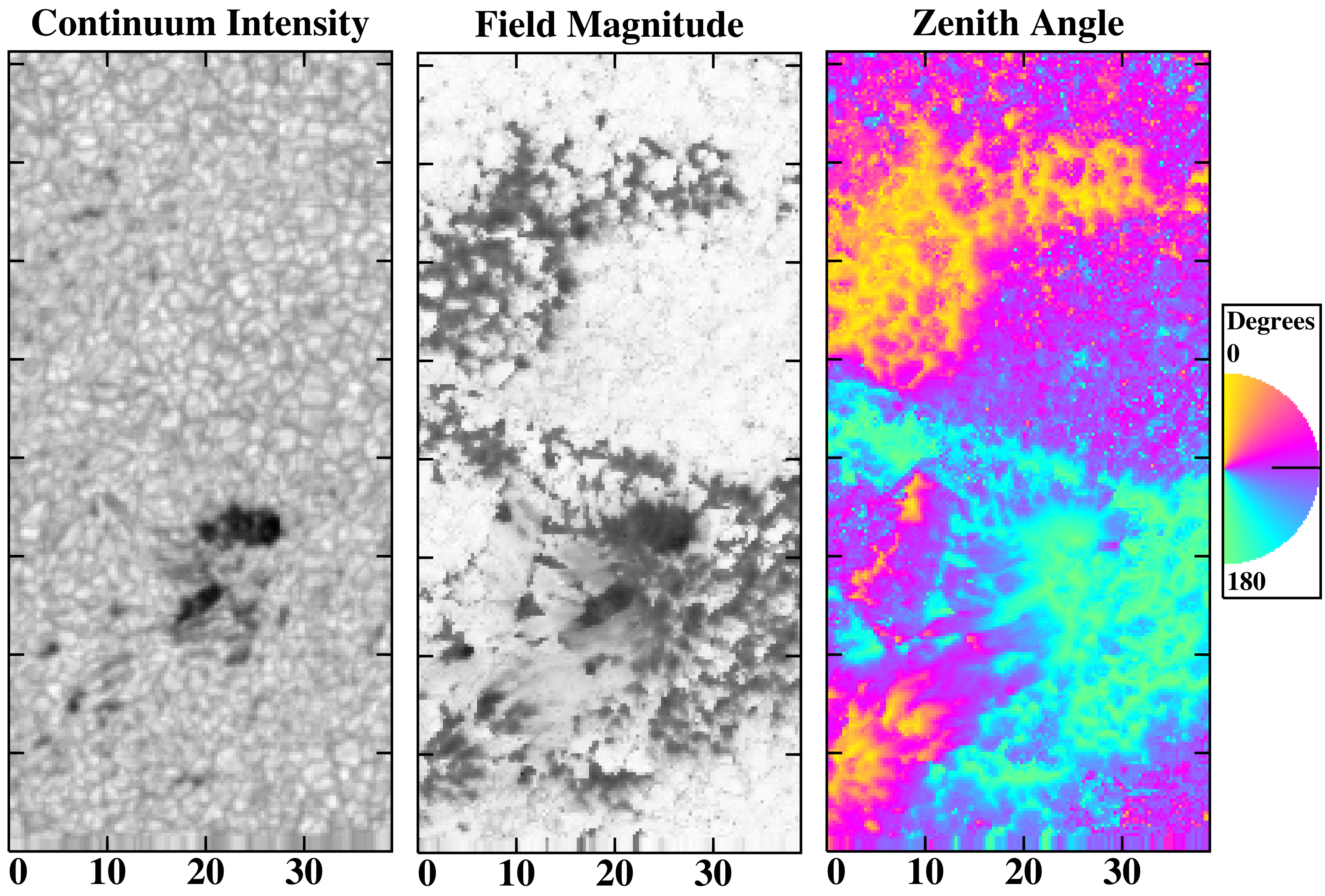
Continual emergence/expansion might explain the chromospheric inverse Evershed effect



What Might Be the Chromospheric Field Structure Over Active Regions?

