Unresolved magnetic field in the solar photosphere

Mykola Gordovskyy
`mykola.gordovskyy@manchester.ac.uk`

with Sergiy Shelyag (Northumbria-Newcastle), Vsevolod Lozitsky (Kiev), Philippa Browning (Manchester)

Solar flares / Ioffe webinar, 14 Nov 2018

Outline

- Brief introduction
  - what am I talking about?
  - how do we know?
  - why do we care?
- Small-scale field diagnostics in relatively quiet regions
- Small-scale field diagnostics in the flaring photosphere
- Summary

Outline

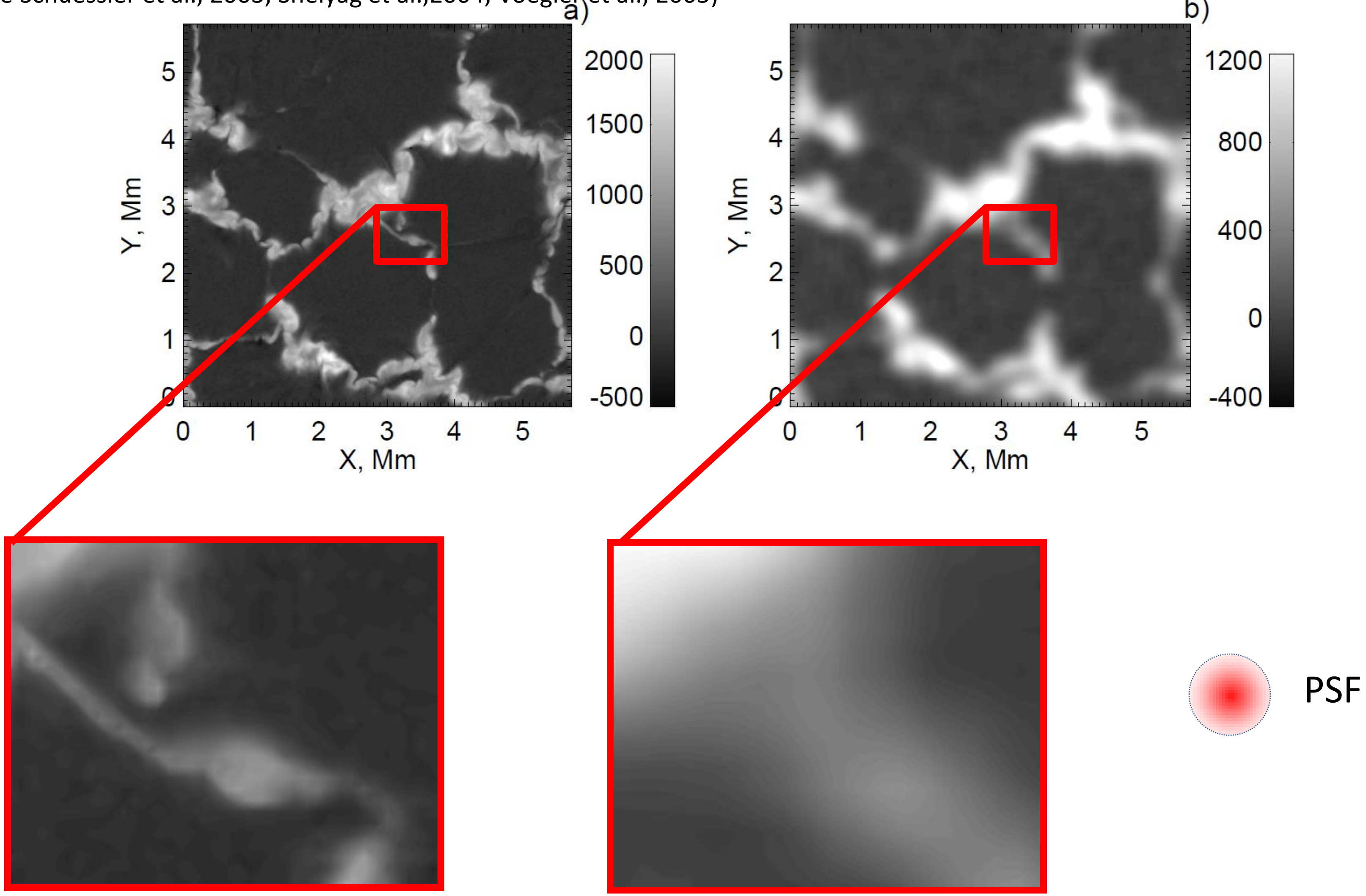
Important papers:

