Small-scale Structure and Dynamics of Sunspots and Related Solar Physics Topics

Sanjiv K. Tiwari

NASA Marshall Space Flight Center, Huntsville, AL, USA

Marshall Space Flight Center

NASA
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THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

Spring 2016 COURSE LISTING

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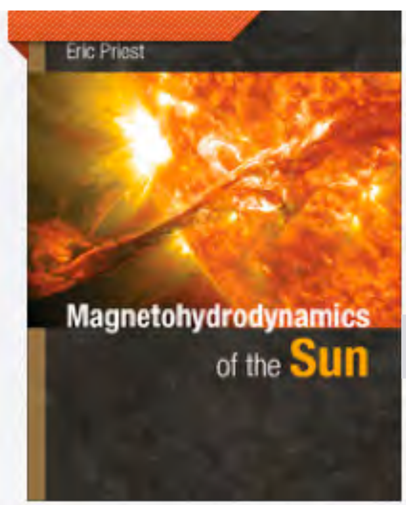
SPA/Space Science

Sec Type	CRN	Course	Title	Credit	Max Enrl	Enrl	Avail	Wait List	Days	Start	End	Bldg	Room	Instructor
	11681	489 01	ST: DEVELOPING CUBESATS	3.0	10	0	10	0	MW	02:20PM	03:40PM	CRH	2076	Briggs Michael
	11682	623 01	TRANSPORT PROCESSES IN SPACE	3.0	20	0	20	0	MW	03:55PM	05:15PM	CRH	2257	Zank Gary
	11683	624 01	SPACE PHYSICS I	3.0	20	0	20	0	TR	03:55PM	05:15PM	CRH	2076	Le Roux Jakobus
	11684	626 01	SPACE WEATHER	3.0	20	0	20	0	TR	11:10AM	12:30PM	CRH	2076	Li Gang
	11685	628 01	SOLAR PHYSICS	3.0	20	0	20	0	MW	03:55PM	05:15PM	CRH	2076	Tiwari Sanjiv
	11686	629 01	ASTROPHYSICAL FLUID DYNAMICS	3.0	20	0	20	0	TR	12:45PM	02:05PM	CRH	2076	Pogorelov Nikolai
	11687	662 01	COMPUTATIONAL PHYSICS	3.0	20	0	20	0	TR	02:20PM	03:40PM	CRH	2076	Florinski Vladimir
	11688	689 02	ST:ADV MATH MTHDS FOR SPA PHYS	3.0	20	0	20	0	MWF	09:10AM	10:05AM	CRH	2096	Hu Qiang

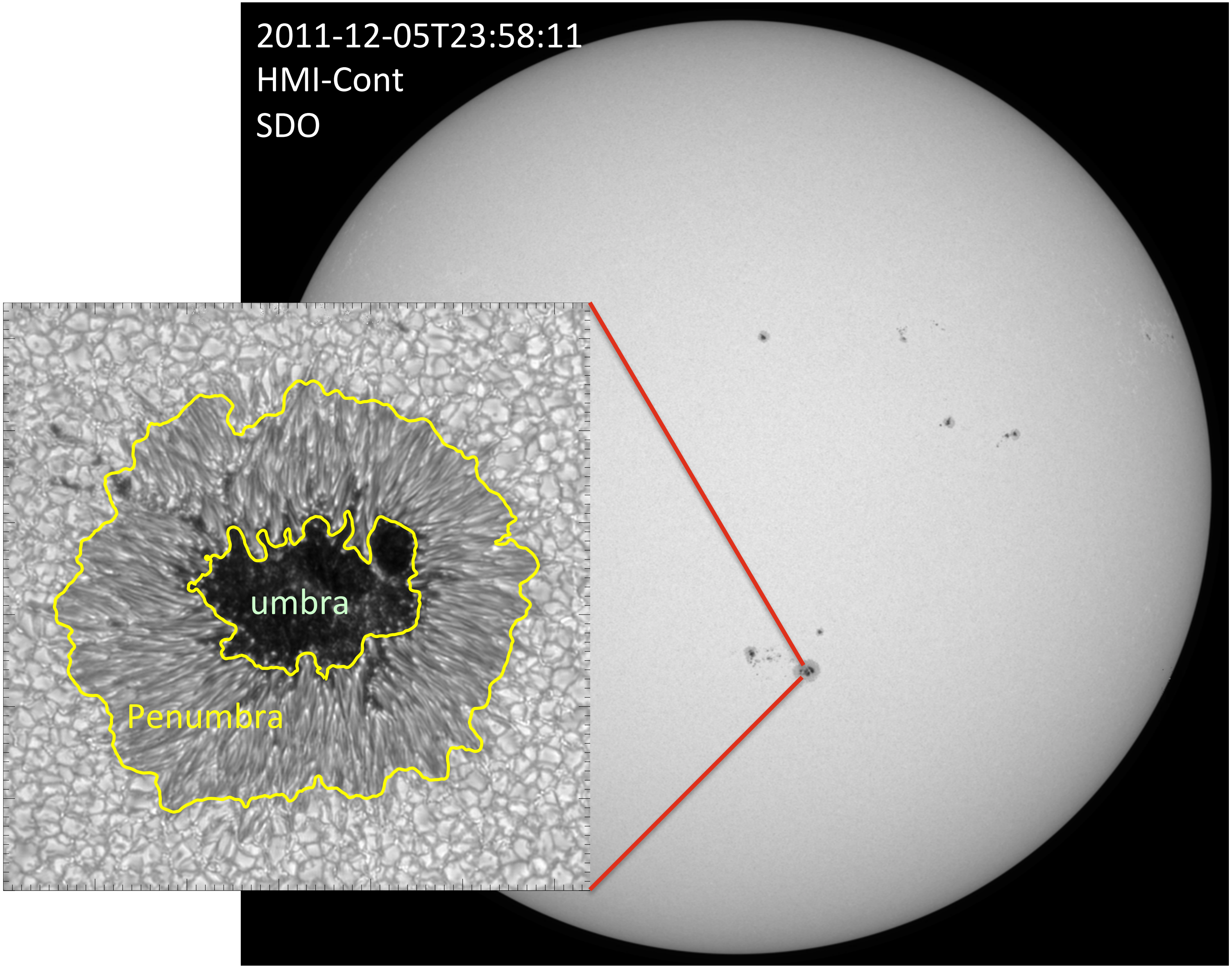
Introduction to:
Fundamental MHD processes on the Sun, Solar dynamo, Structure and dynamics of Sunspots, Coronal heating: ARs and QS, Solar flares and CMEs and their space weather perspective
Unsolved problems in solar physics!

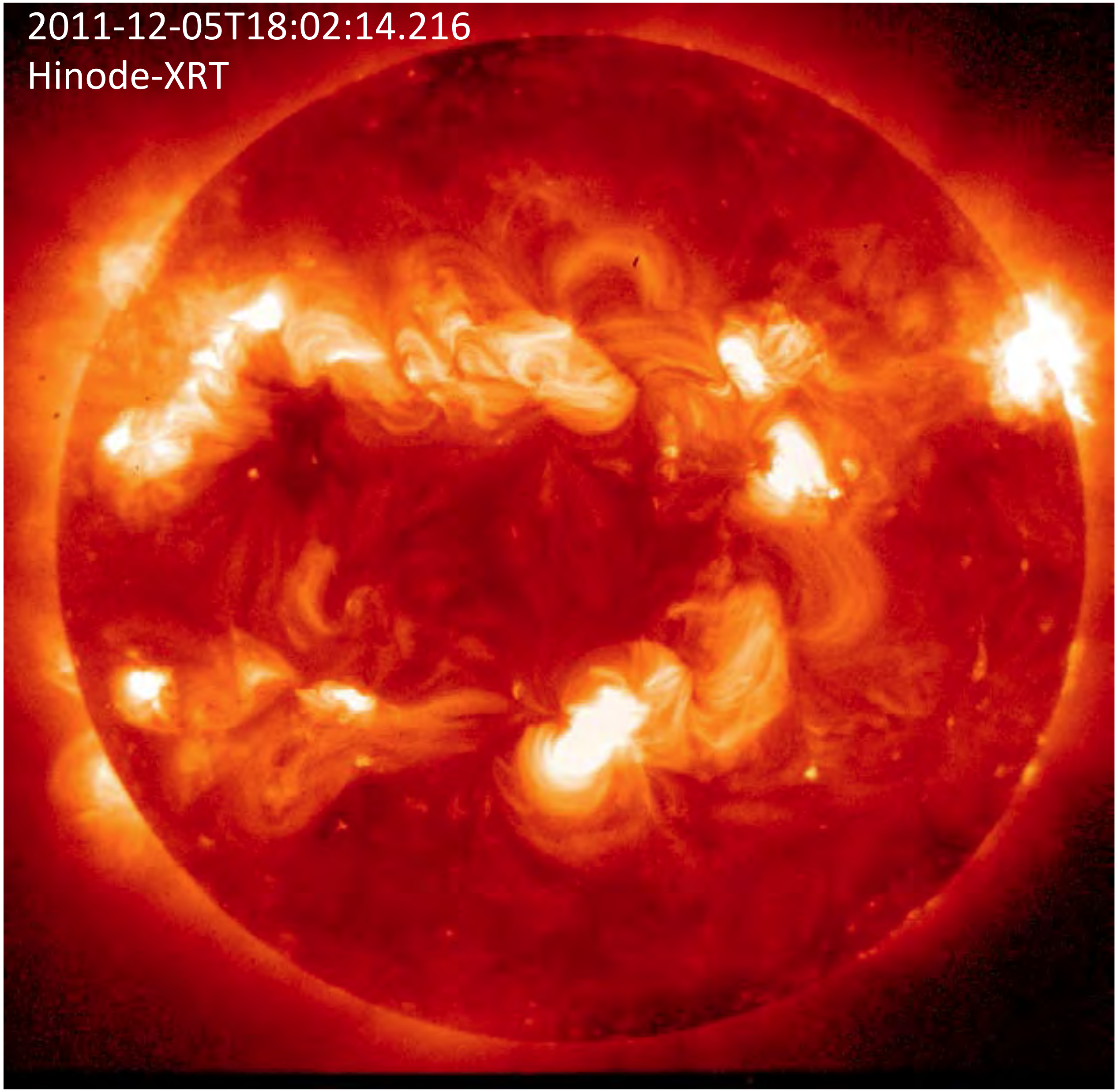


Magnetohydrodynamics of the Sun

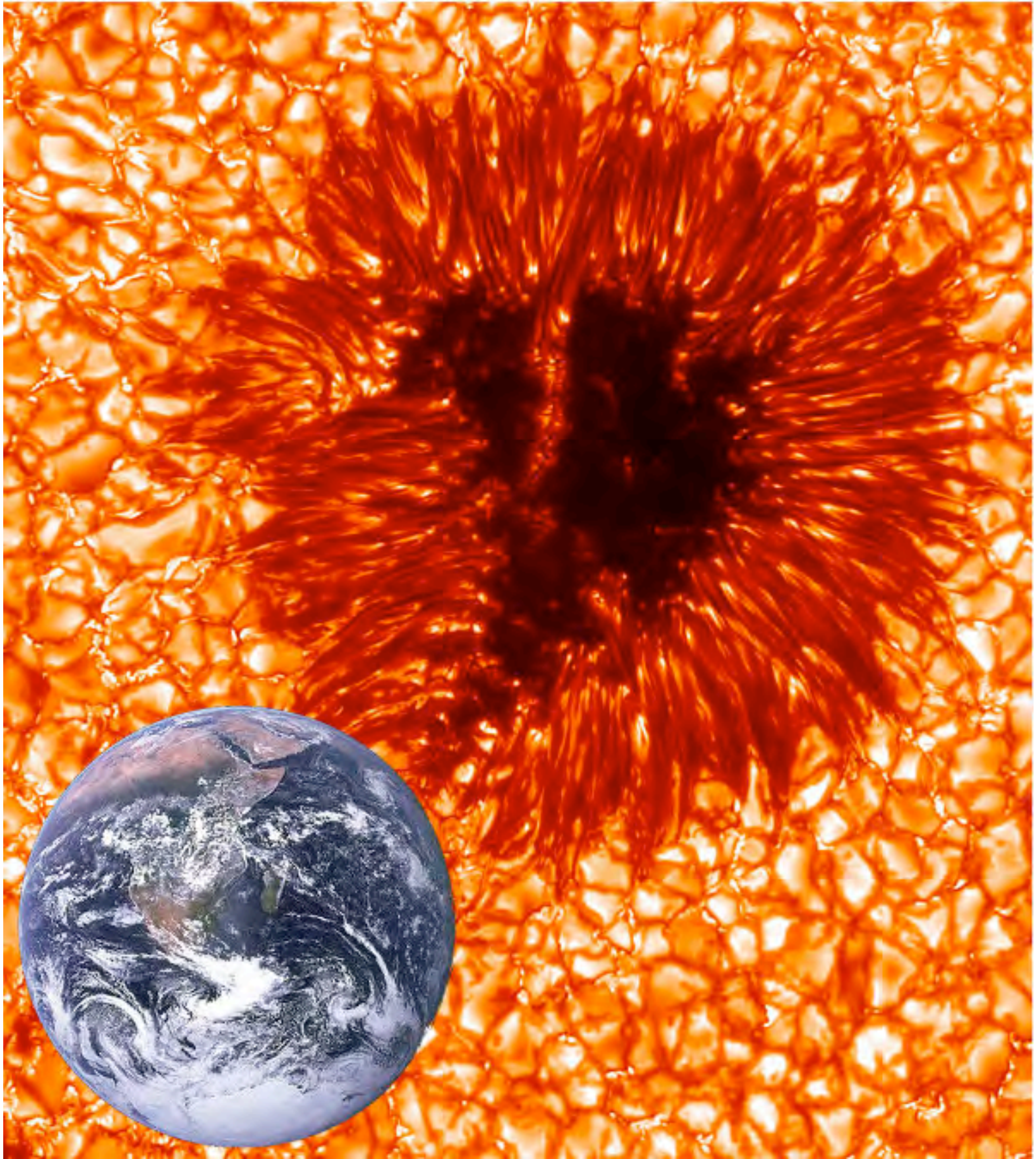
AUTHOR: Eric Priest
DATE PUBLISHED: April 2014
AVAILABILITY: In stock
FORMAT: Hardback
ISBN: 9780521854719

Introduction




2011-12-05T18:02:14.216
Hinode-XRT

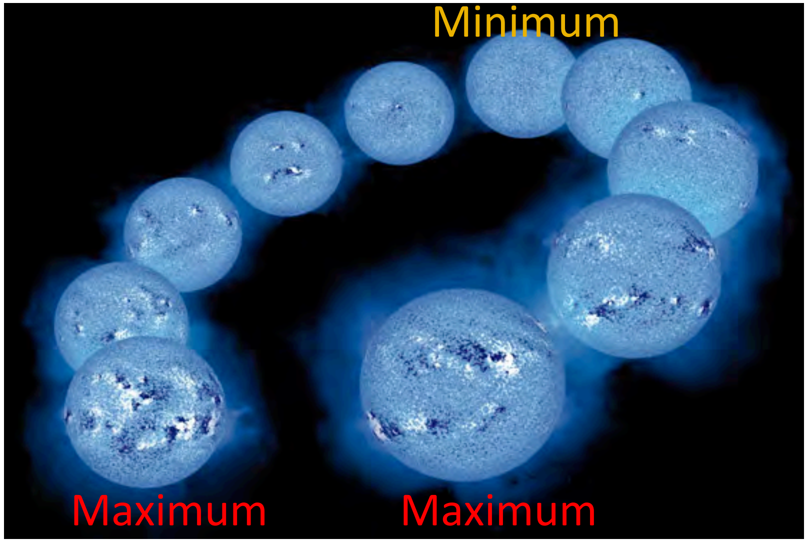
Size: compare with our Earth!