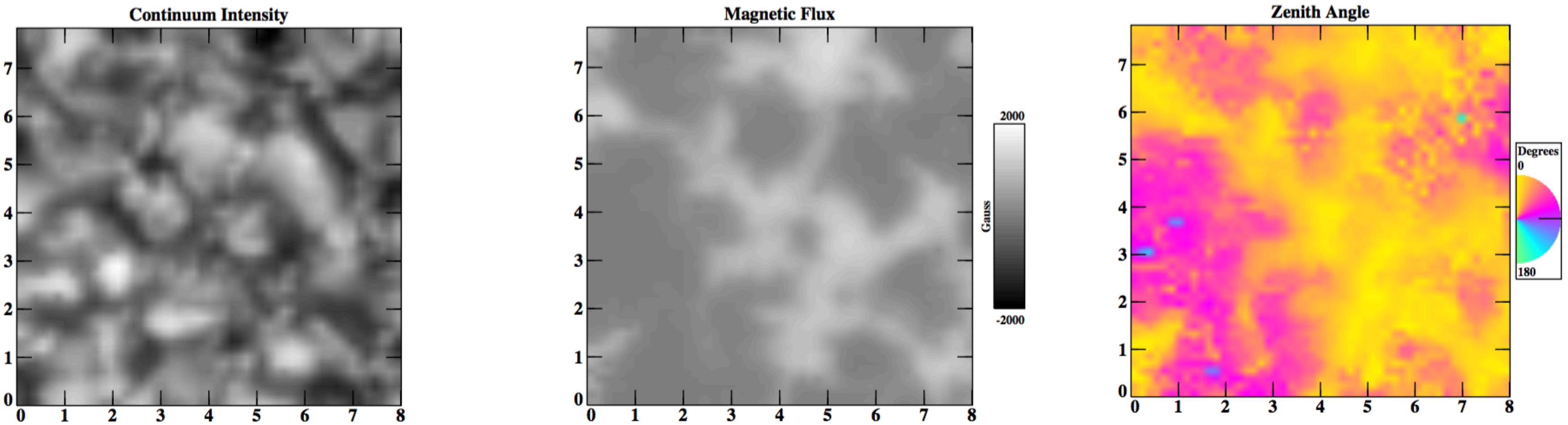
1. The ever-expanding corona over active regions
2. **Plage: the source of most active region chromospheric emission**
3. Sunspots: strong, ordered fields in the chromosphere
4. Filaments/Prominences: flux rope structure in the photosphere/chromosphere

Strong plage has significant fine structure, but appears unipolar with very little or no opposite polarity inclusions:

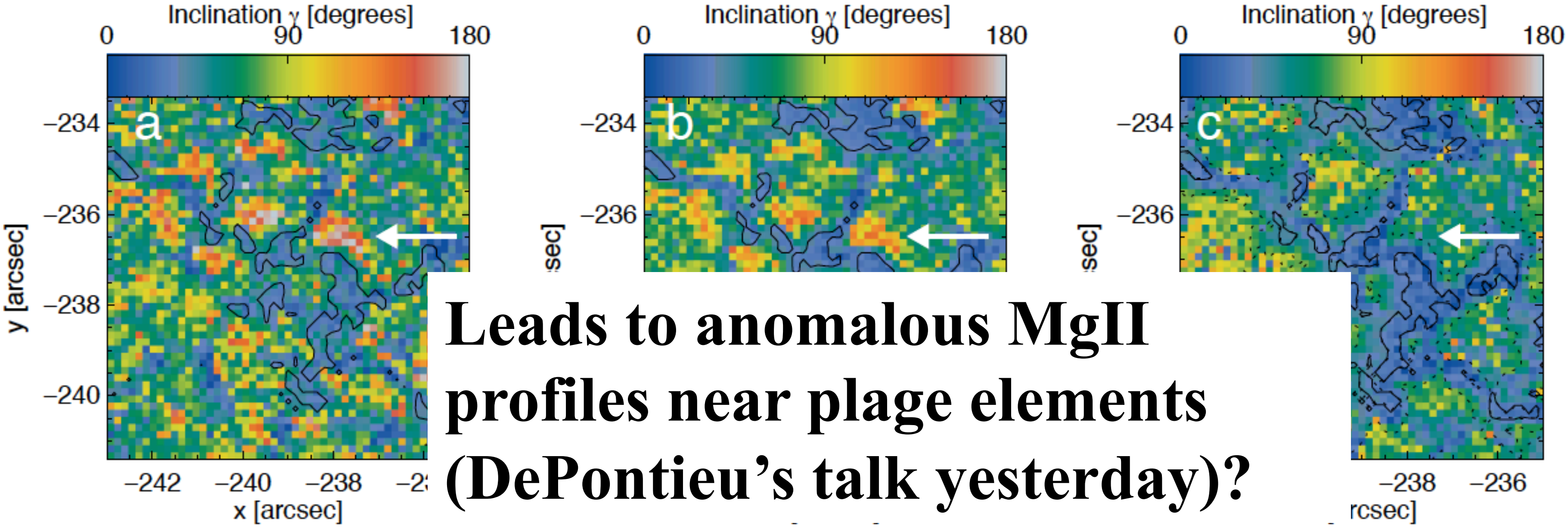


But is plage really unipolar?