- *Solanki (1993, SSRv, 63, 1)* – for review
- *Voegler, Shelyag, Shuessler et al. (2005, A&A, 429, 335)* – MHD simulations
- *Khomenko & Collados (2007, ApJ, 659, 1726)* – MLR callibration
- ***Gordovskyy & Lozitsky (2014, Solar Phys, 289, 3681)*** **– two-component structure in flares**
- *Smitha & Solanki (2017, A&A, 608, A111*) – comparison of MLR for different pairs using MHD simulations of magnetoconvection
- ***Gordovskyy, Shelyag, Browning & Lozitsky (2018, A&A, accepted) – comparison of MLR, SVW and "stat" methods for 6301/6302***

Some background…

⇒We normally measure magnetic flux

Magneto-convection models of the photosphere developed using MURAM code
(see Schuessler et al., 2003, Shelyag et al.,2004, Voegler et al., 2005)



Some background…

⇒We normally measure magnetic flux

Magneto-convection models of the photosphere developed using MURAM code (see Schuessler et al., 2003, Shelyag et al.,2004, Voegler et al., 2005)

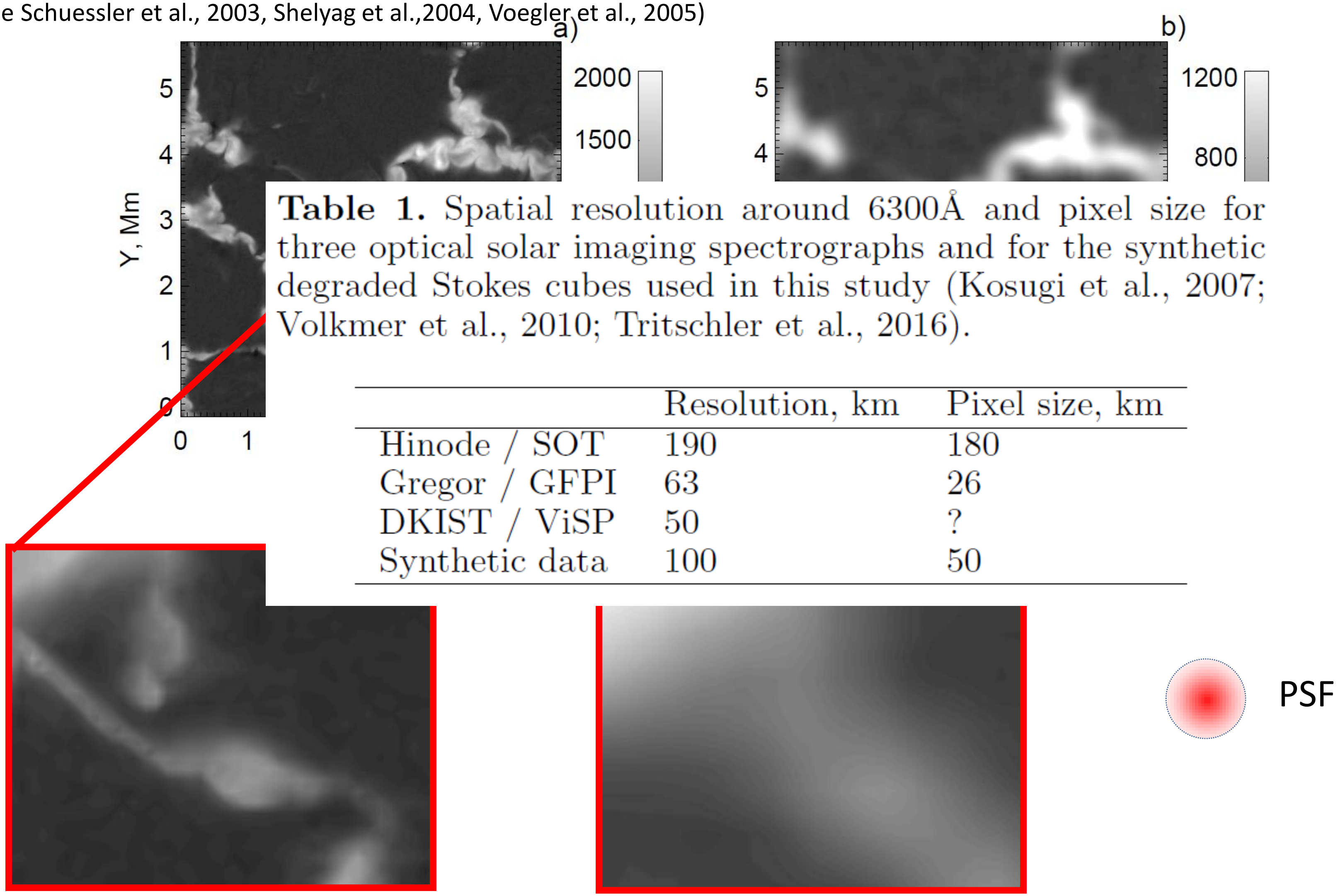
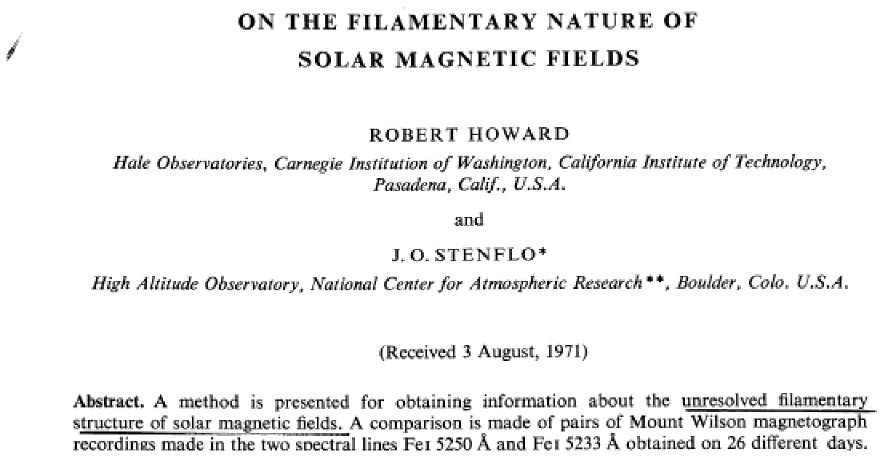