Sunspot magnetic field

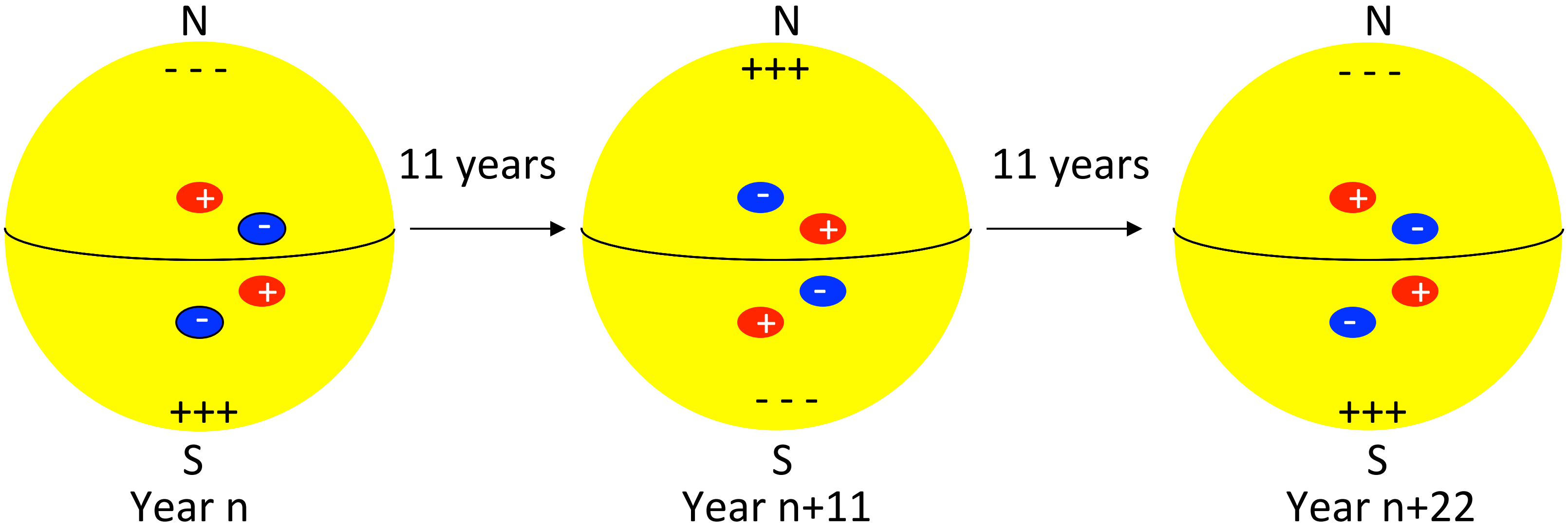
‘‘If it were not for its variable magnetic field , the Sun would have been a rather uninteresting star’’ - Leighten; Parker

- Sunspot cycle ~ 11 Years
- Solar Magnetic cycle ~ 22 Years

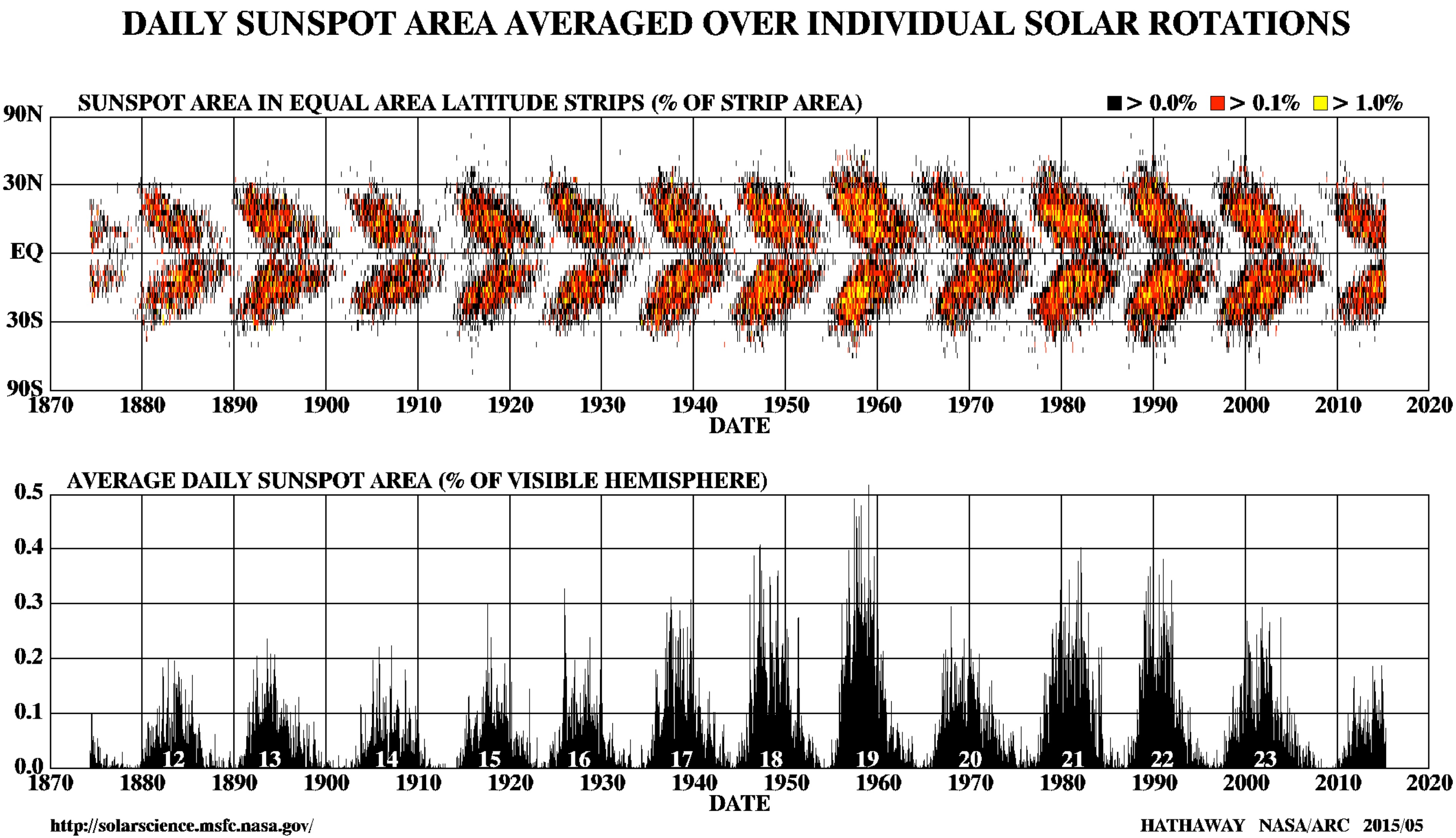


Joy’s Law

Hale’s Polarity Law

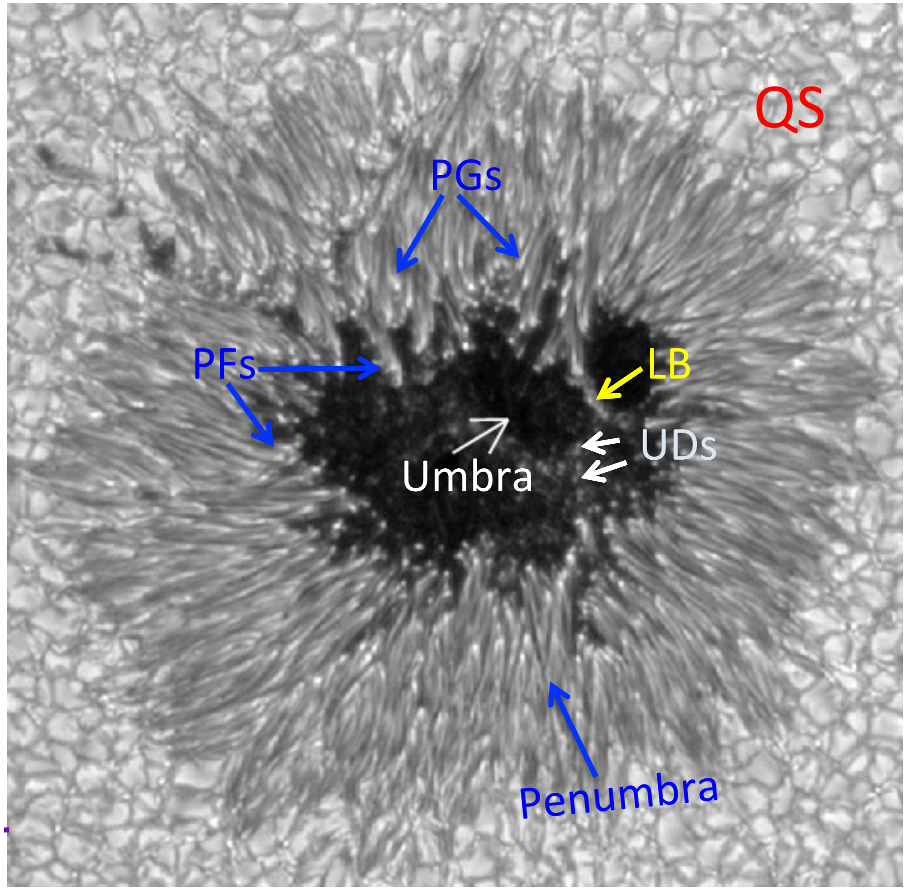


Sunspot cycle: butterfly diagram



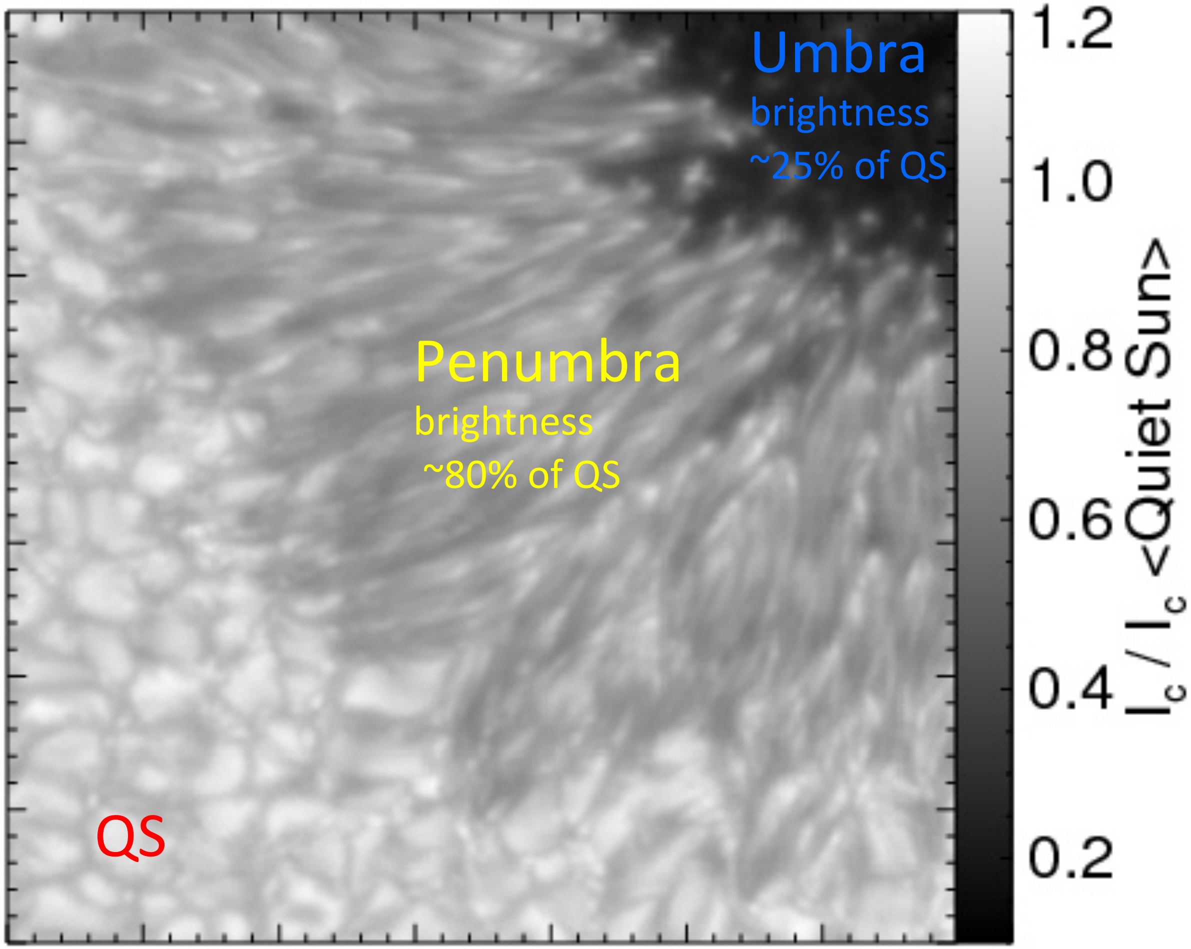
More about Sunspots

- Sunspot fine structure: umbral dots, light bridges, penumbral filaments, spines, peripheral downflows etc.
- Considerable advances in last 2 decades:
  theoretical (Rempel et al. 2009, 2012);
  observational (Solanki 2003, Tiwari et al. 2013, 2015)
  BUT controversies exist!
- Open issues:
  brightness of penumbrae;
  structure of penumbral filaments;
  penumbral grains; umbral dots;
  light bridges; high-speed peripheral downflows; magnetic canopy structure;
  thermal-magnetic relationship;
  the Evershed flow: (magneto-) convection or siphon flow;
  mass flux balance;
  global twist; equilibrium of sunspots etc.



Some instructive reviews:
Solanki, 2003; Borrero & Ichimoto, 2011; Rempel & Schlichenmaier, 2011

Sunspot penumbra



Energy Transport

Magneto-convection

Radial? Azimuthal? or, some combination of the two?

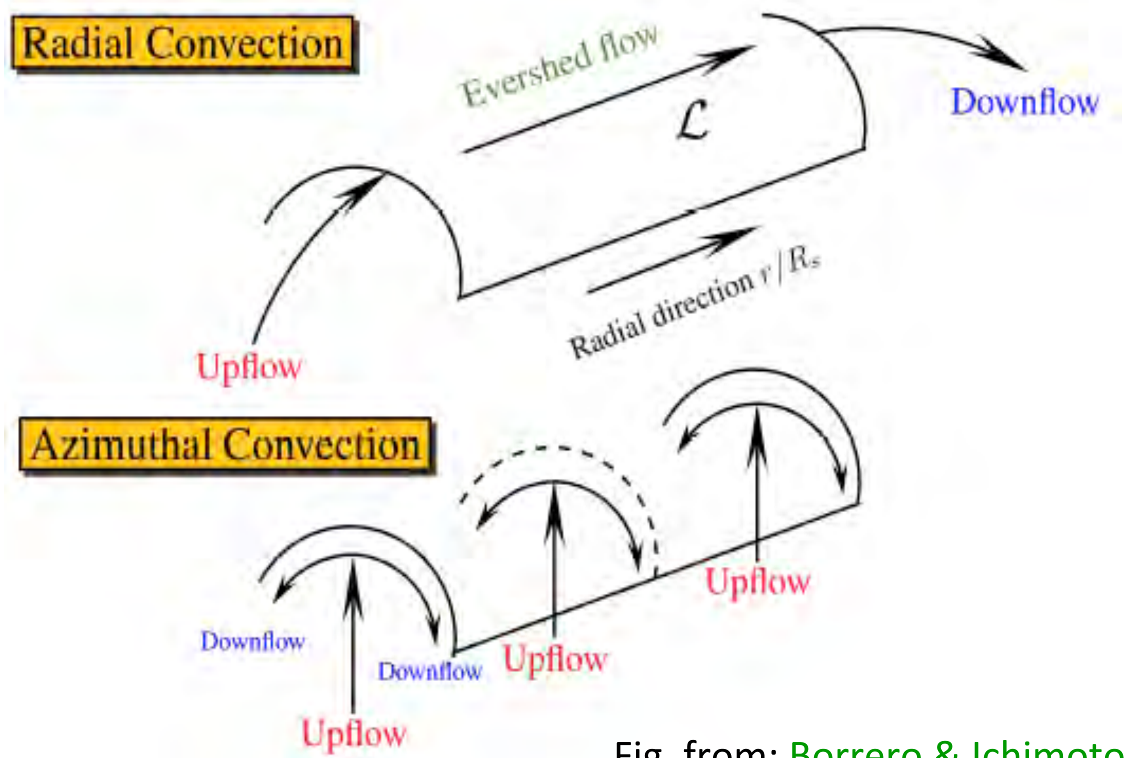


Fig. from: Borrero & Ichimoto, 2011, lrsp

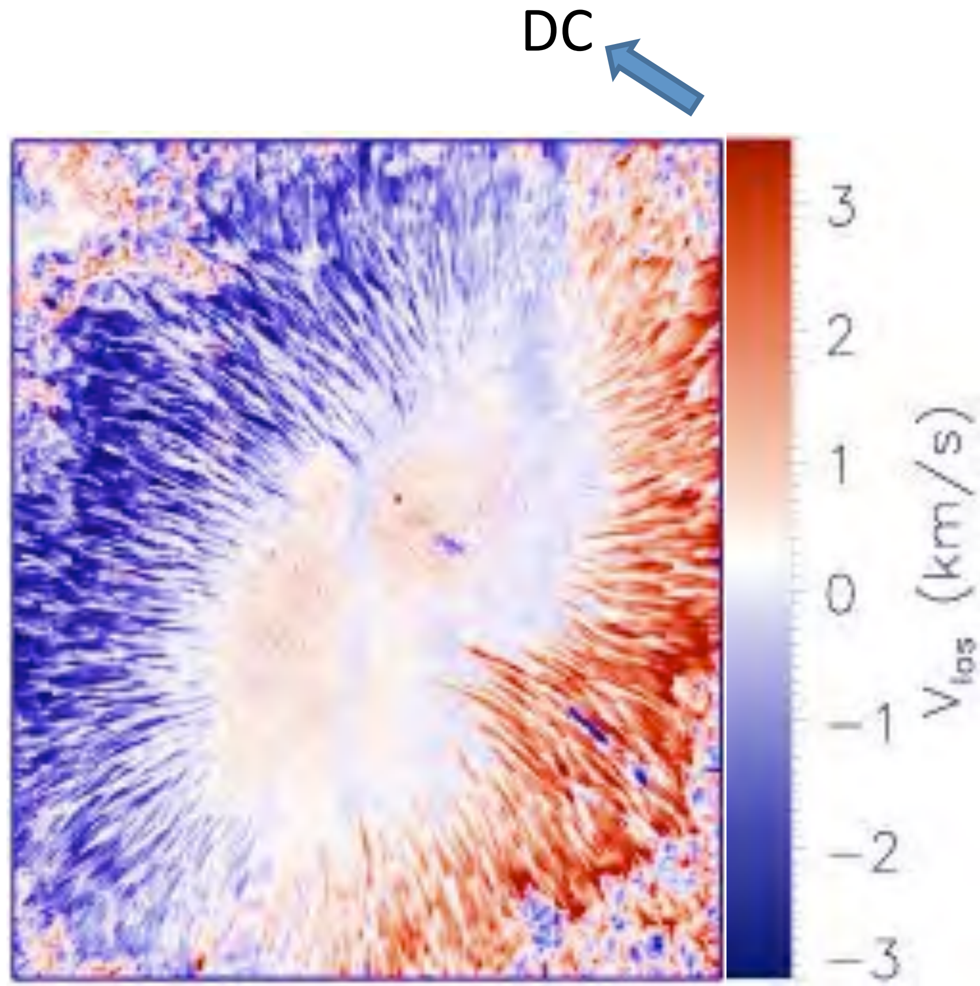
Evershed Flow

a siphon flow driven by
a gradient in magnetic field?
(Meyer & Schmidt 1968;
Montesinos & Thomas; 1997)

or,

a thermal gradient drives it?
(Schlichenmaier et al., 1998; Rempel 2011)

magnetized or
non-magnetized?