Hinode SOT/SP Milne-Eddington Inversion



Spatial Deconvolution Inversion (Buehler et al. 2015)



Leads to anomalous MgII profiles near plage elements (DePontieu's talk yesterday)?

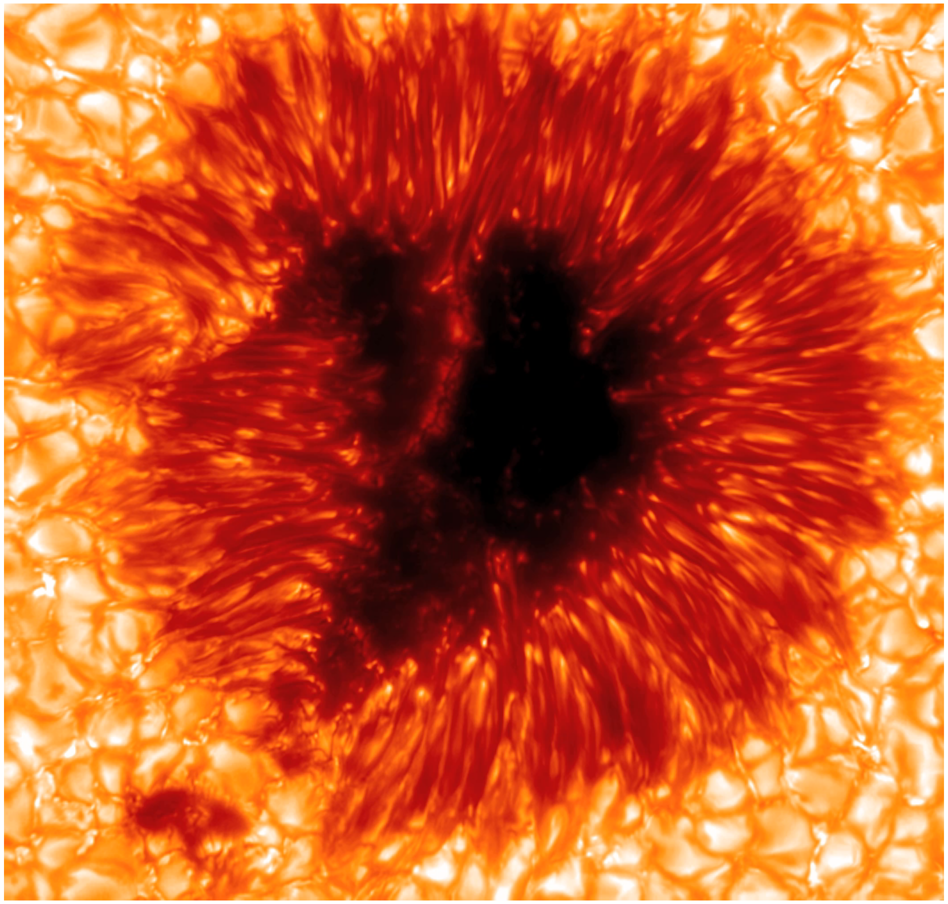
Fig. 20. **a)**–**c)** LOS inclination, γ, at $\log(\tau) = 0, -0.9$ and -2.3, respectively. The black contour lines encompass *core* pixels. The arrows point to the location of the weak opposite polarity at each height.

What Might Be the Chromospheric Field Structure Over Active Regions?

1. The ever-expanding corona over active regions
2. Plage: the source of most active region chromospheric emission
3. **Sunspots: strong, ordered fields in the chromosphere**
4. Filaments/Prominences: flux rope structure in the photosphere/chromosphere

Sunspot magnetic fields:

- Strong, (relatively) stable umbral fields
- Umbra has some fine structure in deep photosphere (umbral dots)
- Stable penumbral fluted structure
- Return flux in small, isolated points in outer penumbra
- Always an extensive magnetic canopy beyond the outer edge of the penumbra



Swedish Solar Telescope, 23 May 2010, de Jorge Henriques

Sunspot chromospheric magnetic fields:

- Simple, low-β plasma (ideal for study of MHD waves)
- Fluted penumbral structure survives to chromosphere, leading to interesting dynamical effects (e.g., penumbral microjets)