Table 1. Spatial resolution around 6300Å and pixel size for three optical solar imaging spectrographs and for the synthetic degraded Stokes cubes used in this study (Kosugi et al., 2007; Volkmer et al., 2010; Tritschler et al., 2016).

	Resolution, km	Pixel size, km
Hinode / SOT	190	180
Gregor / GFPI	63	26
DKIST / ViSP	50	?
Synthetic data	100	50

Some background…

⇒ In magnetographic measuremements based on Zeeman effect, observed magnetic field values depend on the magnetic sensitivity of a spectral lines, aka Lande factor g (*Stenflo 1970, Howard & Stenflo 1972*): <u>less sensitive lines yield higher field values</u>



ON THE FILAMENTARY NATURE OF SOLAR MAGNETIC FIELDS

ROBERT HOWARD

Hale Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena, Calif., U.S.A.

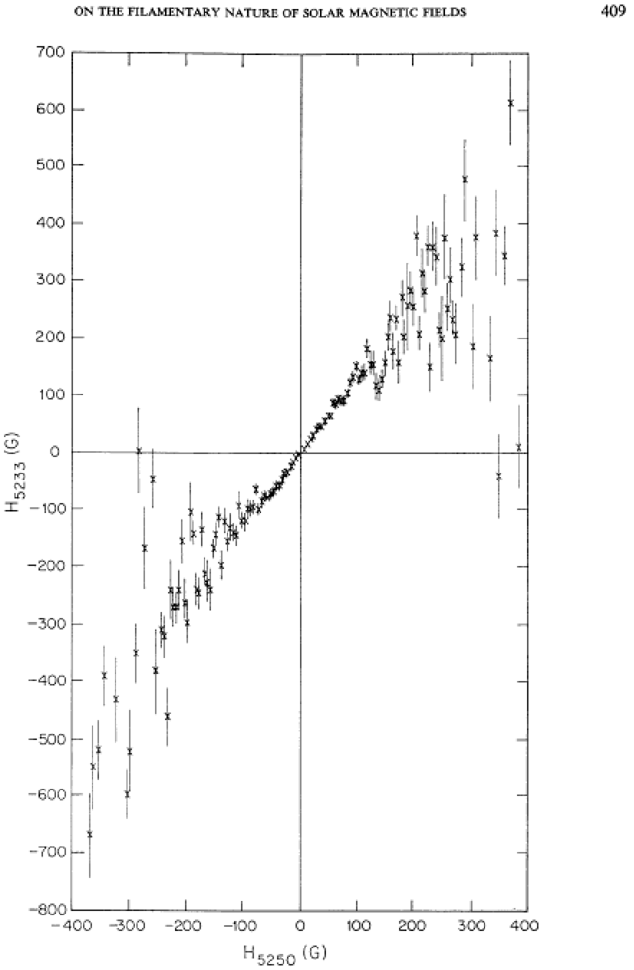
and

J. O. STENFLO*

*High Altitude Observatory, National Center for Atmospheric Research***, *Boulder, Colo. U.S.A.*

(Received 3 August, 1971)

Abstract. A method is presented for obtaining information about the unresolved filamentary structure of solar magnetic fields. A comparison is made of pairs of Mount Wilson magnetograph recordings made in the two spectral lines Fe I 5250 Å and Fe I 5233 Å obtained on 26 different days.



ON THE FILAMENTARY NATURE OF SOLAR MAGNETIC FIELDS 409

Some background…

⇒ Saturation in magnetographic measurements

M. Gordovskyy, V.G. Lozitsky

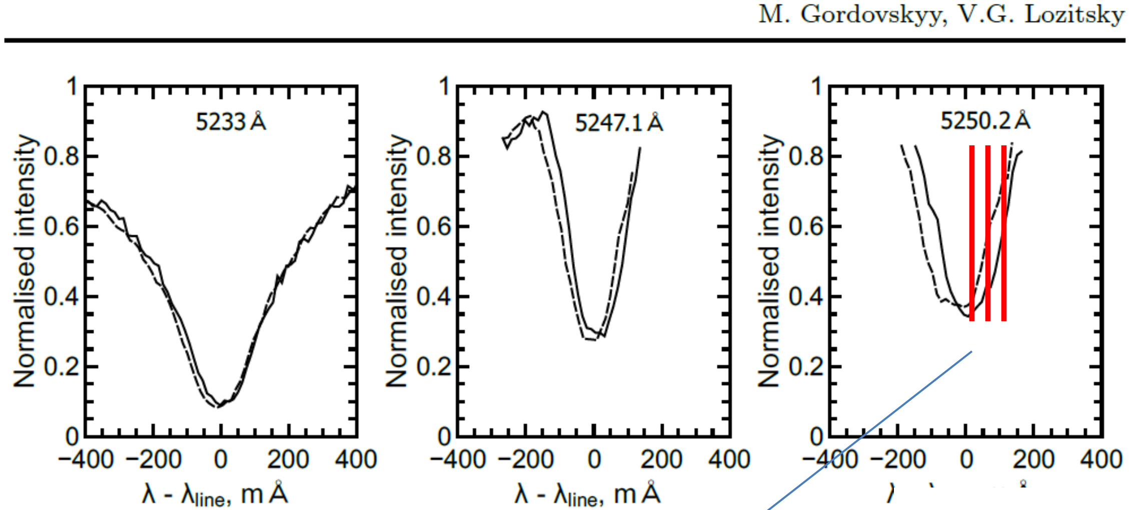
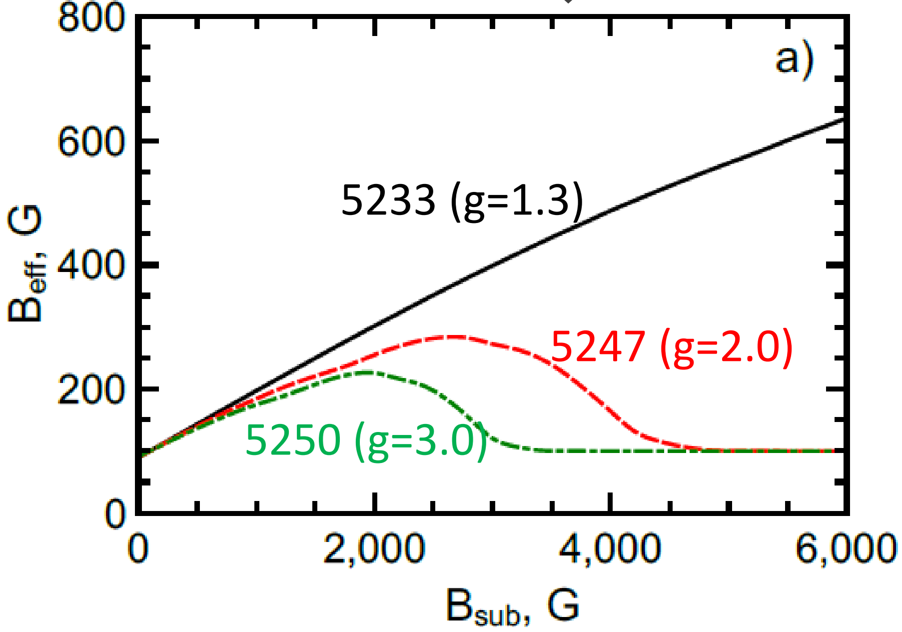