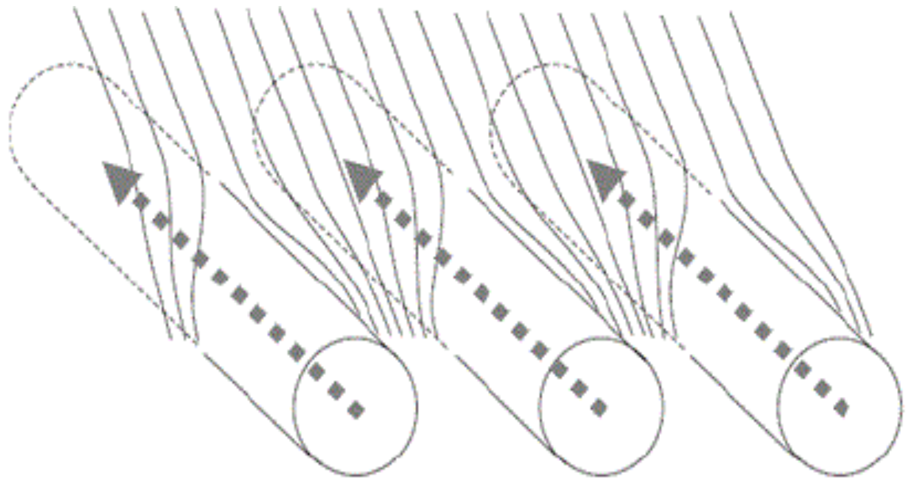


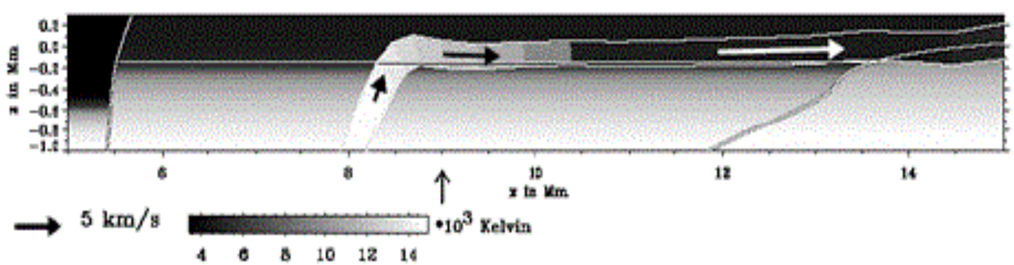
courtesy of G. Narayan

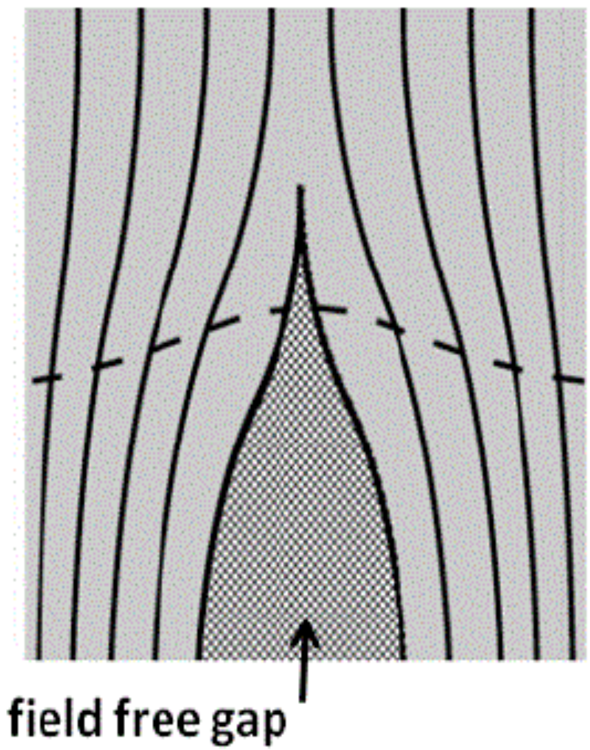
Idealized Penumbral Models

Embedded flux-tube model (Solanki & Montavan, 1993) or, its dynamical extension: rising flux tube model (Schlichenmaier et al., 1998)

Field-free gap model (Spruit & Scharmer, 2006; Scharmer & Spruit, 2006)







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Astronomy & Astrophysics

Structure of sunspot penumbral filaments: a remarkable uniformity of properties

Sanjiv Kumar Tiwari[1], Michiel van Noort[1], Andreas Lagg[1], and Sami K. Solanki[1,2]

[1] Max-Planck-Institut für Sonnensystemforschung, Max-Planck-Str. 2, 37191 Katlenburg-Lindau, Germany
e-mail: [tiwari;vannoort;lagg;solanki]@mps.mpg.de
[2] School of Space Research, Kyung Hee University, Yongin, 446-701 Gyeonggi, Republic of Korea

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ABSTRACT

Context. The sunspot penumbra comprises numerous thin, radially elongated filaments that are central for heat transport within the penumbra, but whose structure is still not clear.
Aims. We aim to investigate the fine-scale structure of these penumbral filaments.
Methods. We perform a depth-dependent inversion of spectropolarimetric data of a sunspot very close to solar disk center obtained by Solar Optical Telescope/Spectropolarimeter onboard the Hinode spacecraft. We have used a recently developed, spatially coupled 2D inversion scheme, which allows us to analyze the fine structure of individual penumbral filaments up to the diffraction limit of the telescope.
Results. Filaments of different sizes in all parts of the penumbra display very similar magnetic field strengths, inclinations, and velocity patterns. The temperature structure is also similar, although the filaments in the inner penumbra have cooler tails than those in the outer penumbra. The similarities allowed us to average all these filaments and to subsequently extract the physical properties common to all of them. This average filament shows upflows associated with an upward-pointing field at its inner, umbral end (head) and along its axis, as well as downflows along the lateral edge and strong downflows in the outer end (tail) associated with a nearly vertical, strong, and downward-pointing field. The upflowing plasma is significantly, i.e., up to 800 K, hotter than the downflowing plasma. The hot, tear-shaped head of the averaged filament can be associated with a penumbral grain. The central part of the filament shows nearly horizontal fields with strengths in the range of 1 kG. The field above the filament converges, whereas a diverging trend is seen in the deepest layers near the head of the filament. The fluctuations in the physical parameters along and across the filament increase rapidly with depth.
Conclusions. We put forward a unified observational picture of a sunspot penumbral filament. It is consistent with such a filament being a magneto-convective cell, in line with recent magnetohydrodynamic simulations. The uniformity of its properties over the penumbra sets constraints on penumbral models and simulations. The complex and inhomogeneous structure of the filament provides a natural explanation for a number of long-running controversies in the literature.

Key words. Sun: photosphere – sunspots – Sun: surface magnetism

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October 16, 2015

Depth-dependent global properties of a sunspot observed by Hinode using the Solar Optical Telescope/Spectropolarimeter

Sanjiv K. Tiwari[1,2], Michiel van Noort[1], Sami K. Solanki[1,3], and Andreas Lagg[1]

[1] Max-Planck-Institut für Sonnensystemforschung, Justus-von-Liebig-Weg 3, 37077 Göttingen, Germany
e-mail: [tiwari;vannoort;solanki;lagg]@mps.mpg.de
[2] NASA Marshall Space Flight Center, ZP 13, Huntsville, AL 35812, USA
[3] School of Space Research, Kyung Hee University, Yongin, 446-701 Gyeonggi, Republic of Korea

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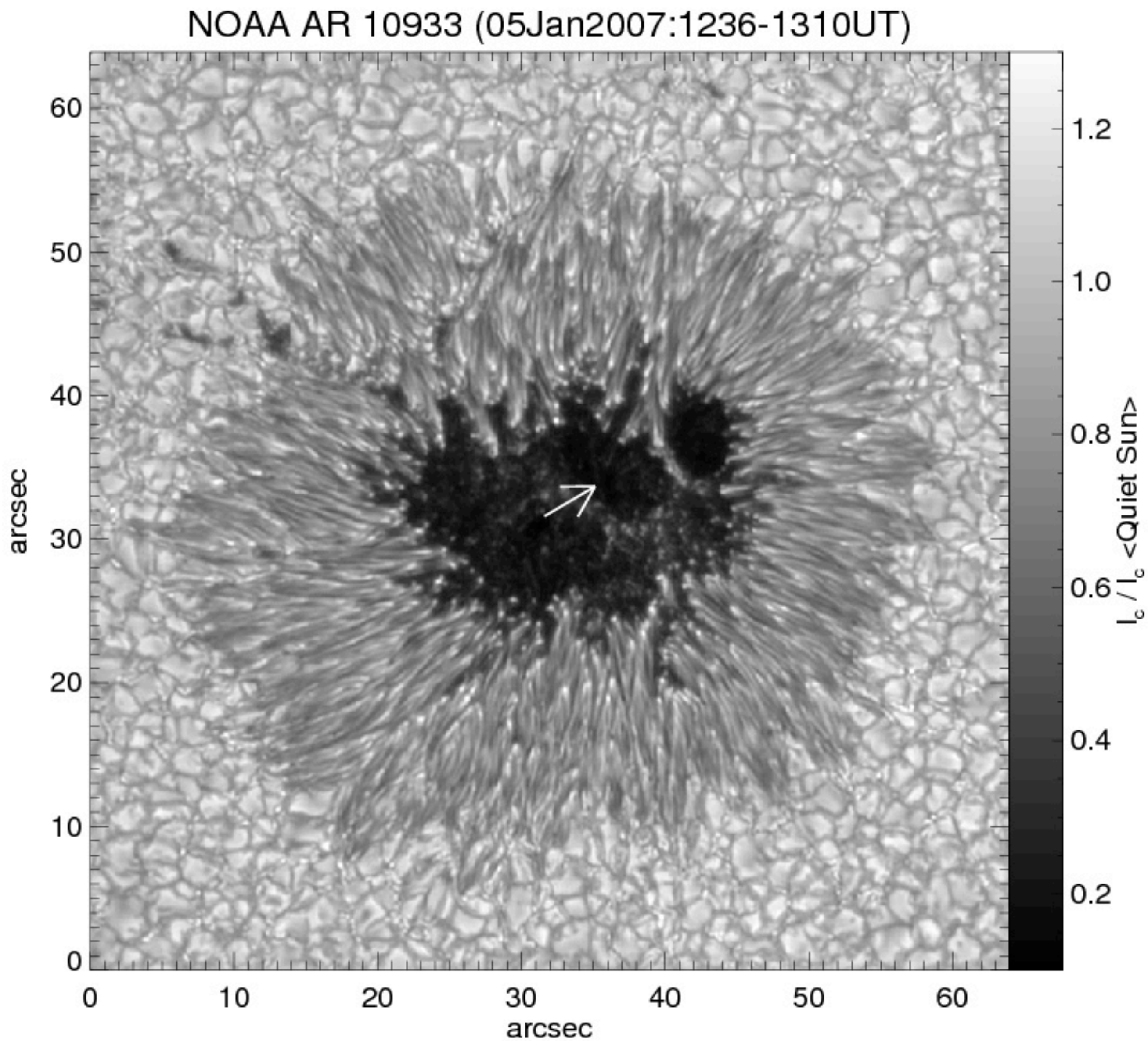
ABSTRACT

Context. For the past two decades, the three-dimensional structure of sunspots has been studied extensively. A recent improvement in the Stokes inversion technique prompts us to revisit the depth-dependent properties of sunspots.
Aims. In the present work, we aim to investigate the global depth-dependent thermal, velocity, and magnetic properties of a sunspot, as well as the interconnection between various local properties.
Methods. We analysed high-quality Stokes profiles of the disk-centred, regular, leading sunspot of NOAA AR 10933, acquired by the Solar Optical Telescope/Spectropolarimeter (SOT/SP) on board the Hinode spacecraft. To obtain depth-dependent stratification of the physical parameters, we used the recently developed, spatially coupled version of the SPINOR inversion code.
Results. First, we study the azimuthally averaged physical parameters of the sunspot. We find that the vertical temperature gradient in the lower- to mid-photosphere is at its weakest in the umbra, while it is considerably stronger in the penumbra, and stronger still in the spot's surroundings. The azimuthally averaged field becomes more horizontal with radial distance from the centre of the spot, but more vertical with height. At continuum optical depth unity, the line-of-sight velocity shows an average upflow of $\sim$300 ms^{-1} in the inner penumbra and an average downflow of $\sim$1300 ms^{-1} in the outer penumbra. The downflow continues outside the visible penumbral boundary. The sunspot shows, at most, a moderate negative twist of $<5^\circ$ at $\log(\tau) = 0$, which increases with height. The sunspot umbra and the spines of the penumbra show considerable similarity with regard to their physical properties, albeit with some quantitative differences (weaker, somewhat more horizontal fields in spines, commensurate with their location being further away from the sunspot's core). The temperature shows a general anti-correlation with the field strength, with the exception of the heads of penumbral filaments, where a weak positive correlation is found. The dependence of the physical parameters on each other over the full sunspot shows a qualitative similarity to that of a standard penumbral filament and its surrounding spines.
Conclusions. The large-scale variation in the physical parameters of a sunspot at various optical depths is presented. Our results suggest that the spines in the penumbra are basically the outward extension of the umbra. The spines and the penumbral filaments, together, are the basic elements that form a sunspot penumbra.

Key words. Sun: magnetic fields – Sun: photosphere – sunspots

Data

- NOAA AR 10933, observed from SOT/SP onboard Hinode
- The sunspot was observed very close to disk center (μ=0.99) on 05 Jan 2007 at 1213 UT.
- The spectral lines used for polarimetric measurements are the doublet FeI 6301.5 and 6302.5 Å.



Inversion

- Inversion: a process that returns most probable atmosphere that gave rise to the observed spectra.
- ME inversions, simpler atmosphere, analytically solution possible, fast (Harvey et al.,1972; Landi Degl' Innocenti & Landolfi 2004)
  :HeLIx (Lagg et al., 2004)
  :MERLIN (Lites et al., 2007)
- Depth-dependent inversions (use response functions) (Landi Degl' Innocenti & Landi Degl' Innocenti,1977)
  :SIR (Ruiz Cobo & del Toro Iniesta 1992)
  :SPINOR (Frutiger et al., 2000)
- Line forming region (log $\tau_{min-max}$)
- RTEs for polarized light in LTE are solved numerically
- χ^2 minimization

Inversion

SPINOR (Frutiger et al., 2000; Solanki, 1987):
Spatially coupled inversion (van Noort, 2012; van Noort, Lagg, Tiwari, Solanki, 2013)