Simulations show fluted field, return flux in lowest layers

THE ASTROPHYSICAL JOURNAL, 729:5 (22pp), 2011 March 1 (Rempel) REMPEL

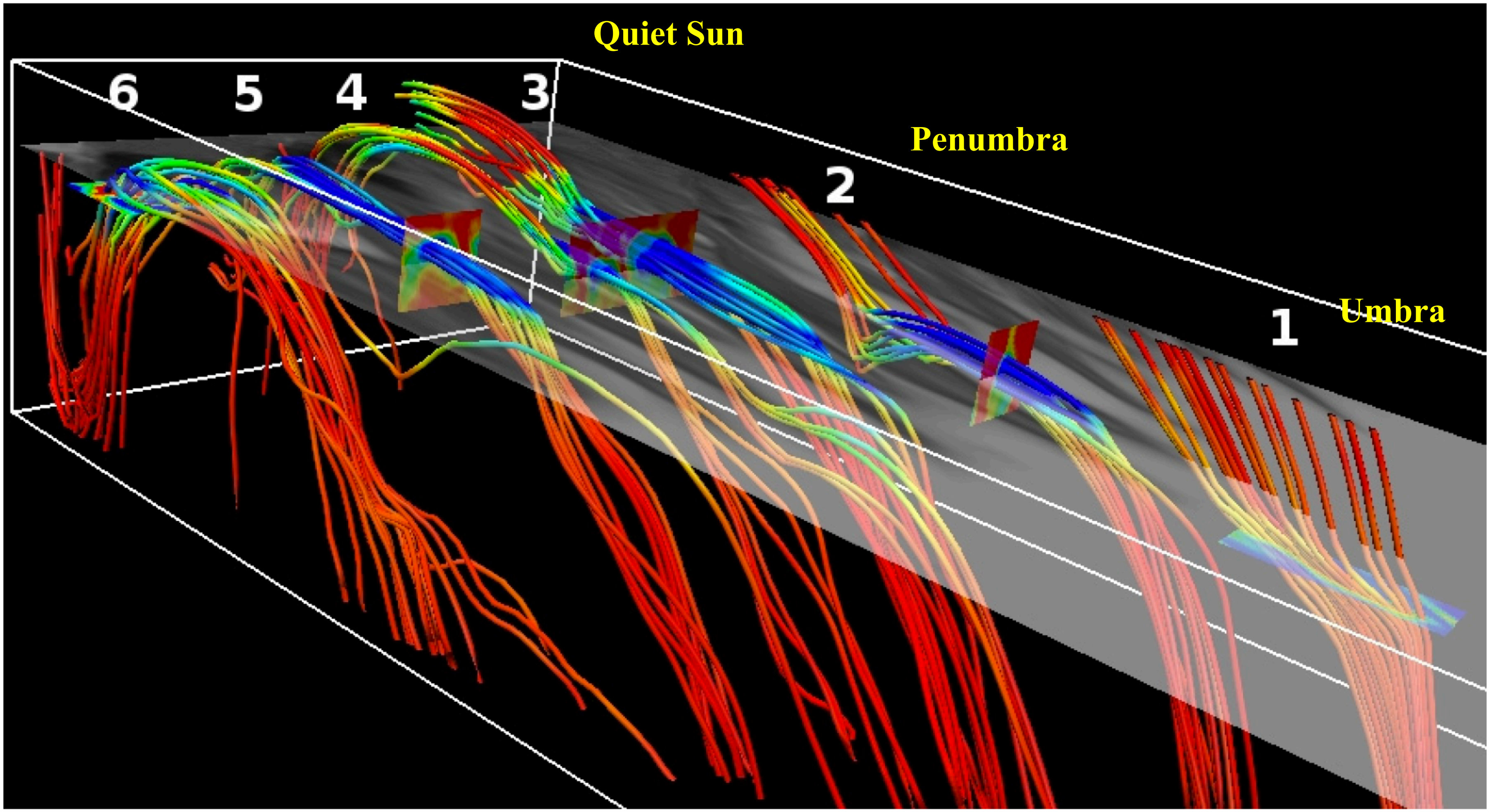
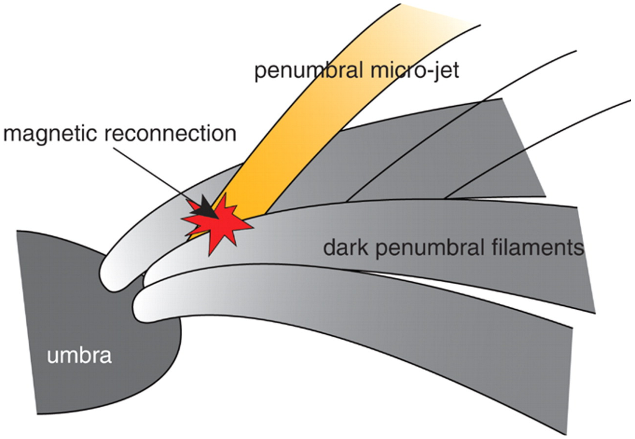


Figure 19. Field-line connectivity and associated horizontal flow speeds in simulated penumbra. The color of the field lines indicates the radial flow velocity (the colors red, yellow, green, and blue correspond to velocities of $<0, 2, 4$, and >8 km s^{-1}, respectively). Filament 1 indicates a peripheral umbral dot almost transitioning to a penumbral filament. Filaments 2–6 sample different radial position in the penumbra. The semi-transparent plane indicates a magnetogram near (average) $\tau = 1$. Smaller horizontal and vertical cross section indicate the regions from which we selected the seed points for the field-line integration.