Figure 2. Typical $I + V$ (solid lines) and $I - V$ (dashed lines) Stokes profi (left panel), 5247.1 Å (middle panel), and 5250.2 Å (right panel) lines obse

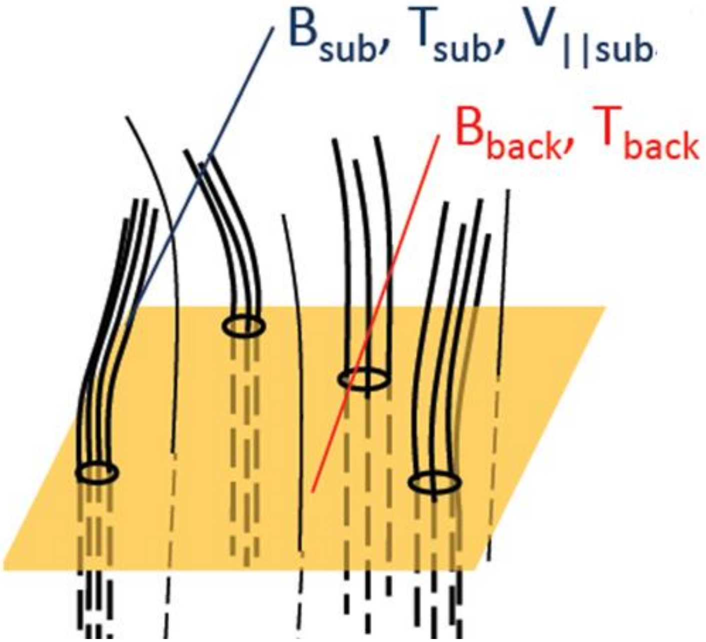
Zeeman splitting measured using centres-of-mass of σ-components in presence of strong field (B_{sub}) with small filling factor (10%) and ambient field of 200G

Difference between Stokes I+/-V (or Stokes V intensity) is measured in a line wing. When the field is very strong, so that Zeeman splitting is > line width, this signal decreases



Some background…

⇒ Magnetic field is very inhomogeneous at small scales, unresolved by most existing instruments



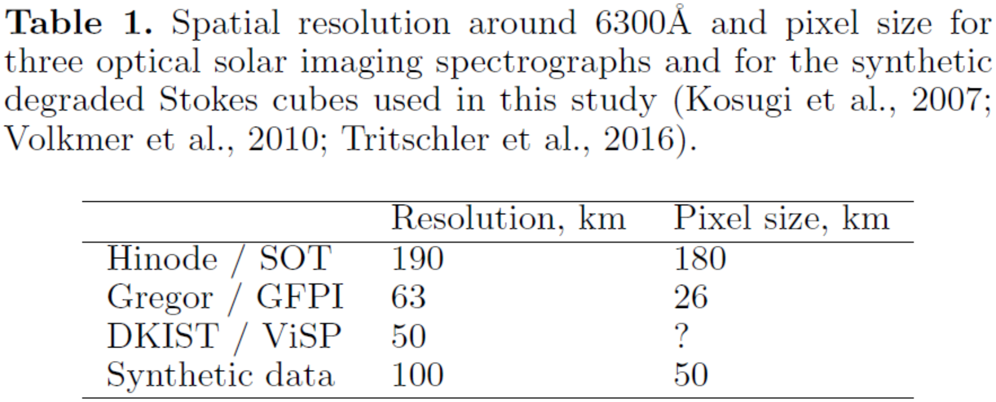


Table 1. Spatial resolution around 6300Å and pixel size for three optical solar imaging spectrographs and for the synthetic degraded Stokes cubes used in this study (Kosugi et al., 2007; Volkmer et al., 2010; Tritschler et al., 2016).