-2D maps of spectro-polarimetric data can be inverted simultaneously

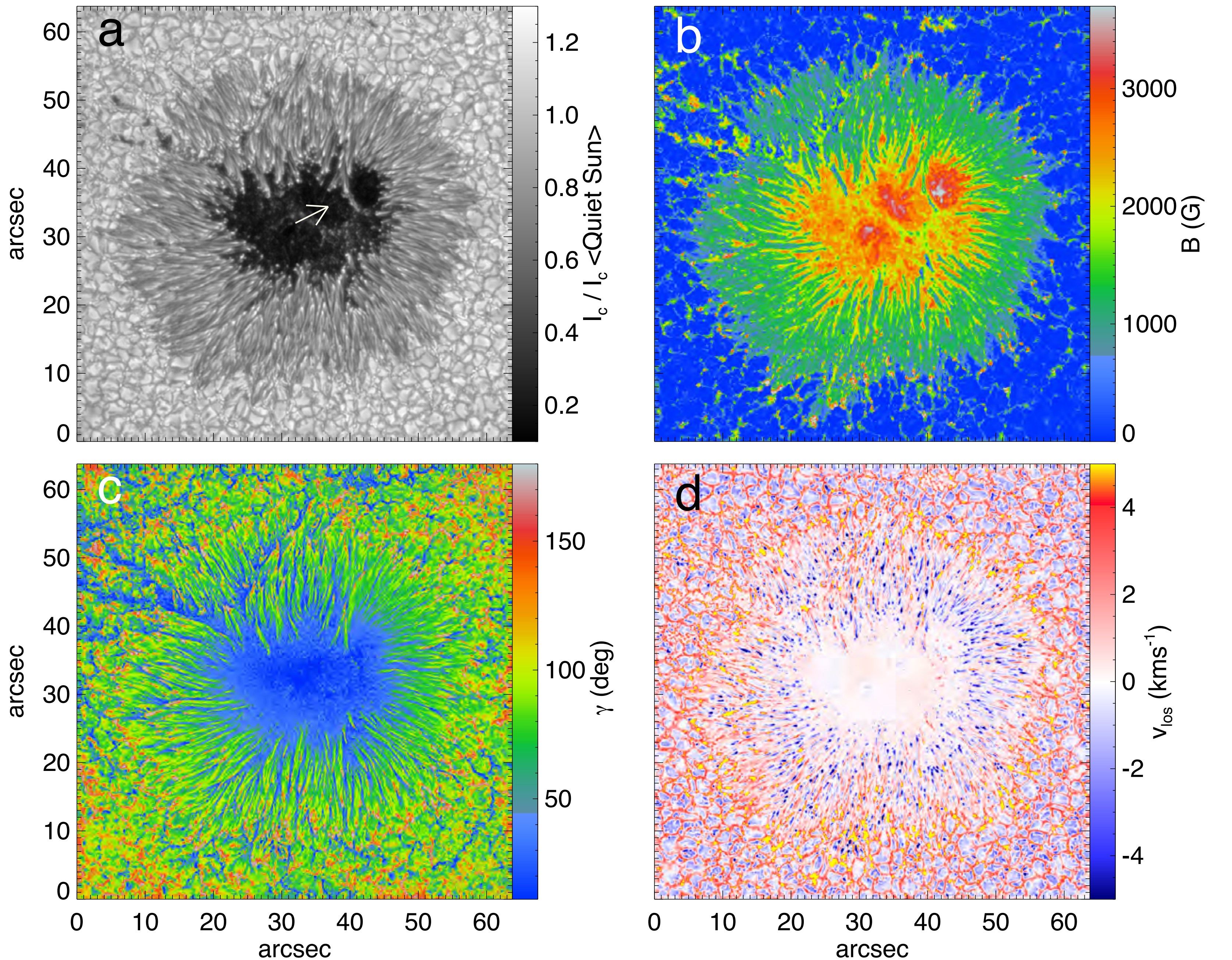
-accounts for telescope diffraction psf

-self-consistent solution, very accurate Stokes profile's fitting

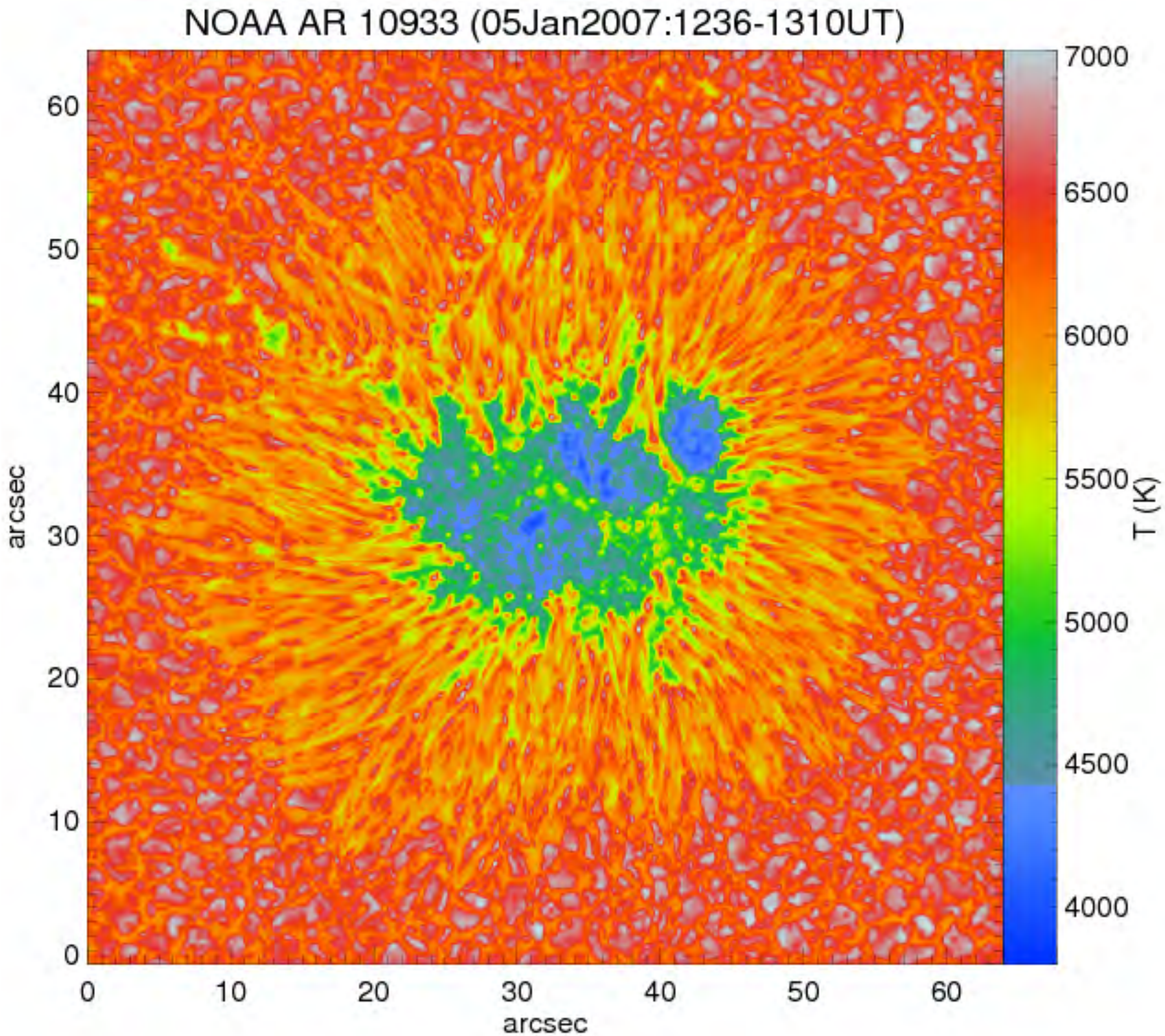
-stable to spatial oversampling of the solution; up to diffraction limit

-log(τ) node positions: -2.5, -0.9, 0

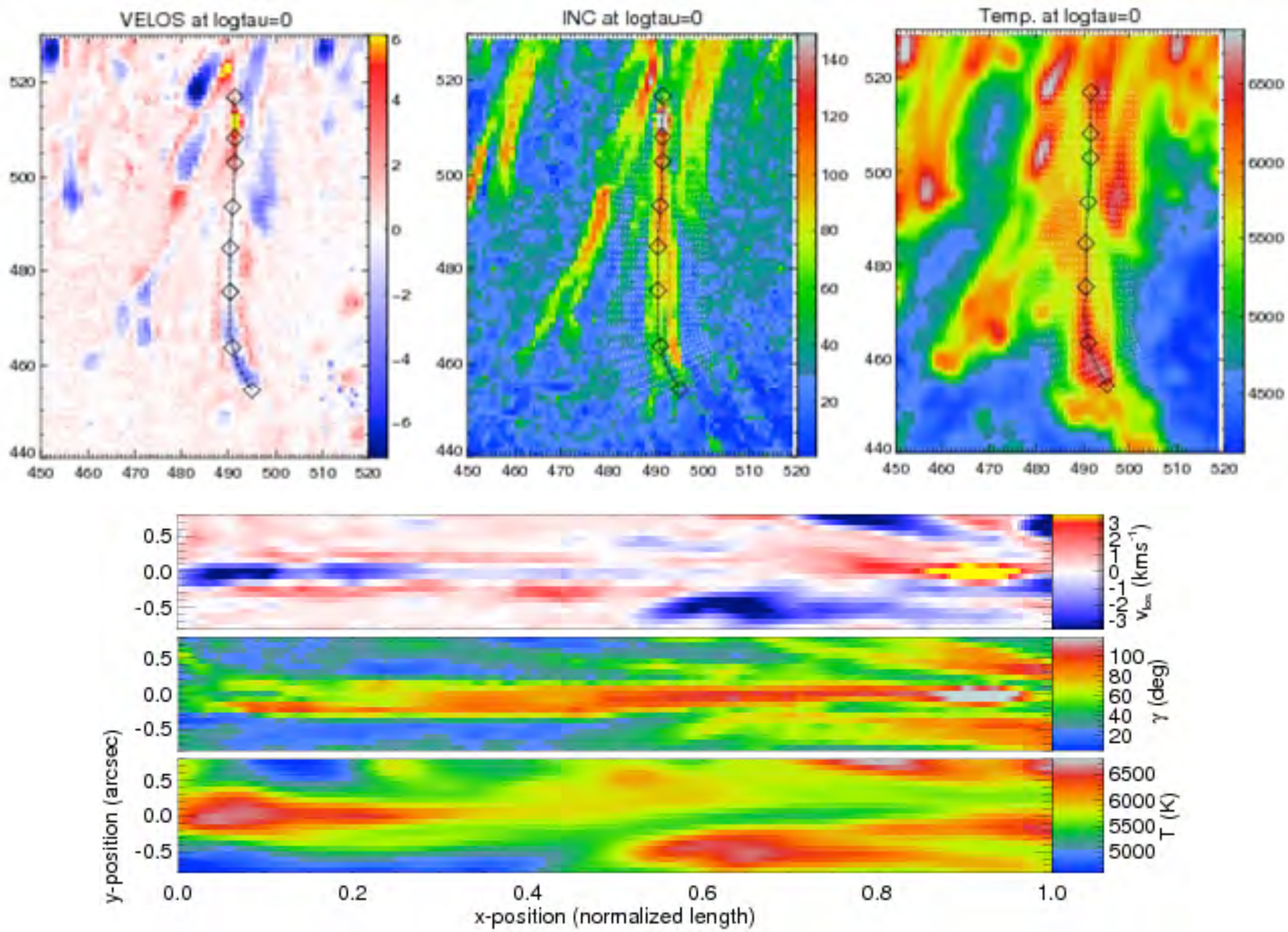
-Free parameters: temperature, magnetic field strength, inclination, azimuth, line-of-sight velocity, micro turbulent velocity



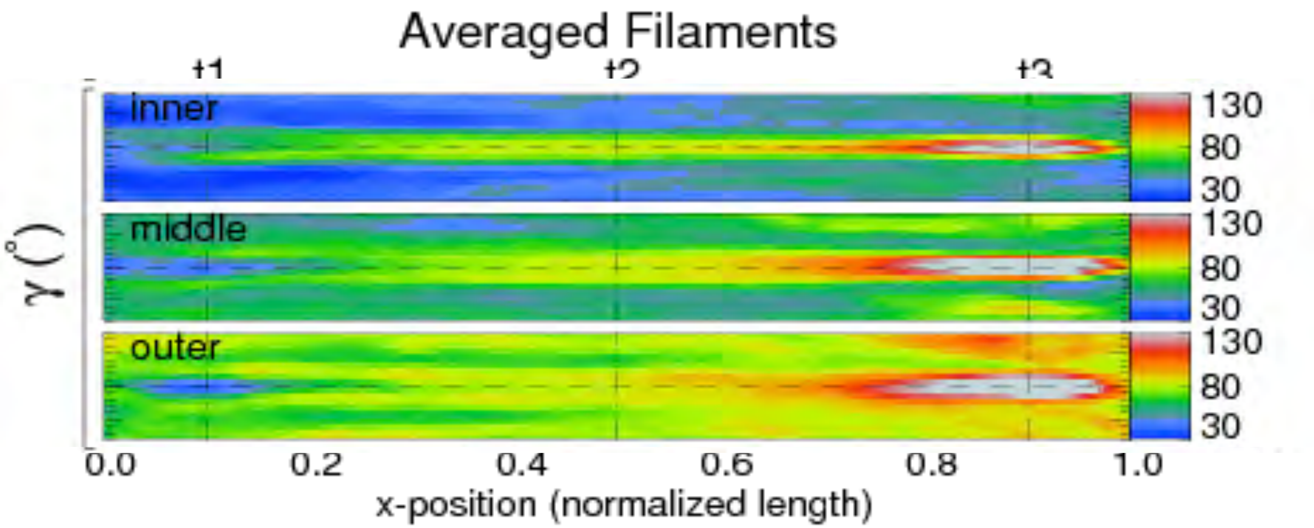
a
b
c
d
arcsec
I_c / I_c <Quiet Sun>
B (G)
γ (deg)
v_los (kms^-1)


NOAA AR 10933 (05Jan2007:1236-1310UT)
arcsec
arcsec
T (K)
0
10
20
30
40
50
60
7000
6500
6000
5500
5000
4500
4000

Filament selection



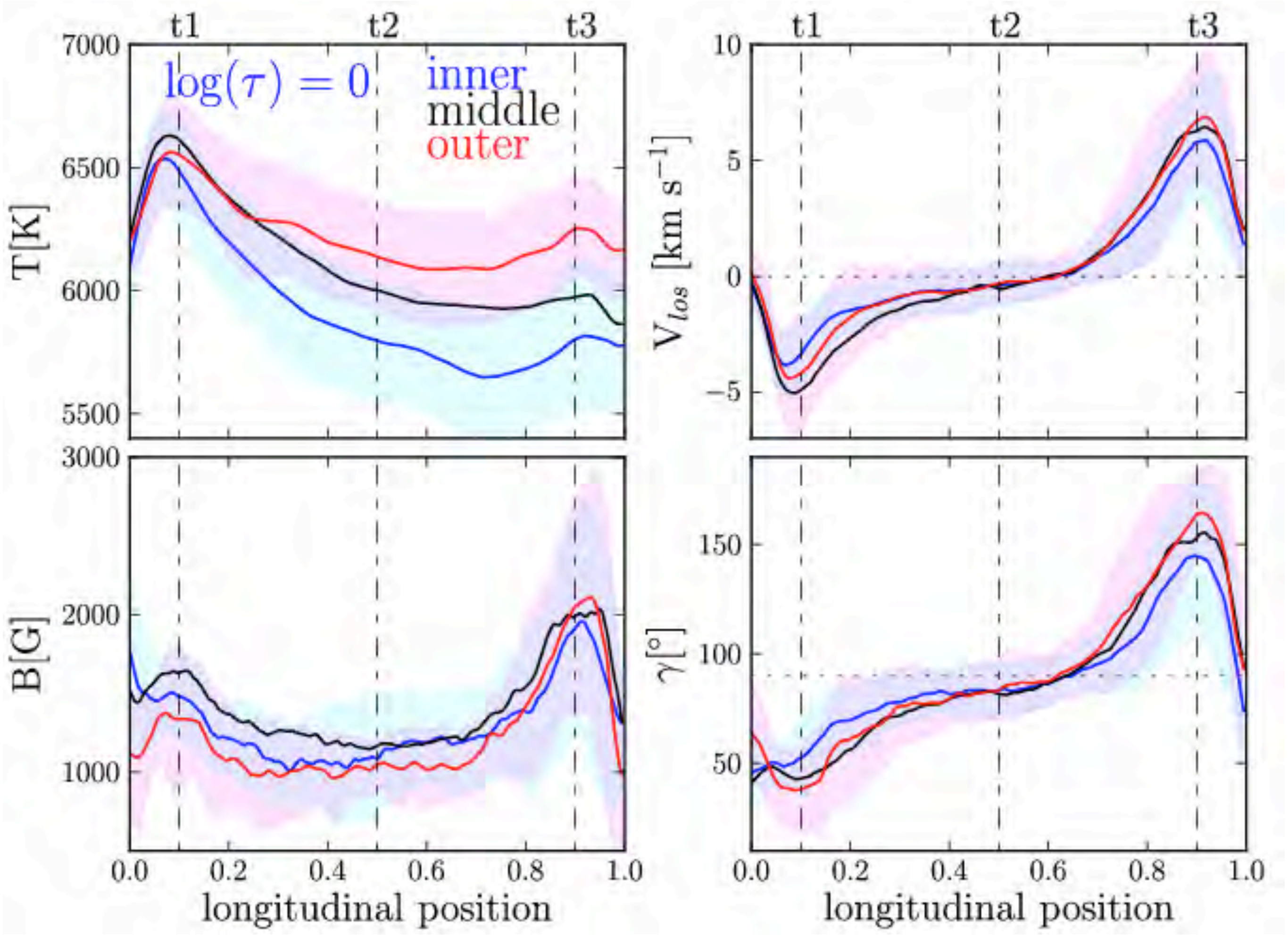
Averaged filaments: qualitative picture



Remarkably uniform throughout penumbra!!