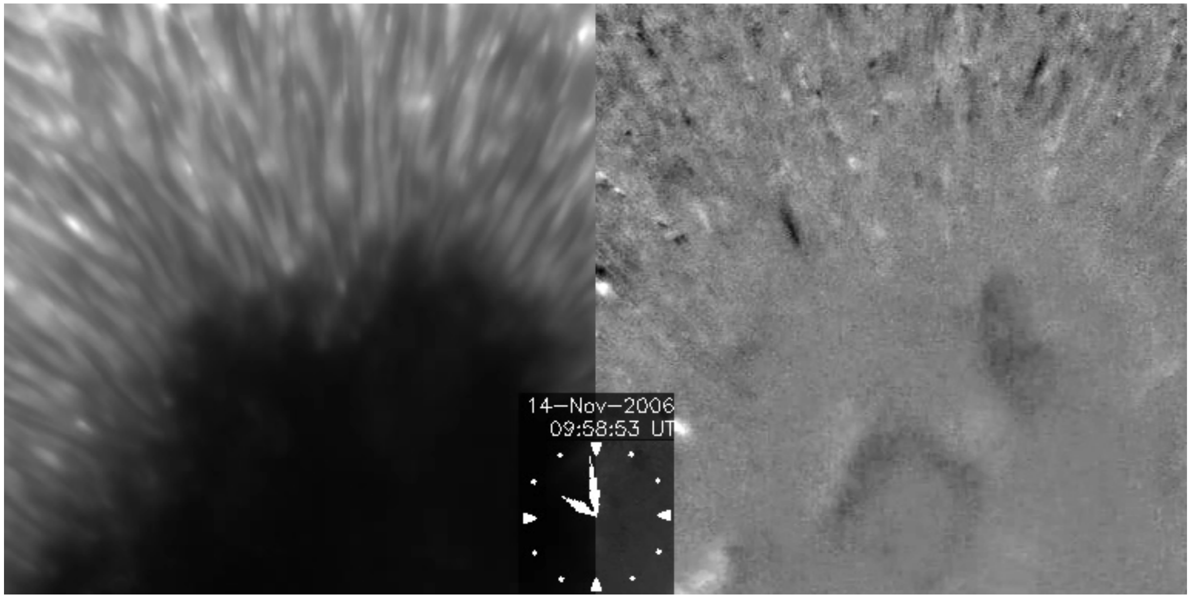
Chromospheric penumbral micro-jets

Likely caused by reconnection in fluted field lines

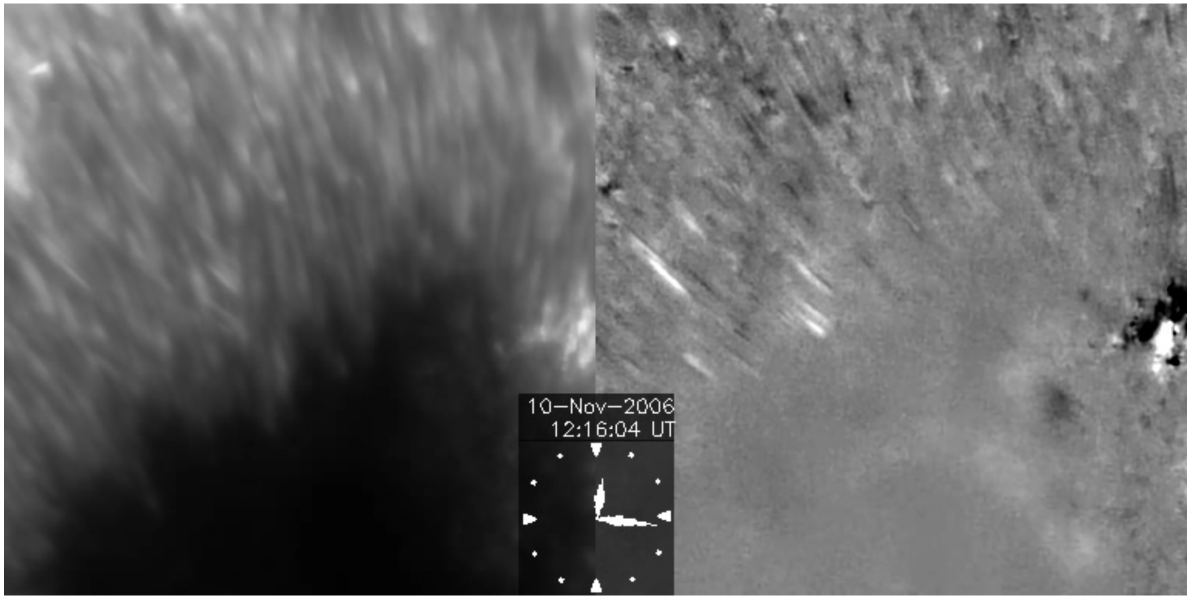


Katsukawa et al., 2007

Disk Center



μ = 0.5



What Might Be the Chromospheric Field Structure Over Active Regions?