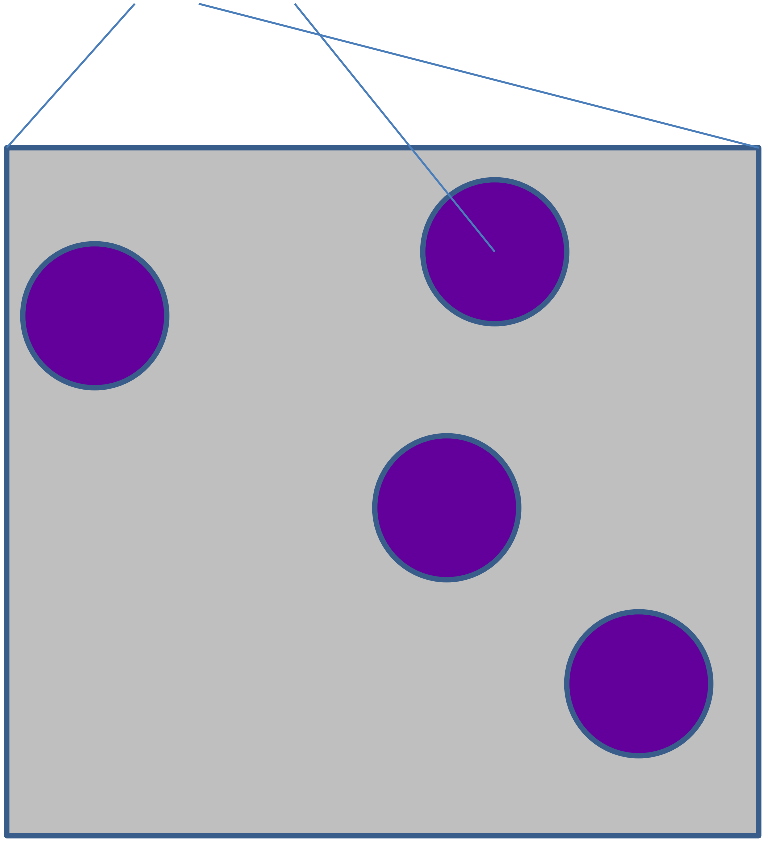
	Resolution, km	Pixel size, km
Hinode / SOT	190	180
Gregor / GFPI	63	26
DKIST / ViSP	50	?
Synthetic data	100	50

Terms and definitions

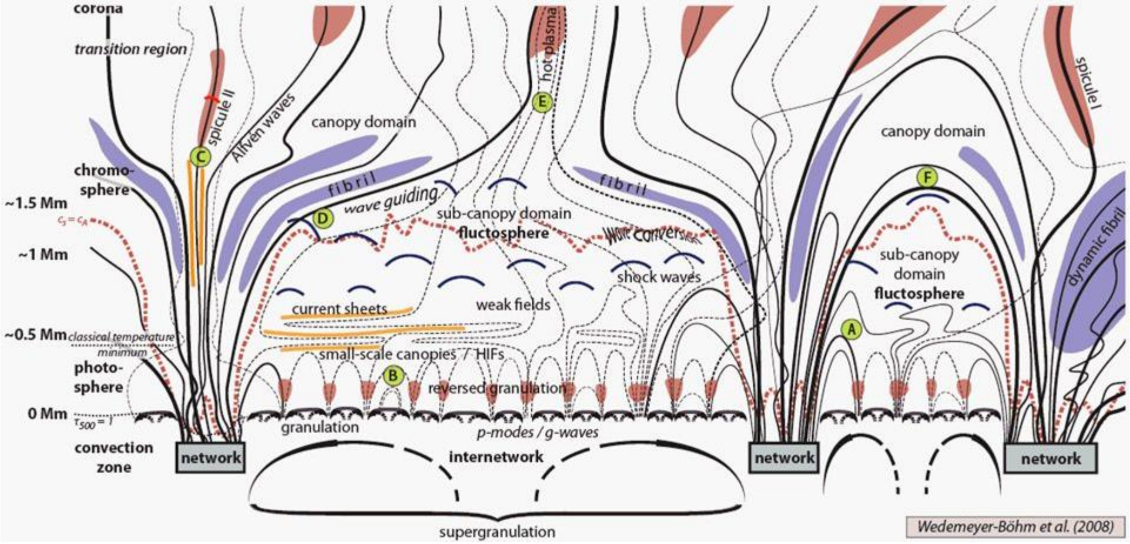
- This presentation is based on two papers, which used slightly different notations.
- If in doubt – please, ask! (mykola.gordovskyy@manchester.ac.uk)