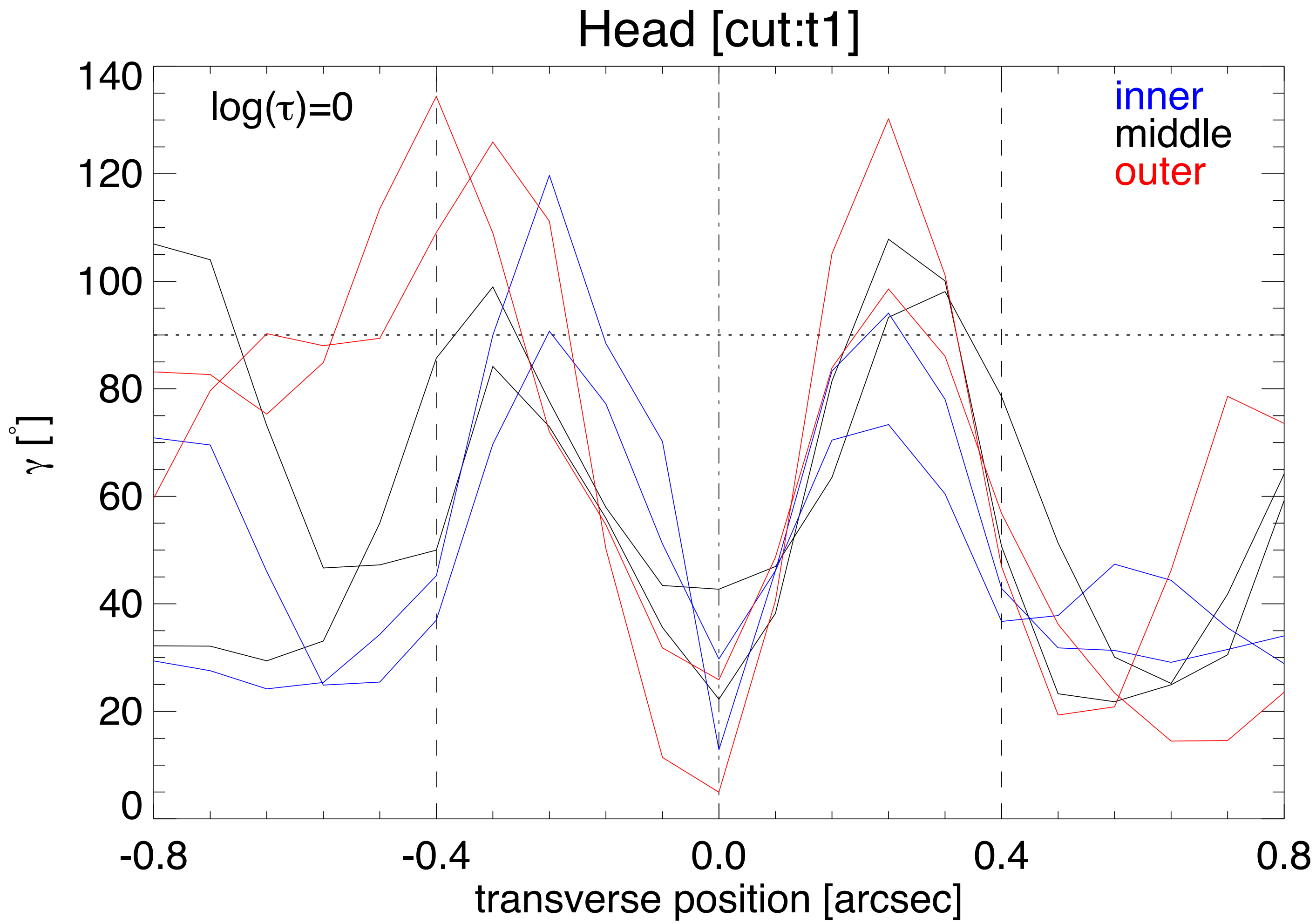
Quantitative picture

longitudinal cut

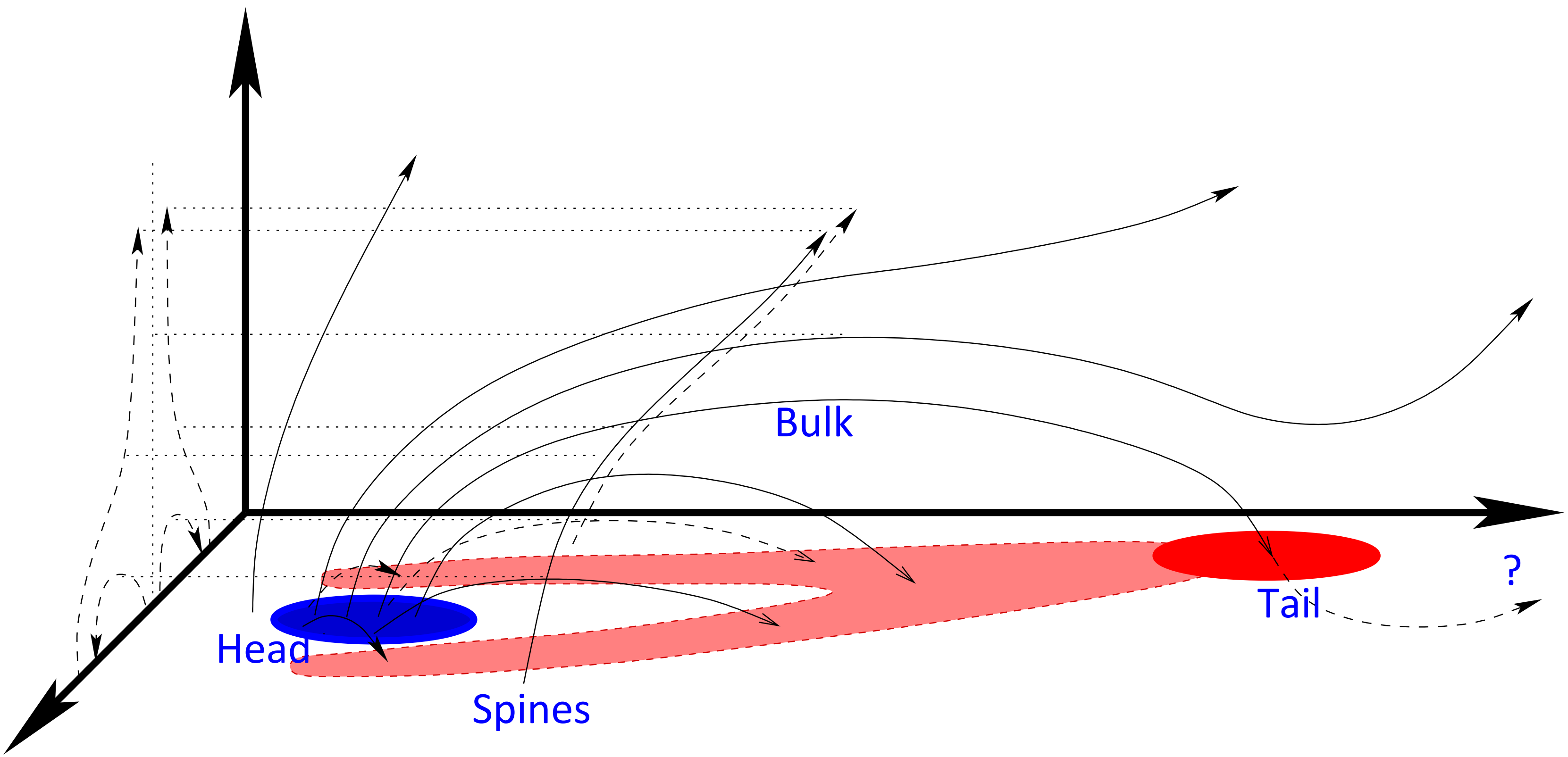


Quantitative picture

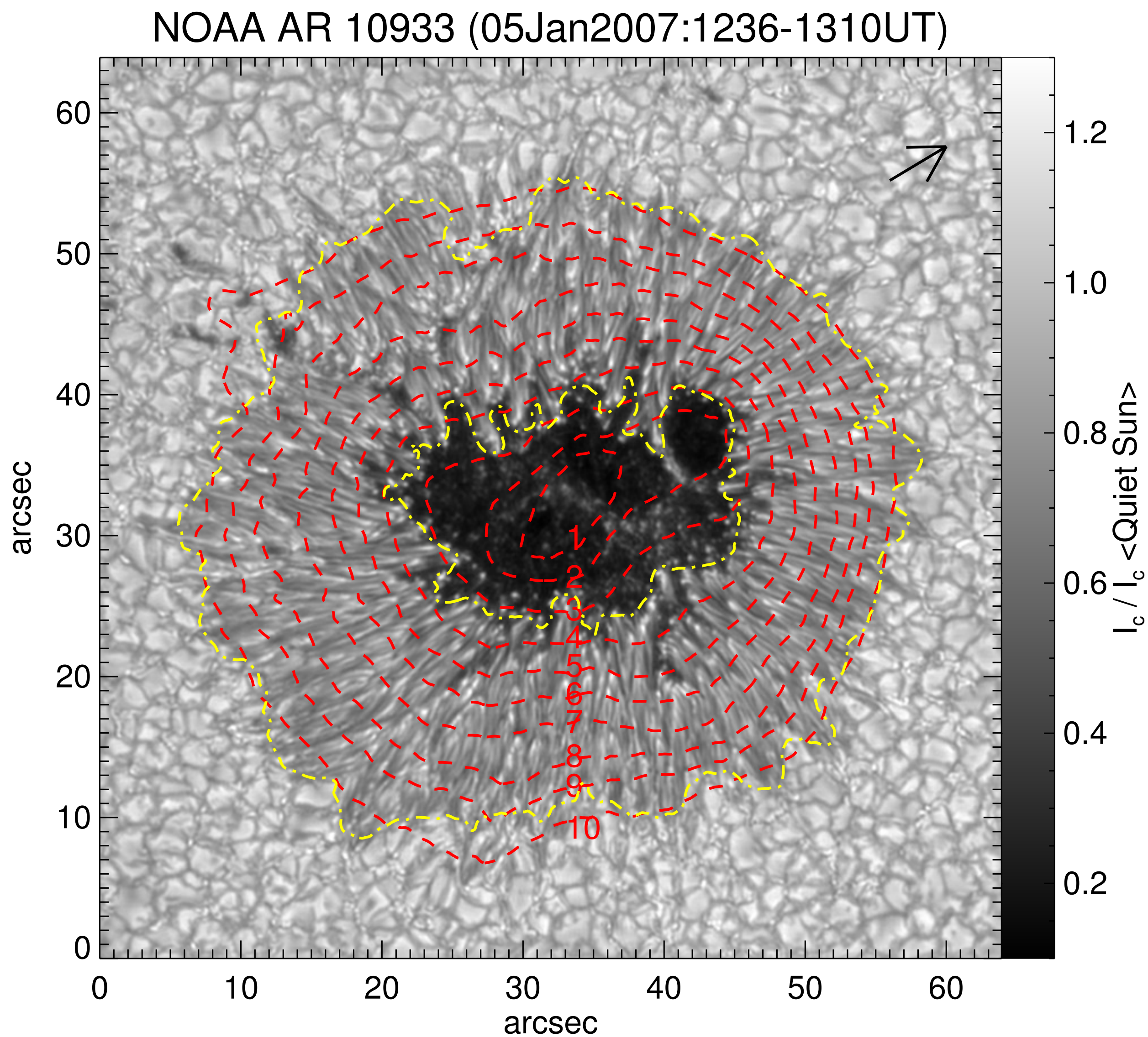
opposite polarity at sides



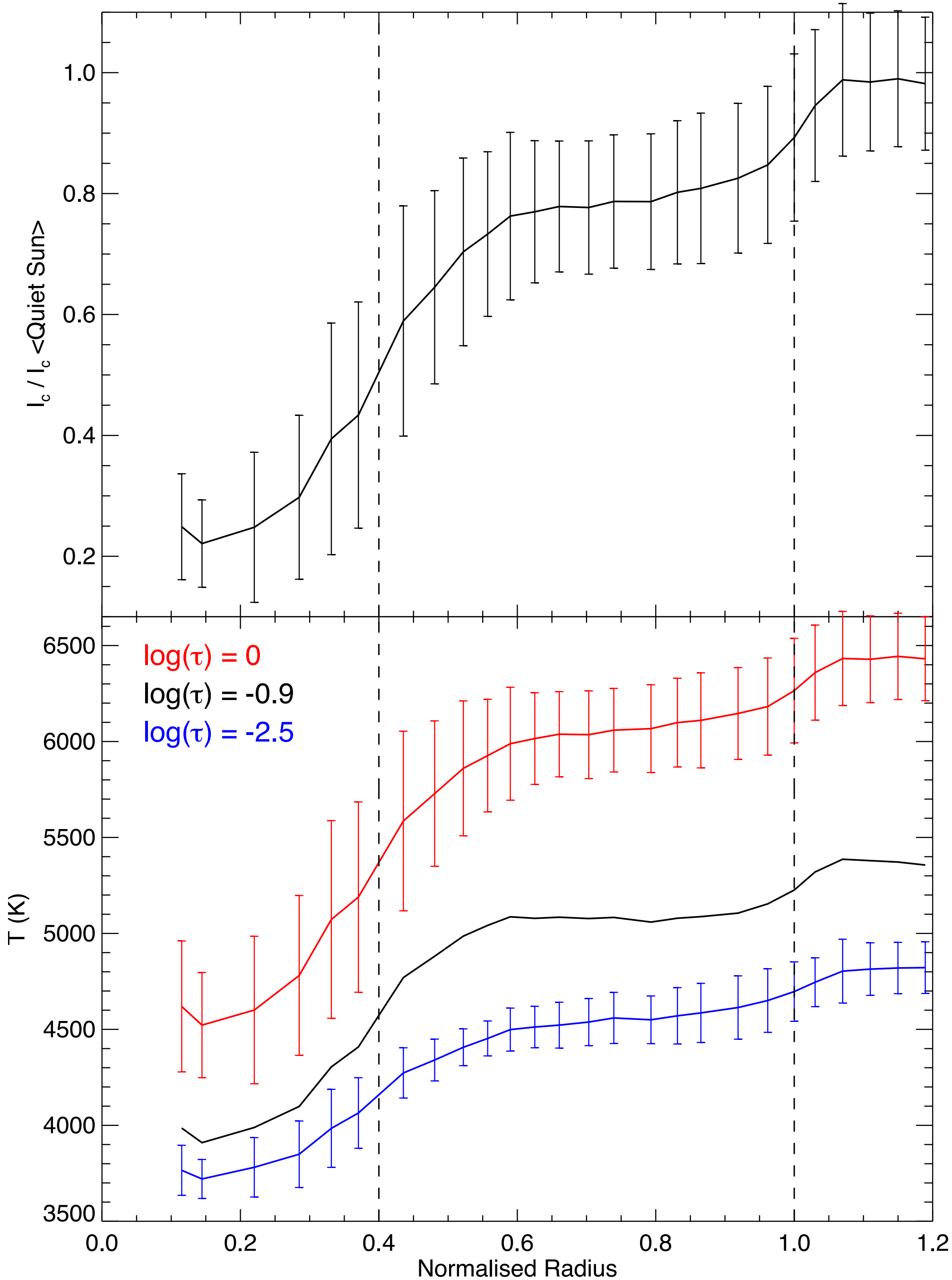
Schematic sketch



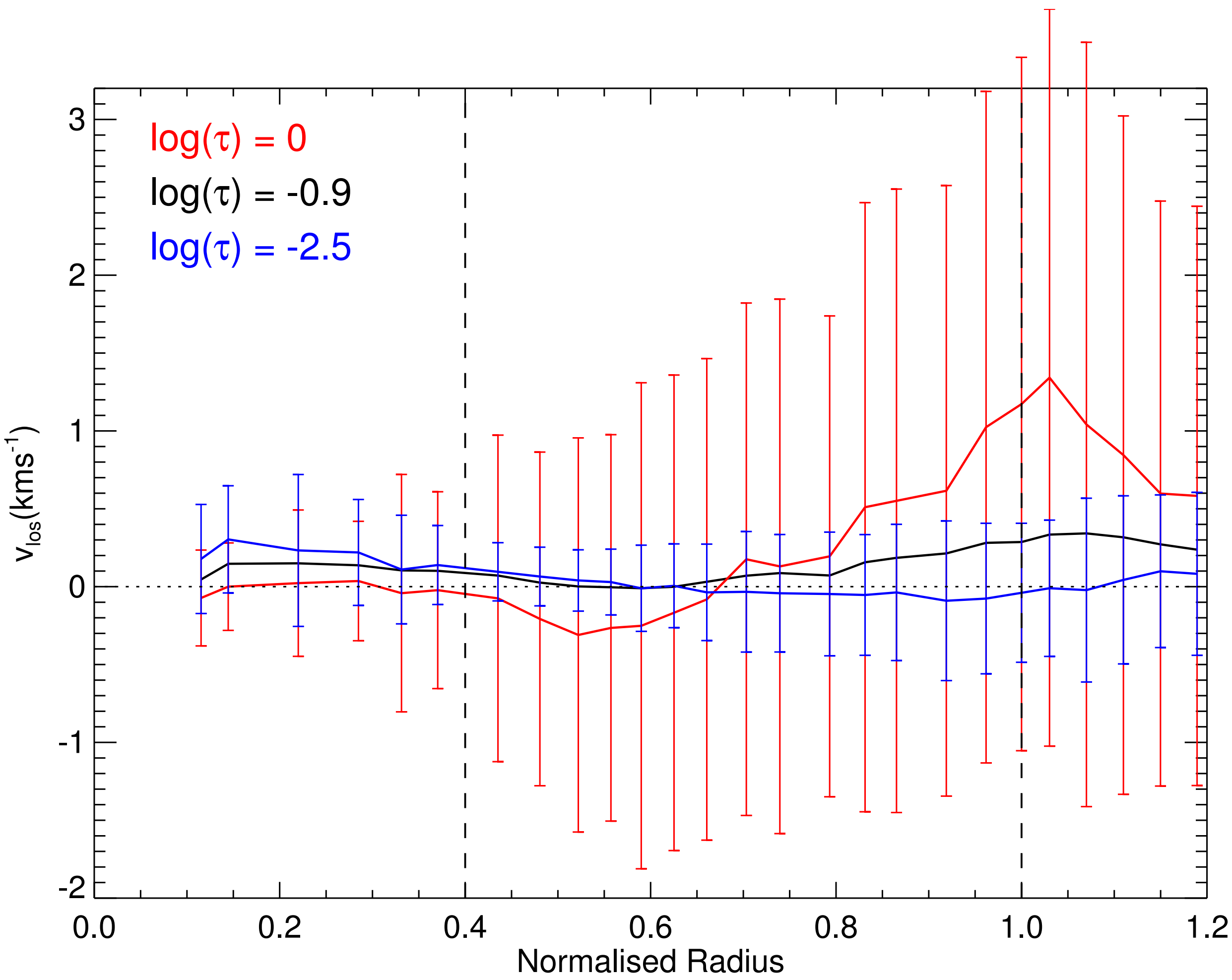
Global structure of Sunspot in light of fine-scale structure of penumbral filaments



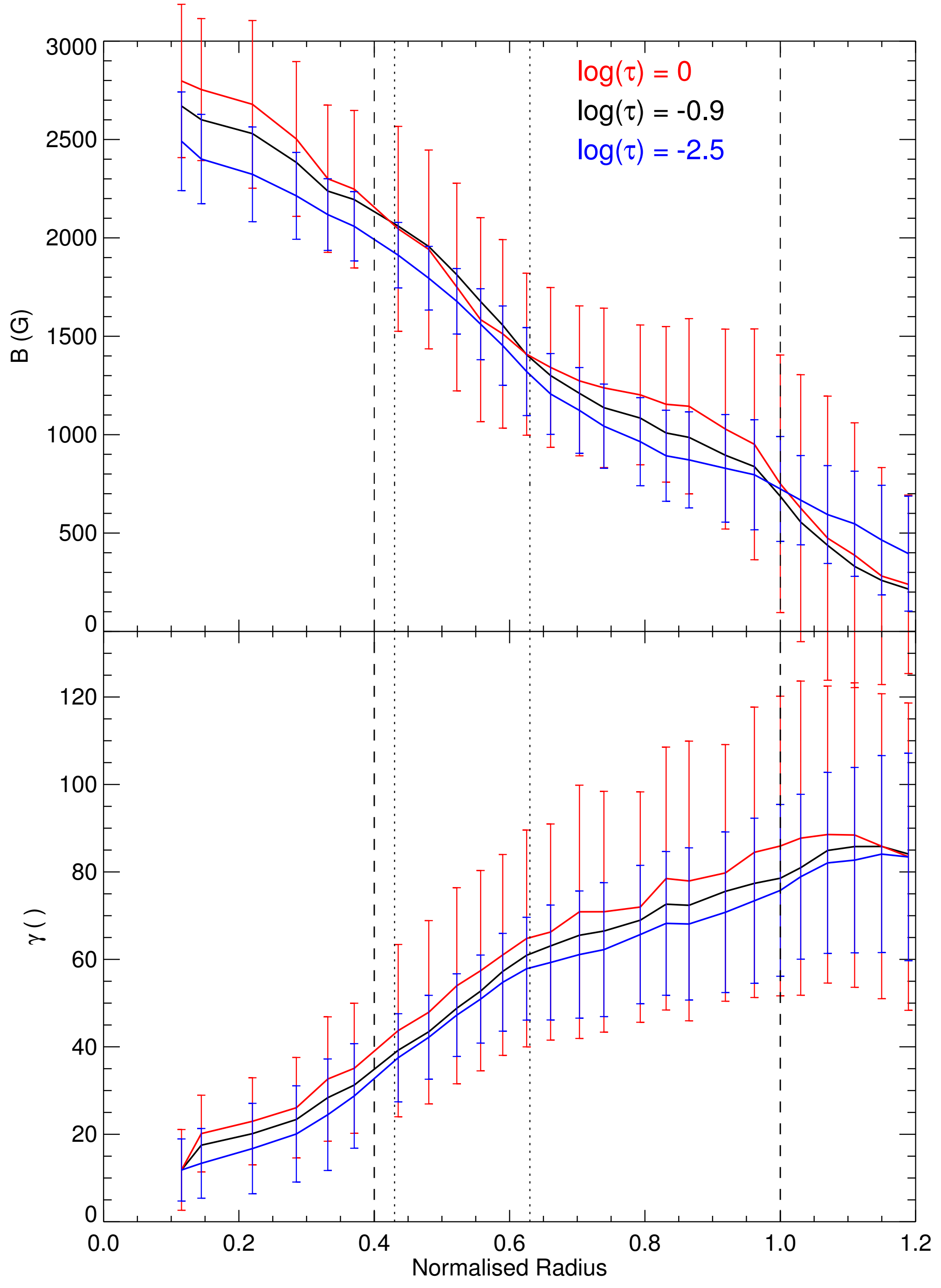
Thermal properties:



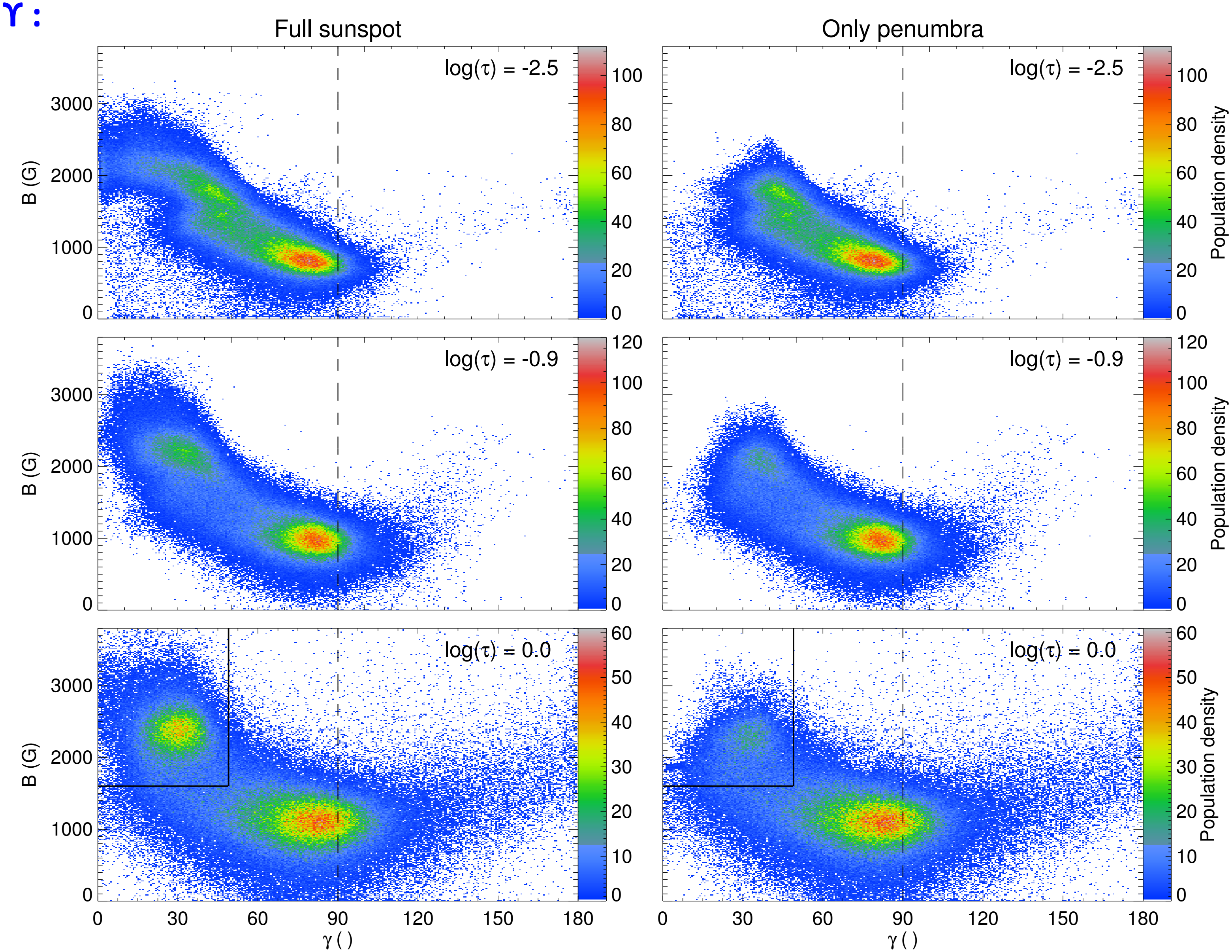
LOS velocity:



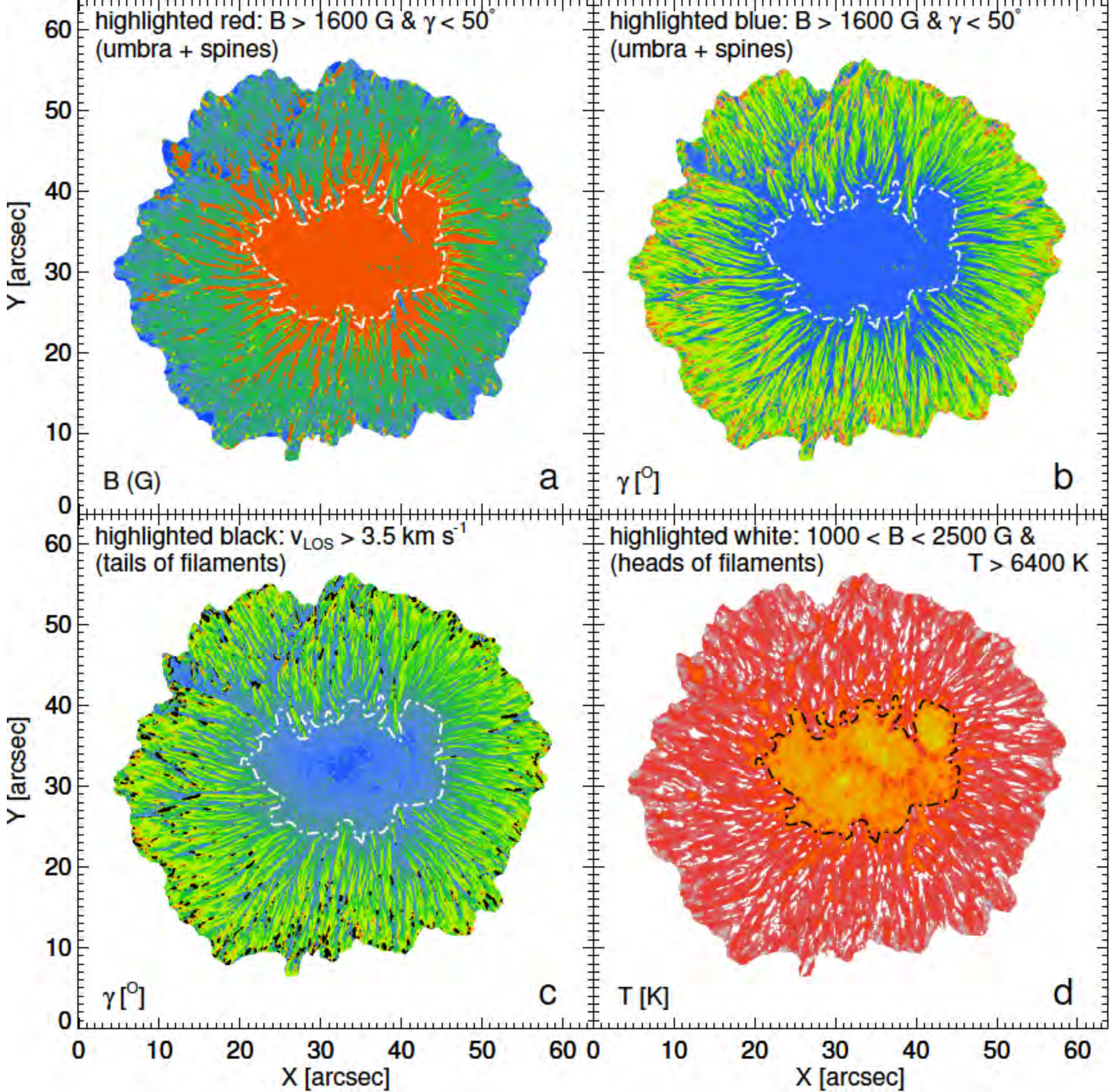
Magnetic properties:



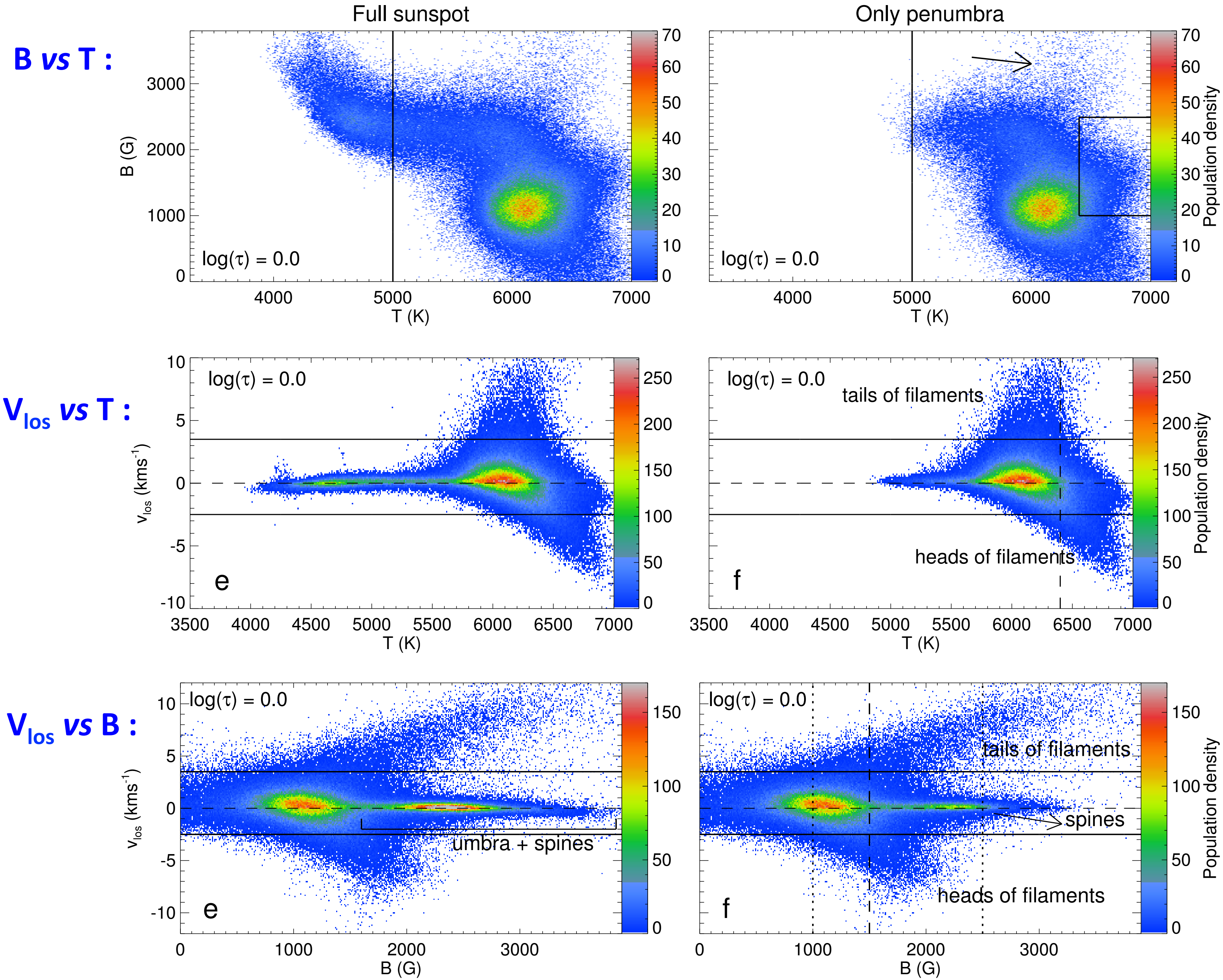
B *vs* ϒ :



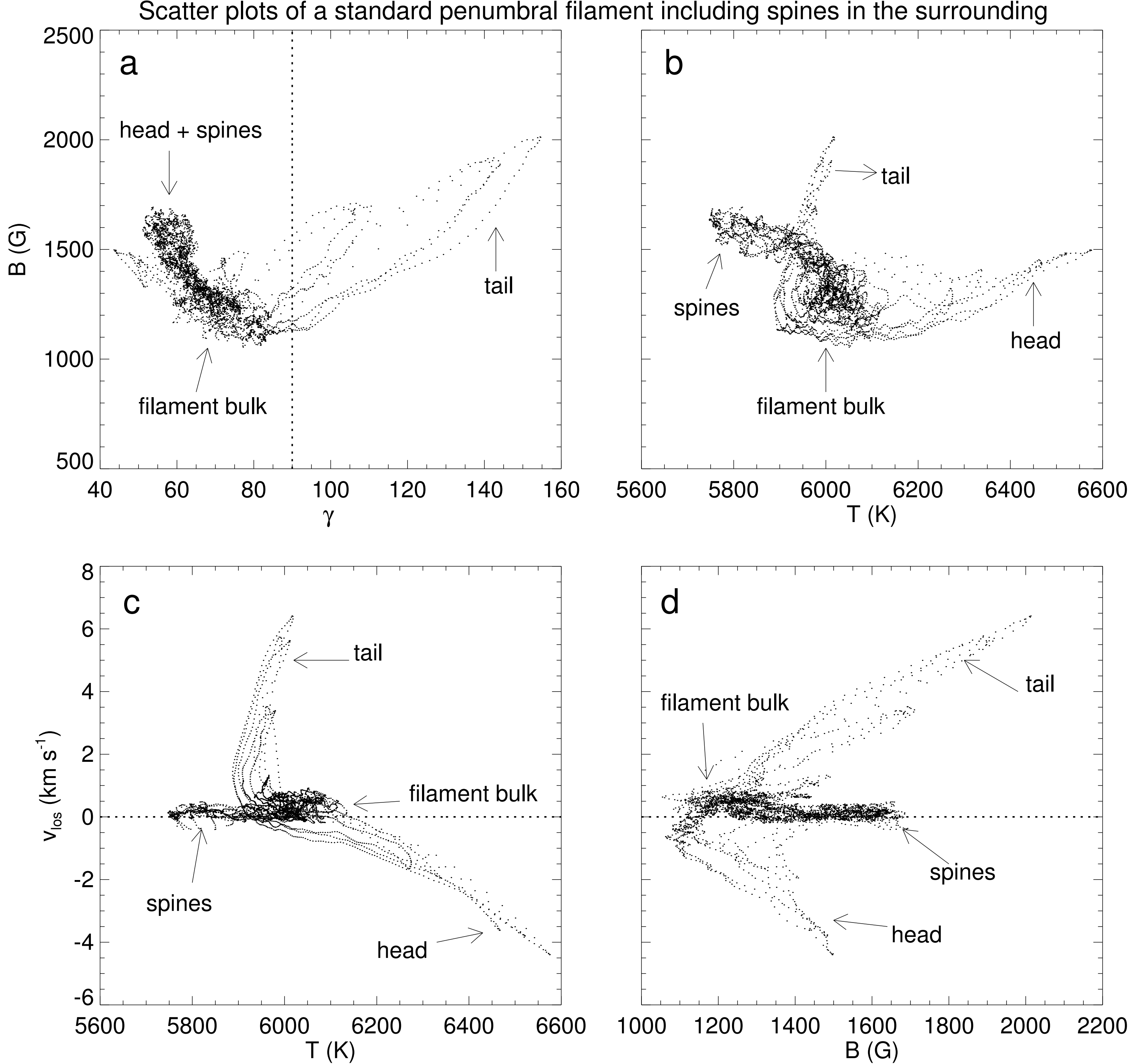
Full sunspot
Only penumbra
log(τ) = -2.5
log(τ) = -0.9
log(τ) = 0.0
B (G)
γ ( )
Population density
0
1000
2000
3000
0
30
60
90
120
150
180



highlighted red: B > 1600 G & γ < 50°
(umbra + spines)
B (G)
a
highlighted blue: B > 1600 G & γ < 50°
(umbra + spines)
γ [°]
b
highlighted black: v_LOS > 3.5 km s^-1
(tails of filaments)
γ [°]
c
highlighted white: 1000 < B < 2500 G &
(heads of filaments)
T > 6400 K
T [K]
d
Y [arcsec]
X [arcsec]
0
10
20
30
40
50
60



Full sunspot
Only penumbra
B vs T :
V$_{los}$ vs T :
V$_{los}$ vs B :
B (G)
T (K)
log(τ) = 0.0
Population density
v$_{los}$ (kms^{-1})
tails of filaments
heads of filaments
umbra + spines
spines
e
f
B (G)



Scatter plots of a standard penumbral filament including spines in the surrounding
a
head + spines
filament bulk
tail
B (G)
γ
b
tail
spines
filament bulk
head
T (K)
c
tail
filament bulk
spines
head
v_{los} (km s^{-1})
T (K)
d
filament bulk
tail
spines
head
B (G)

Conclusions

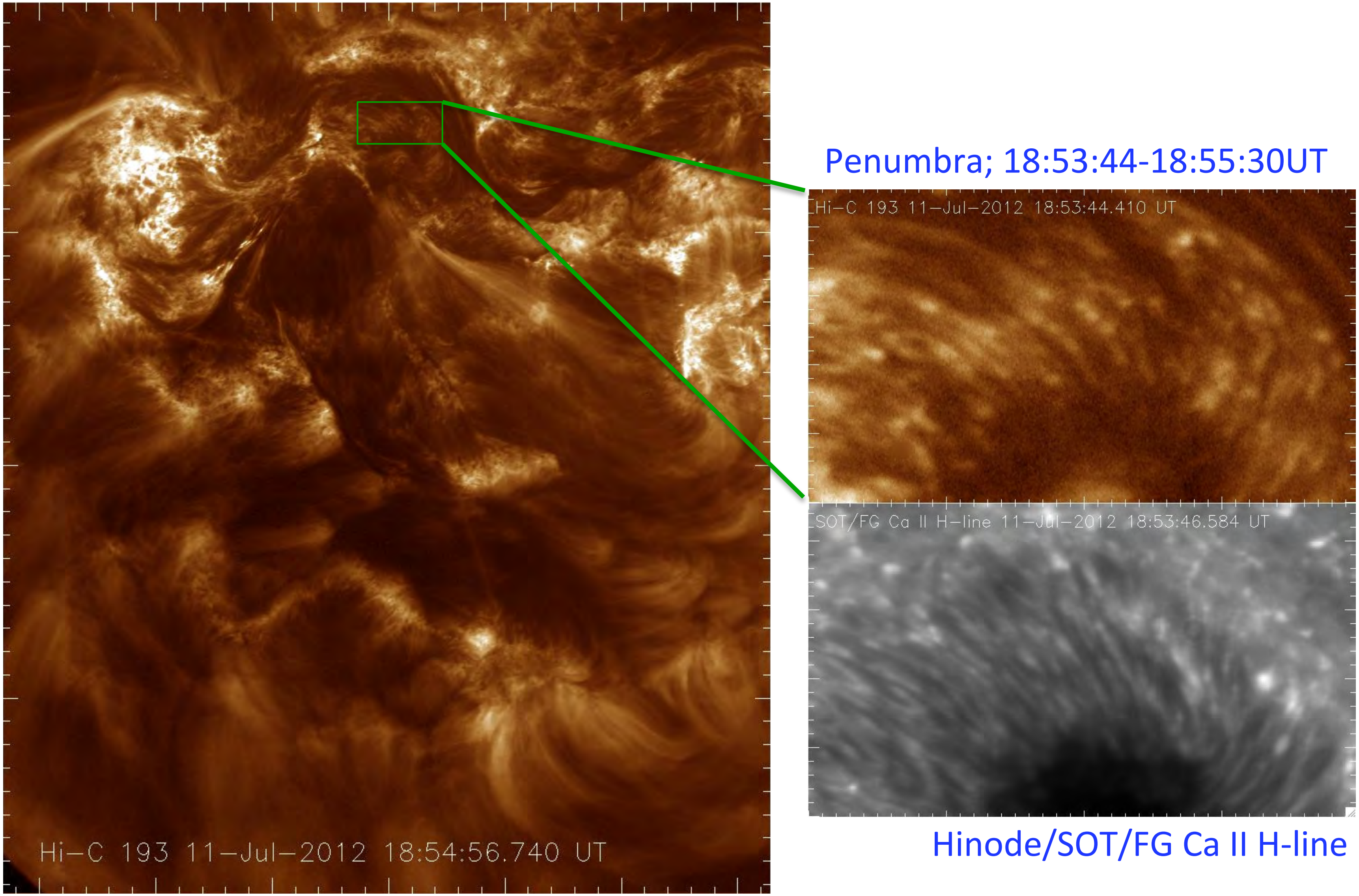
- Clear evidence of convection in penumbral filaments: both in lateral and radial directions
- Evershed flow: source at filament head, sink at tail, cools during travel at bulk; clearly magnetised@1kG; driver?
- Combines aspects of both the penumbral models: flux-tube & field-free gap
- Spines are outward extension of umbra
- Spines + filaments = penumbra