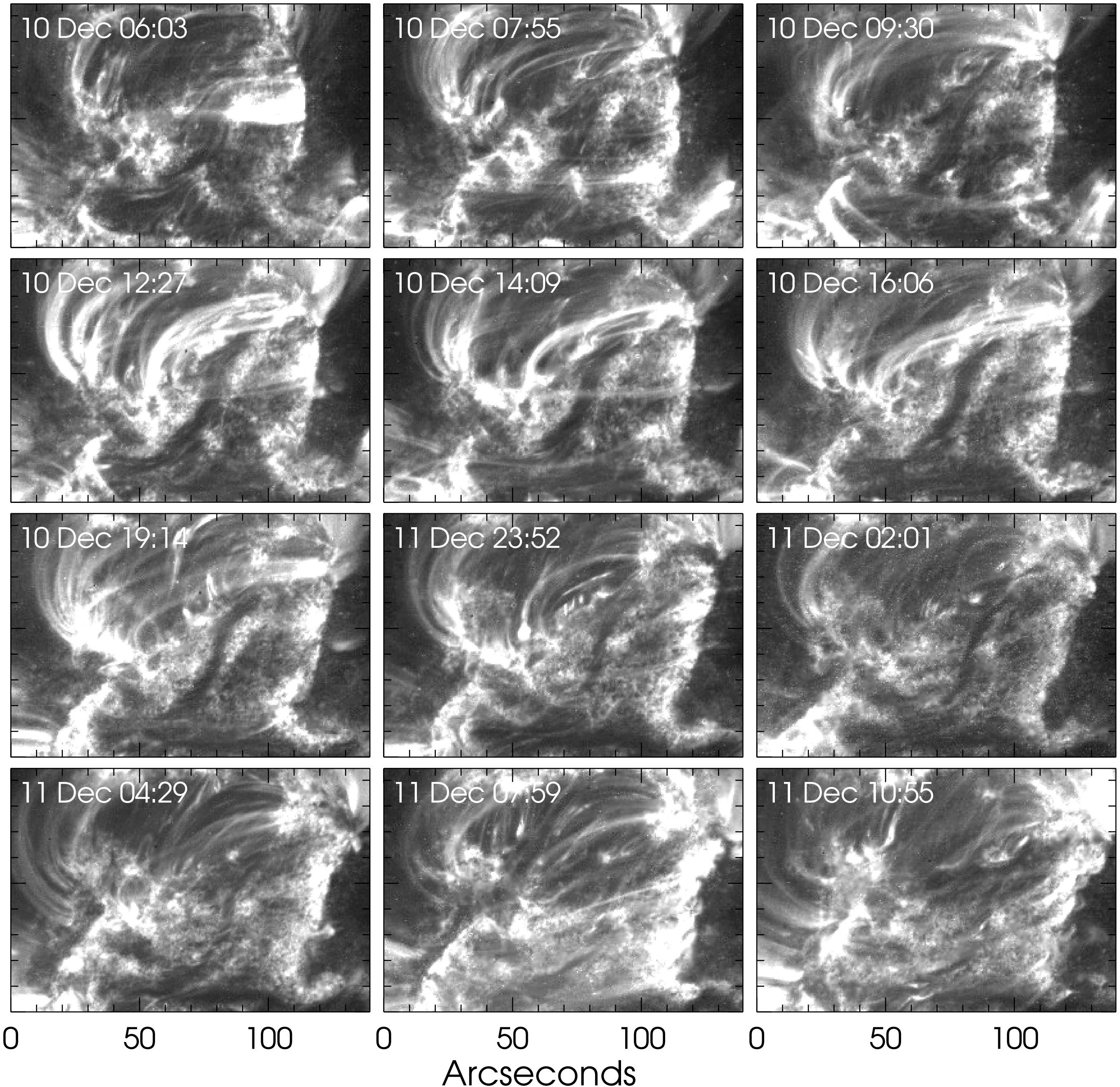
1. **The ever-expanding corona over active regions**
2. **Plage: the source of most active region chromospheric emission**
3. **Sunspots: strong, ordered fields in the chromosphere**
4. **Filaments/Prominences: flux rope structure in the photosphere/chromosphere**