Terms and definitions

- We measure B_{obs} (aka observed field, aka B_{eff})
- Intrinsic magnetic field strength B_{real} (aka real field, aka strong field, aka B_{sub})
- Filling factor $\alpha = B_{eff} / B_{real}$



Why is it important?



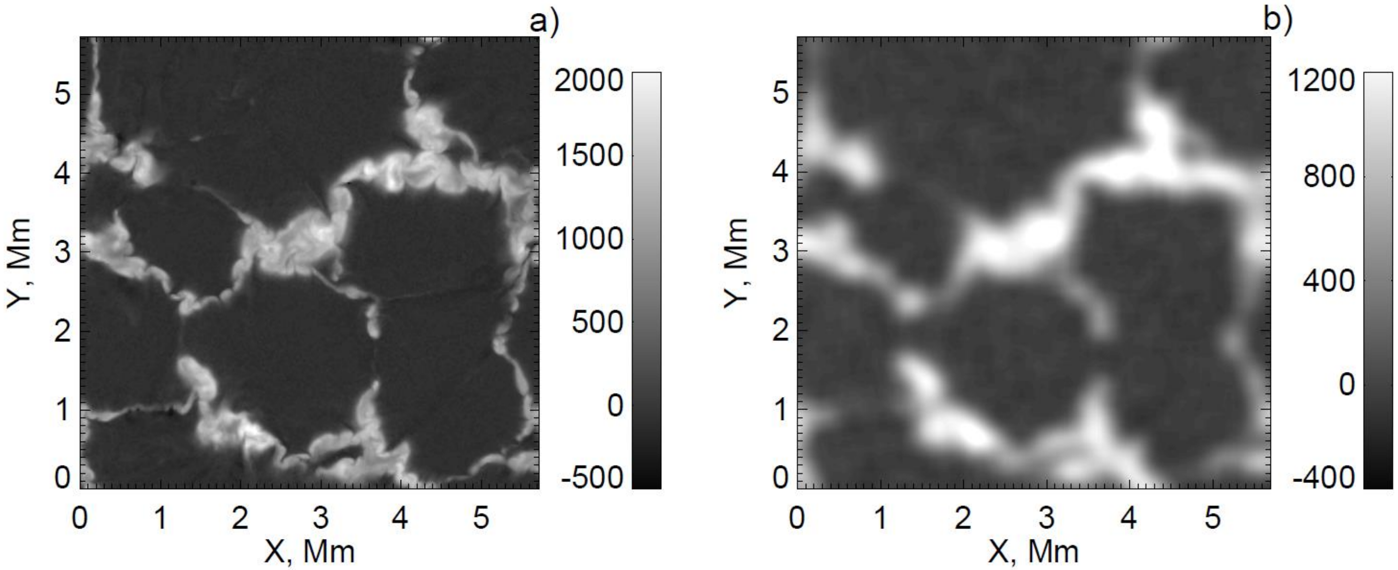
(Wedemeyer-Bohm et al., 2008)

- Coronal field reconstruction should be unaffected (not sensitive to small scales)
- Magnetic field energy density ~ Flux^2/α
- Characteristic timescale is ~L, hence ~$\sqrt{\alpha}$
- Currents ~1/L, hence ~1/$\sqrt{\alpha}$