Long-standing controversies (see review by Solanki, 2003)

- Evershed flow: bright/dark; strong/weak field strength
- Spine/inter-spine: bright/dark; vertical/inclined, strong/weak field; structure of penumbral grains

Dynamic Events: Bright penumbral dots and penumbral microjets

Hi-C 193 Å



Penumbra; 18:53:44-18:55:30UT

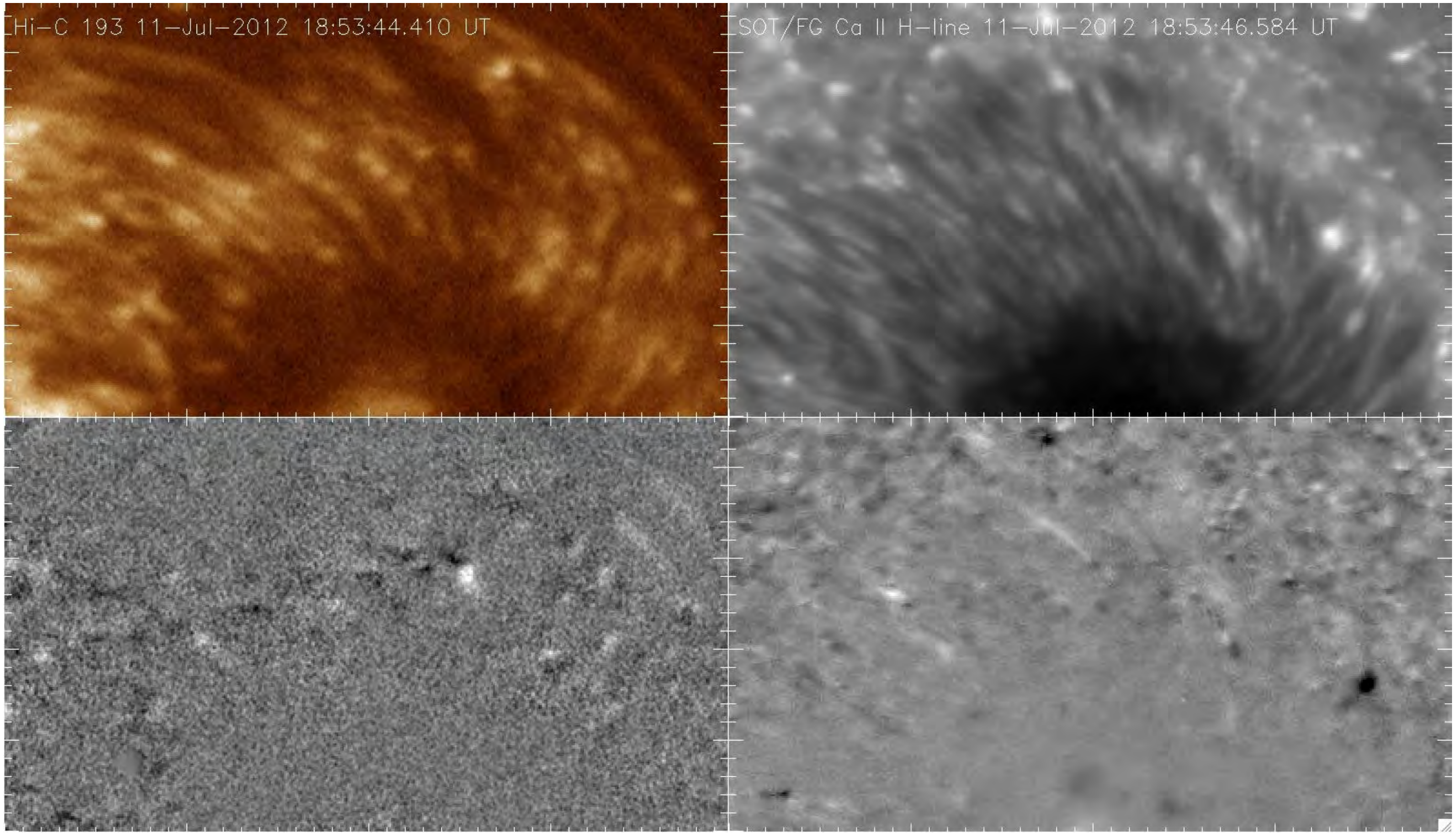
Hinode/SOT/FG Ca II H-line

Tiwari, Moore, Winebarger, Alpert, 2015, *ApJ*, under review

Bright penumbral dots and penumbral microjets

Hi-C 193 Å

SOT/FG Ca II H-line

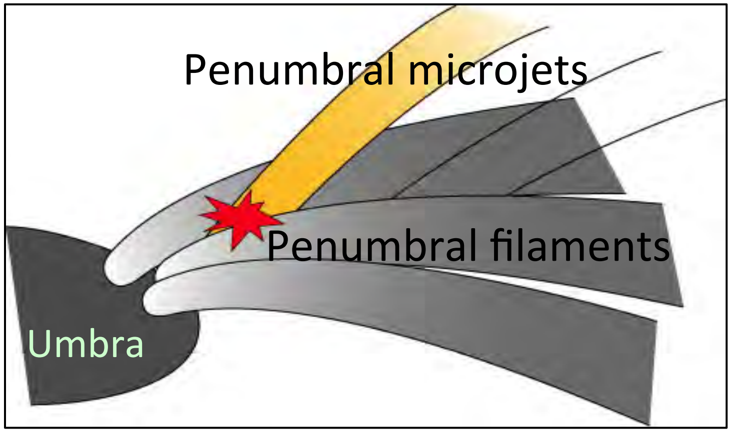


Lower frames are running differences

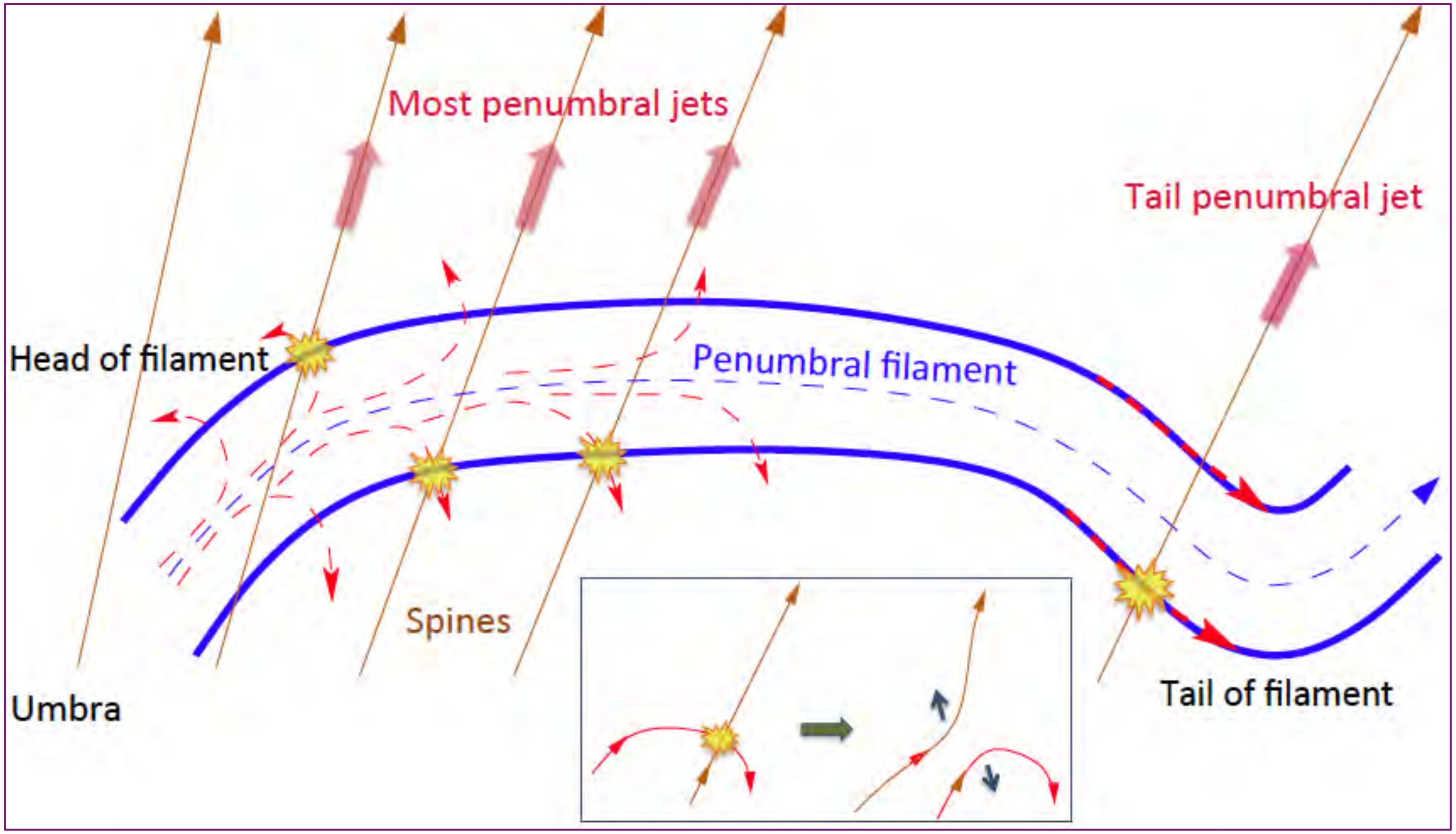
BDs: Alpert, Tiwari, Moore, Winebarger, Savage, 2015, *ApJ Letters*, to be submitted

Jet's origin: magnetic configuration

Katsukawa et al., 2007, *Science*



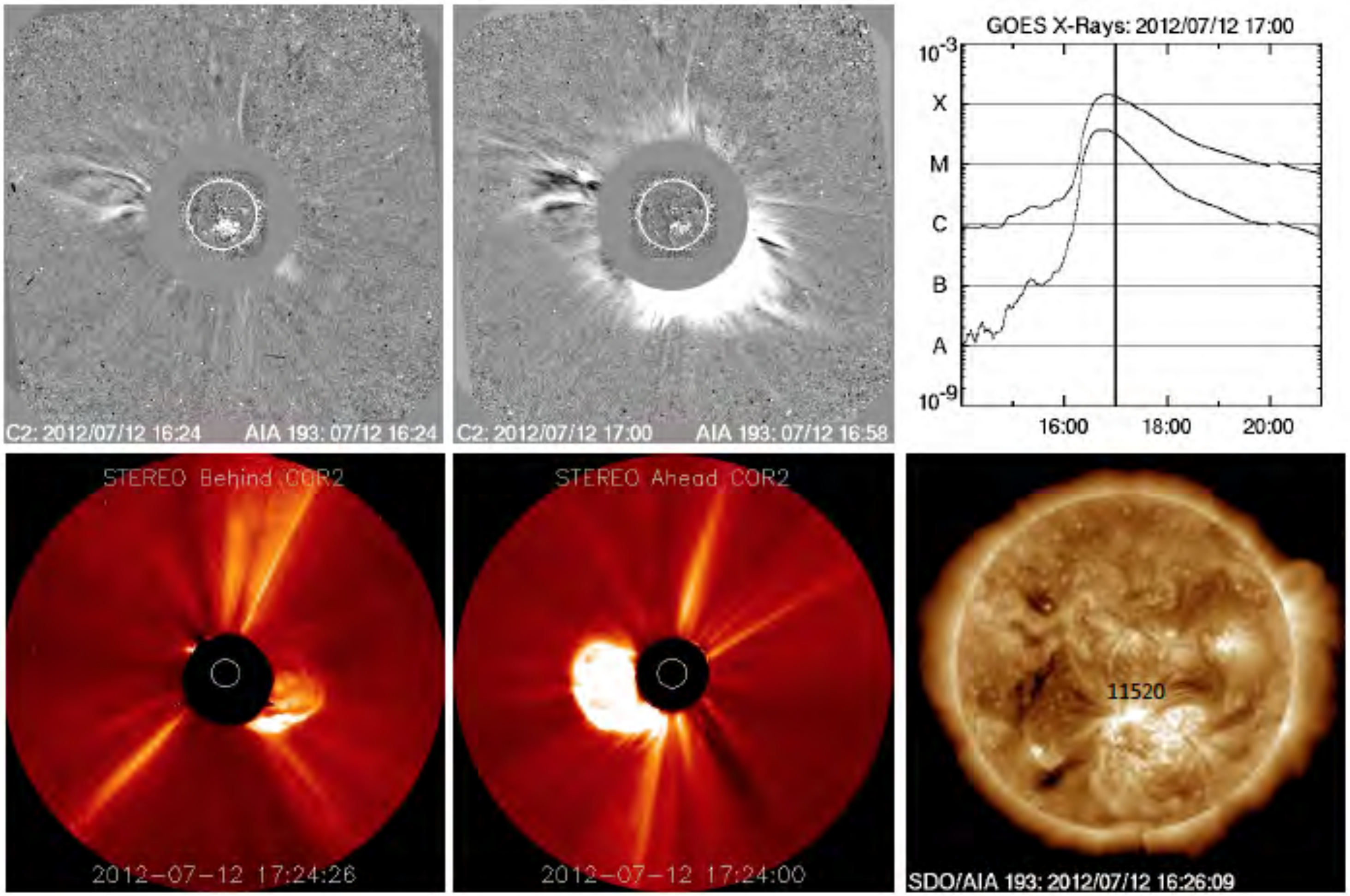
Tiwari et al., 2015, *ApJ, under review*



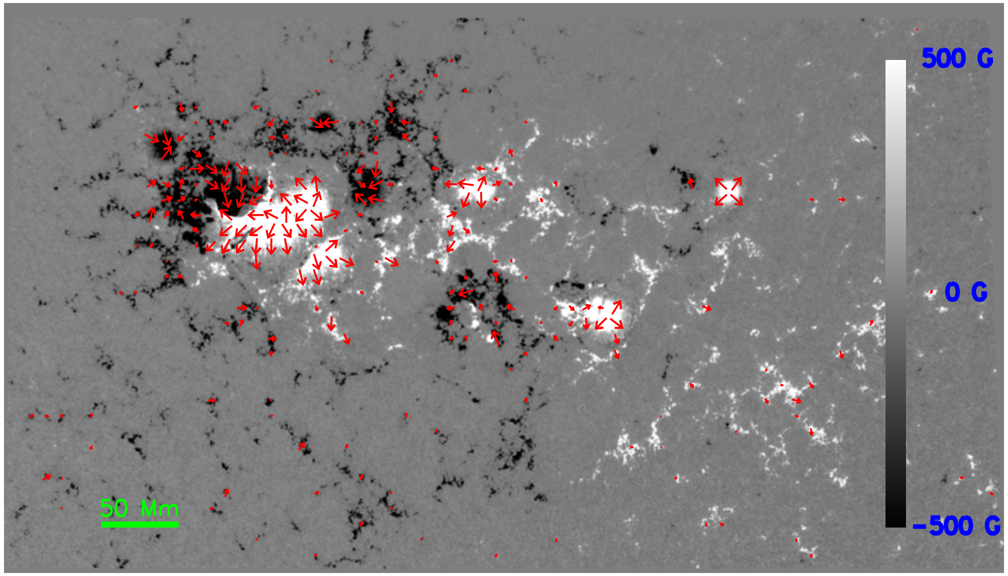
Speed of CMEs vs Magnetic Nonpotentiality of their source ARs

(Tiwari et al. 2015, *GRL*)