Active Region Filaments

- Some active region filaments are low-lying
- Influence magnetic structure of the photosphere
- Field topology at/near photosphere, intensity diagnostics strongly suggest flux rope topology
- Field evolution suggests emergence of flux rope from interior

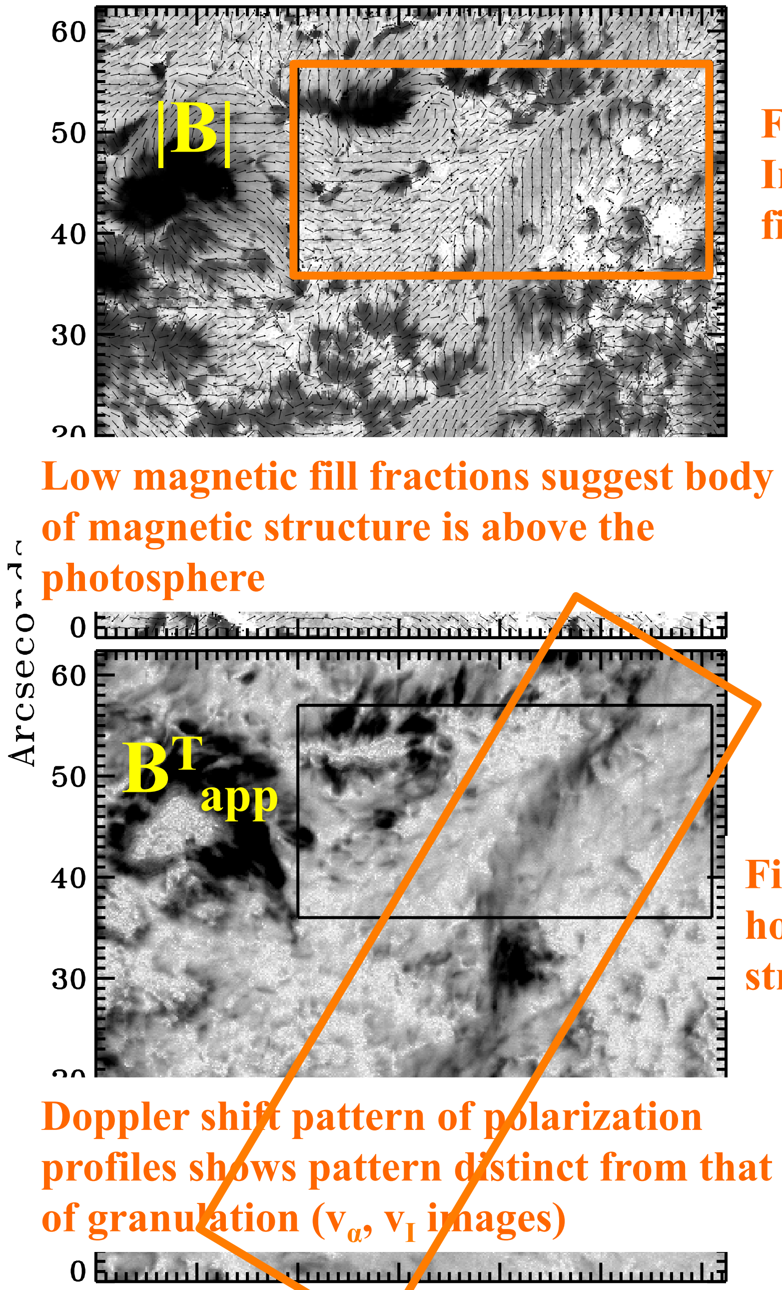
TRACE 171Å

- **Filament in absorption is visible under the arching coronal structures in emission**
- **Structure highly suggestive of a flux rope magnetic field configuration**