Data & Selection procedure



Vector magnetograms: HMI AR Patch

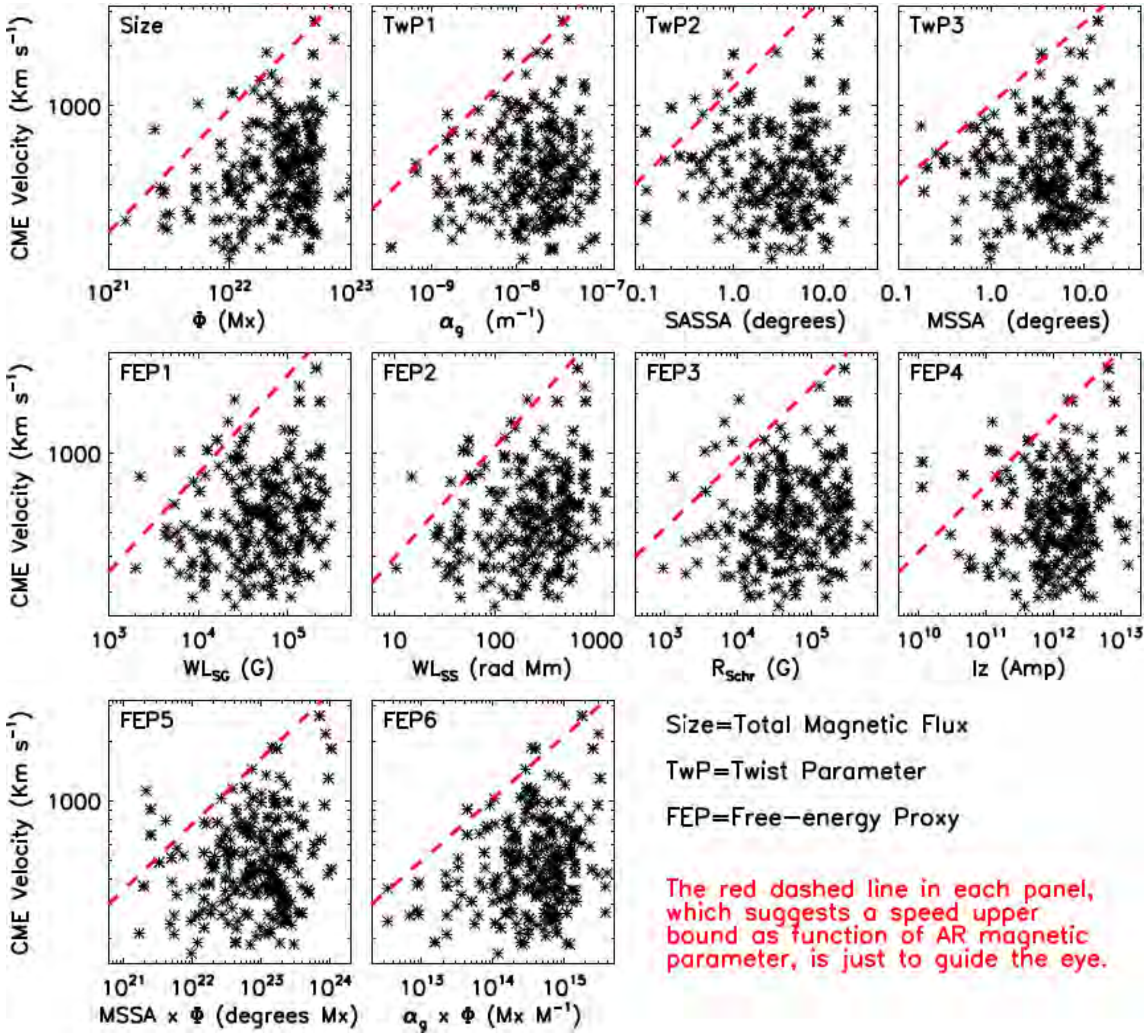


An example deprojected HARP-tile vector magnetogram containing NOAA AR 11520

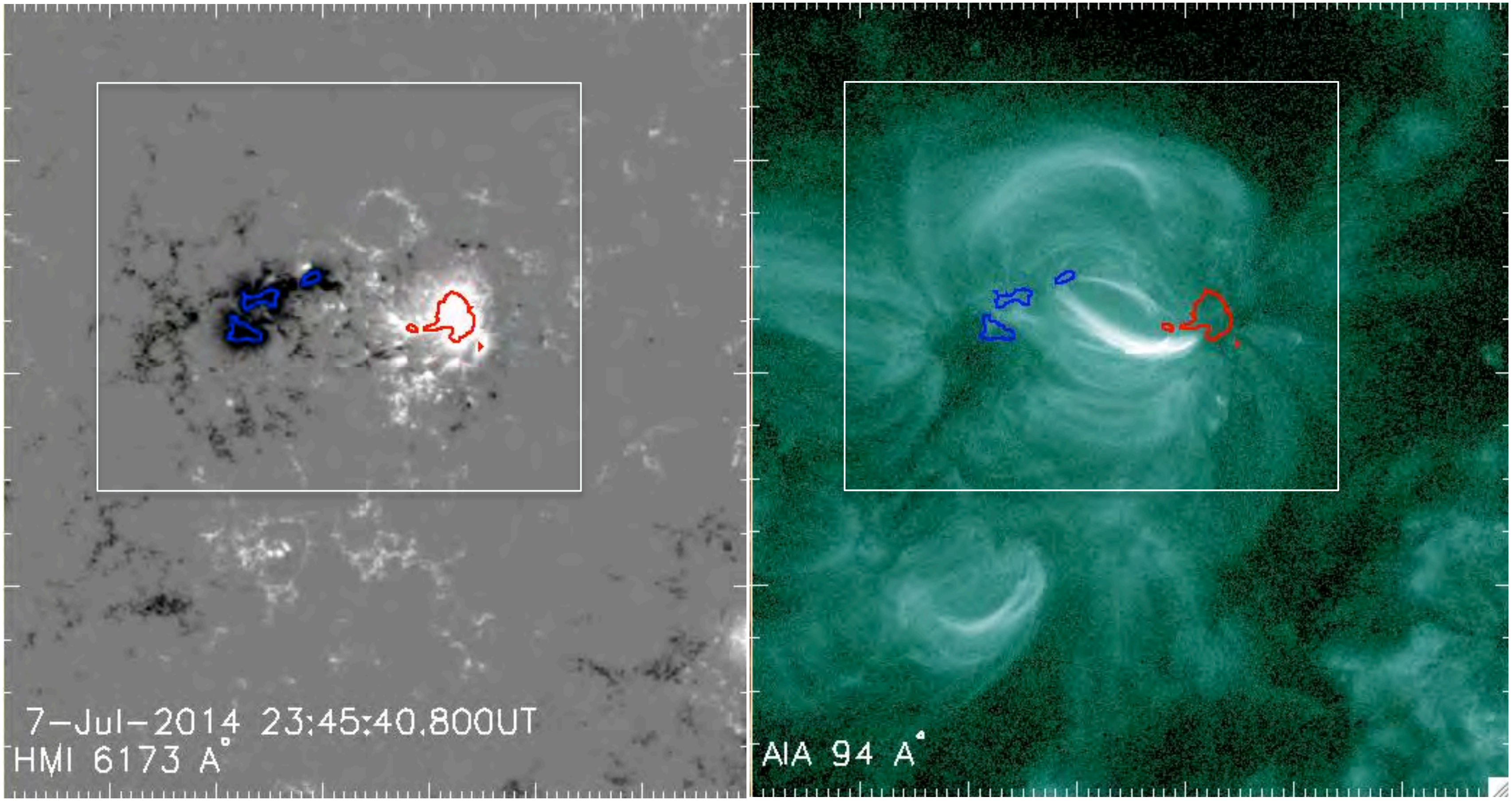
CME speed from LASCO CME catalog

http://cdaw.gsfc.nasa.gov/CME_list/

Results: CME speed vs Magnetic Parameters

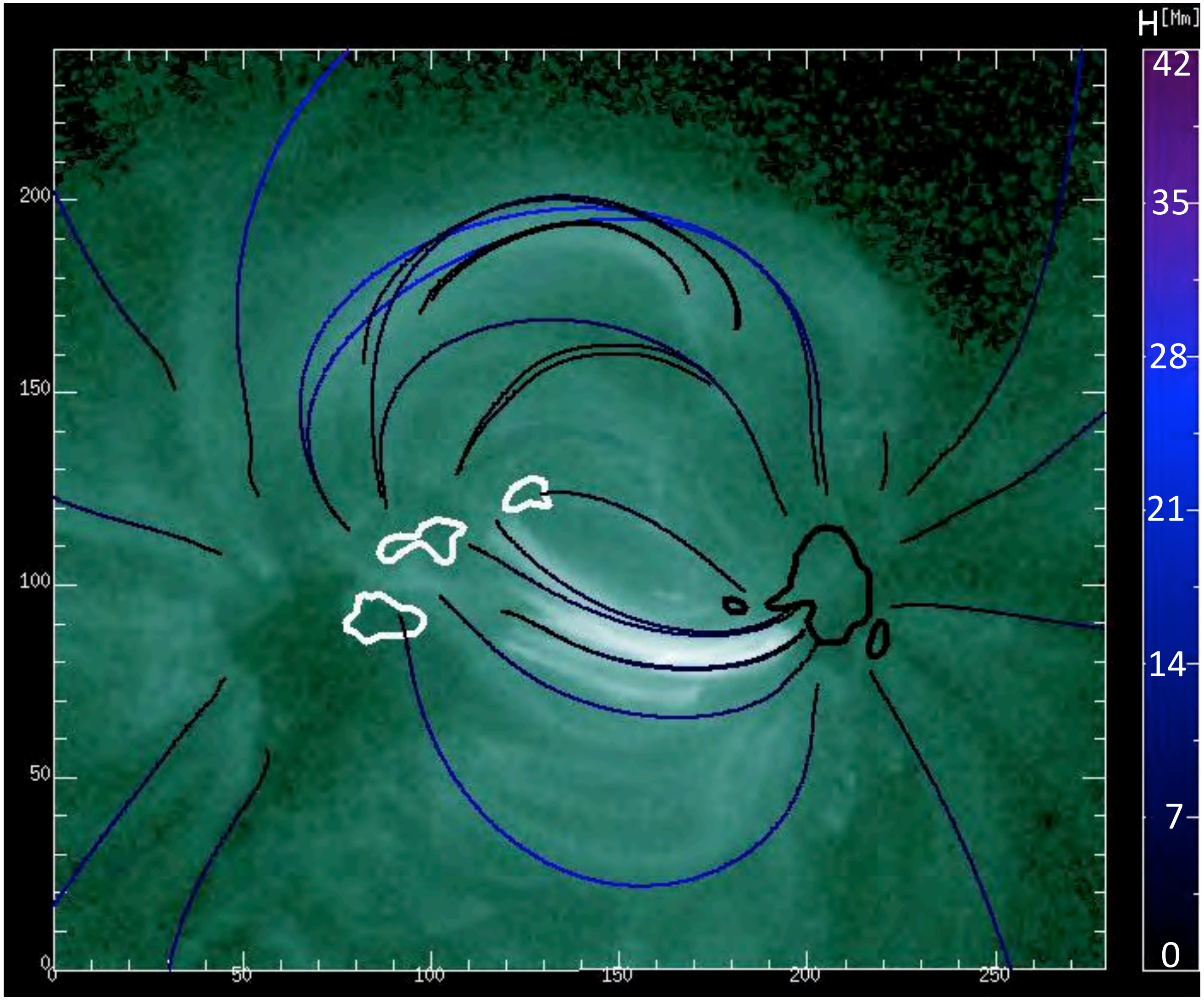


Heating of Coronal Loops Rooted in Opposite Polarity Sunspot Umbrae

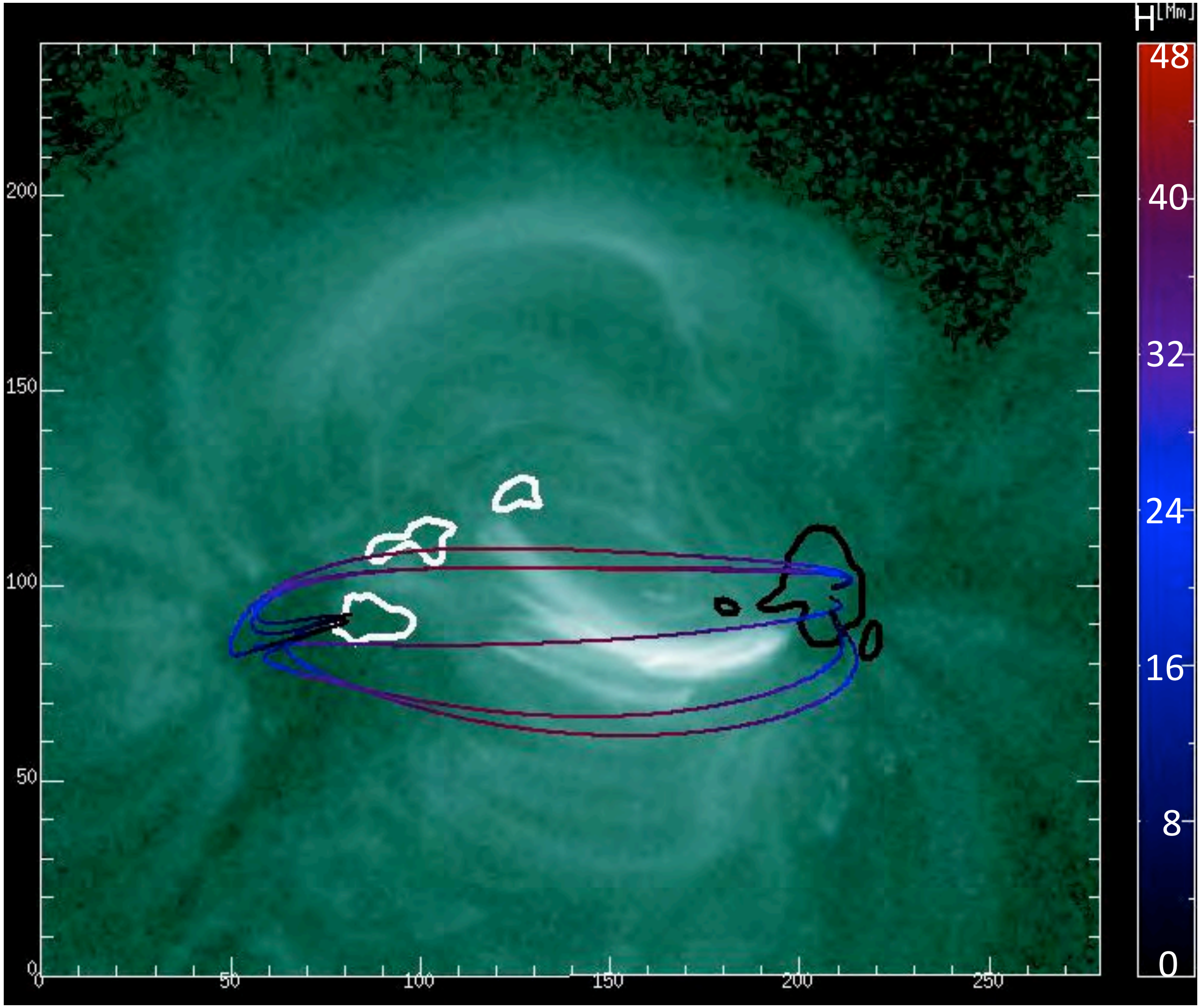


FOV selected for the NLFFF extrapolation

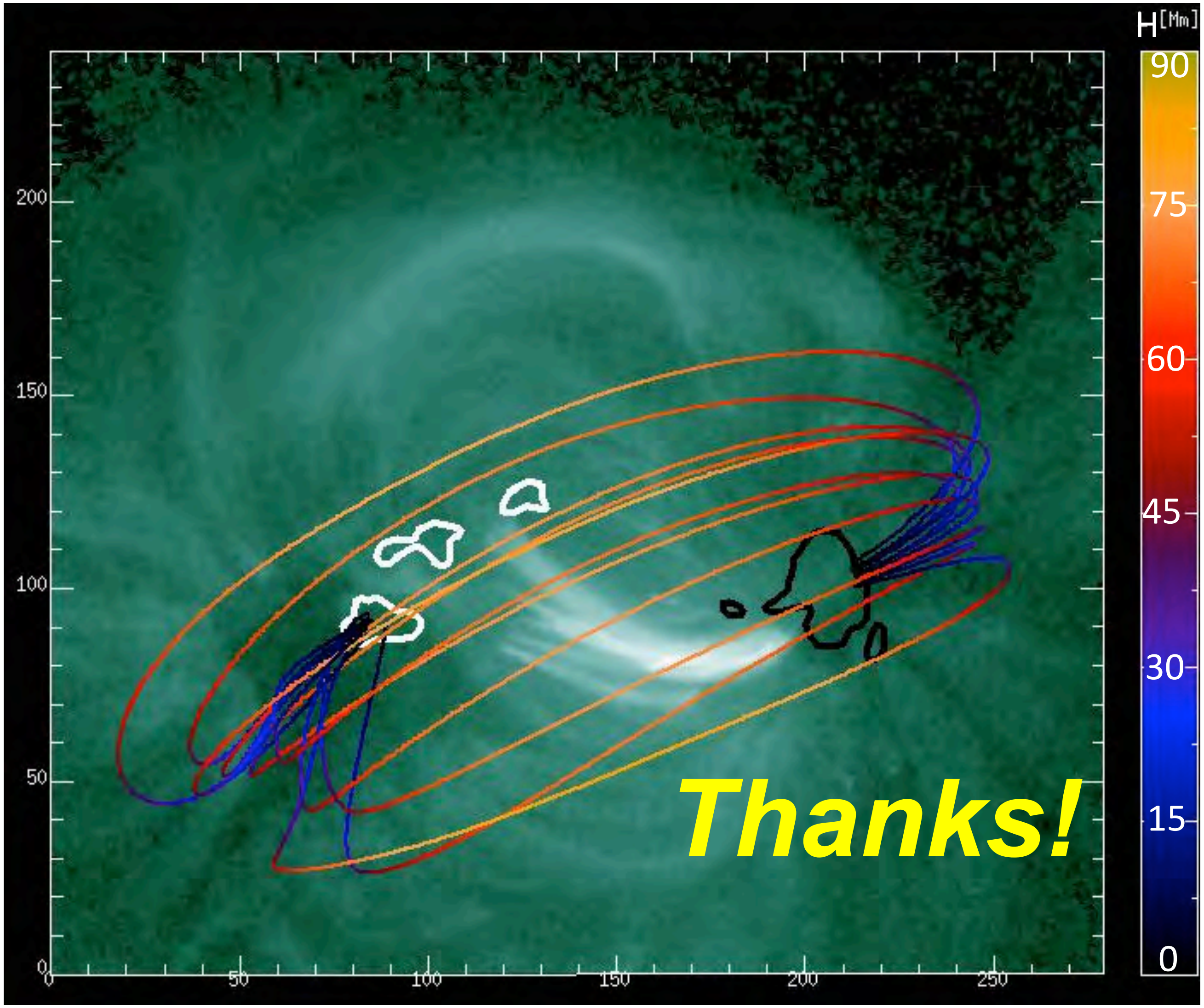
NLFF model field lines



Modeling results: lower umbral loops



Modeling results: high umbral loops



Our hypothesis: Magnetic field strength together with the convective freedom at the feet of the loops determines their coronal temperature