Lites et al. 2010, fig. 2

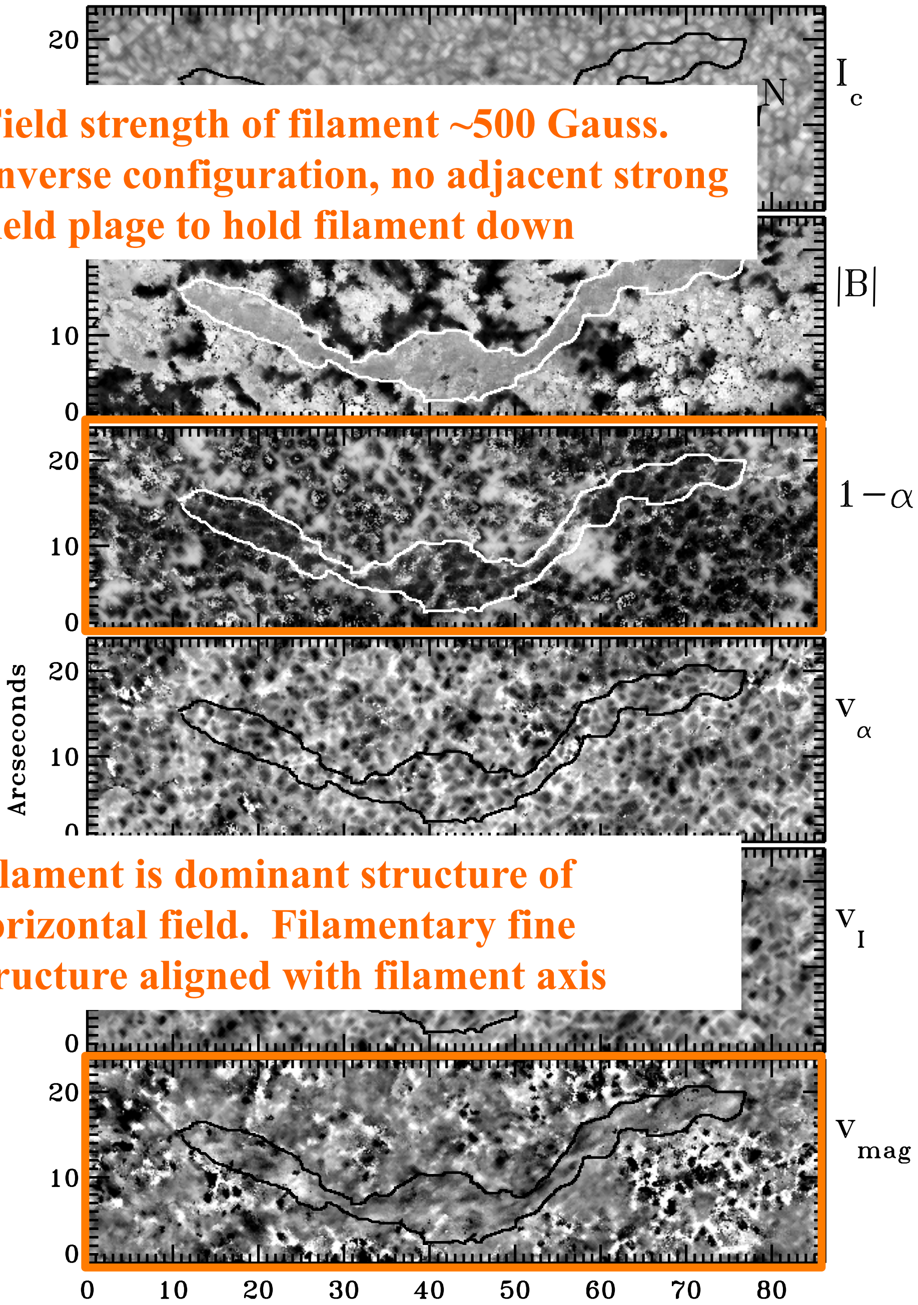
Indicators that Filament Flux Resides Above the Photosphere



Low magnetic fill fractions suggest body of magnetic structure is above the photosphere

Doppler shift pattern of polarization profiles shows pattern distinct from that of granulation (v_α, v_I images)

Lites et al. 2010, fig. 4



Field strength of filament ~500 Gauss. Inverse configuration, no adjacent strong field plage to hold filament down

Filament is dominant structure of horizontal field. Filamentary fine structure aligned with filament axis

Lites et al. 2010, fig. 5

Summary and Outlook

- Extraordinary intermittency of field in deep photosphere probably has little influence on chromosphere and above……Except for interactions of this structure with stronger kiloGauss flux elements that penetrate upward to the chromosphere
- Photospheric flux concentrations (network and plage) provide most of the structure of the quiet and active chromosphere. What are the relative roles of convective buffeting and reconnection driven by advection of opposite polarity from surroundings?
- Magneto-convection at and below photosphere creates a fluted penumbral magnetic field topology. Opposite polarity has now been detected in plage. How important is this topology to energetics of the active region chromosphere?
- Filaments (prominences) might hold the key to progression of the solar cycle, but questions remain as to their formation mechanism. Future observations should strive to establish mechanisms for origin, stabilization, and destabilization of filaments