Quiet photosphere

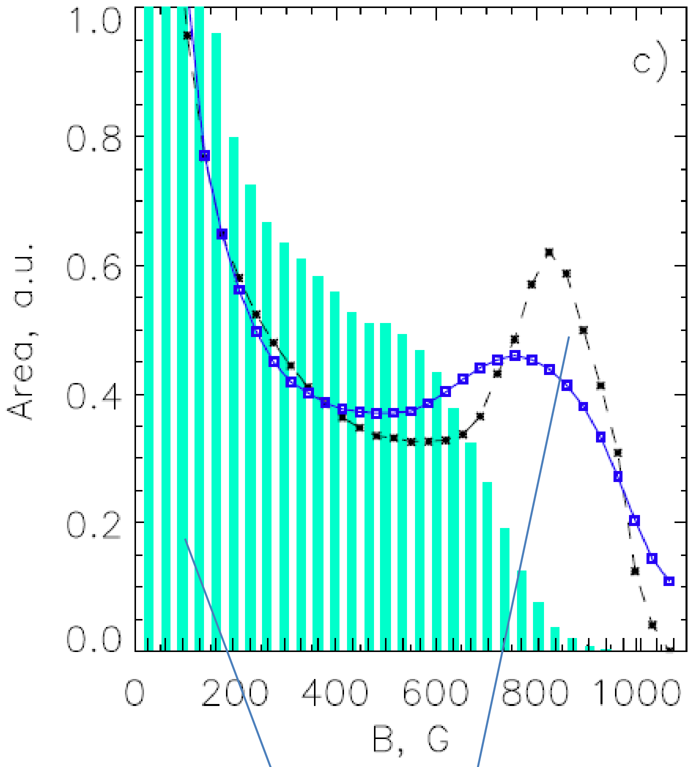
MHD simulations of magnetoconvection in the quiet photosphere using MURAM code (Schuessler et al., 2003, Shelyag et al.,2004, Voegler et al., 2005) performed by Sergiy Shelyag + radiative transfer simulations with NICOLE code (Socas-Navarro et al. 2000)

- Callibration for Stokes profiles of 6301/6302 lines using the radiative transfer simulations with NICOLE code



Quiet photosphere – “collapse”

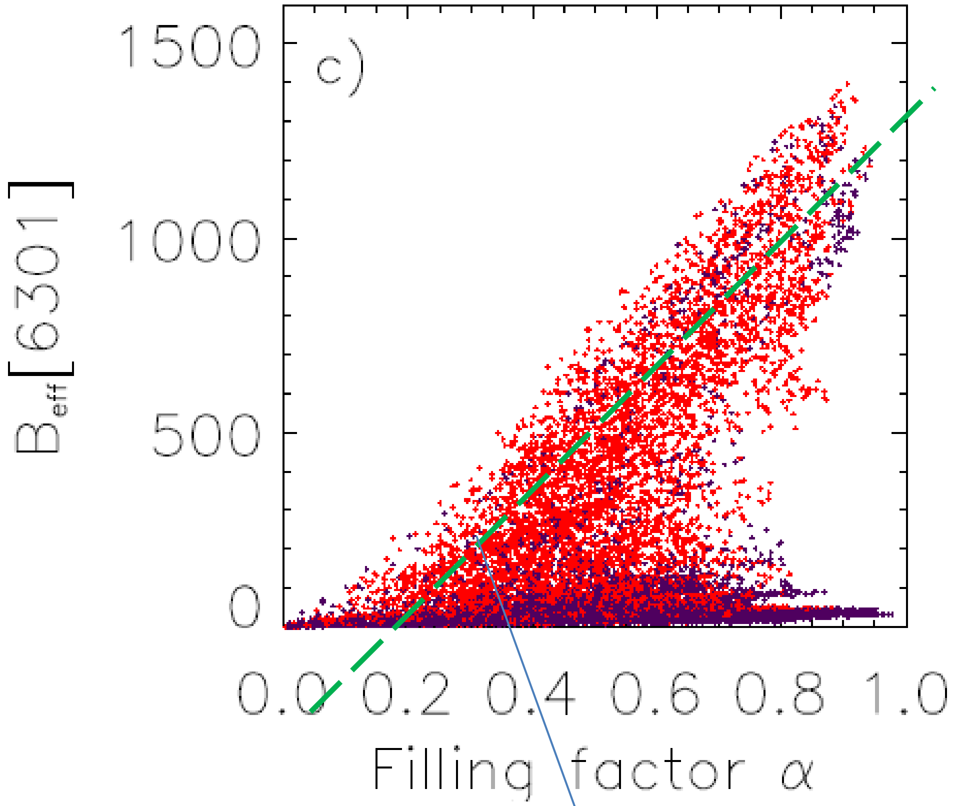
Histograms of B_{eff} from high-res simulations (line) + degraded field (bars)



High-res

Low-res

Effective (degraded to realistic spatial resolution) field v. actual filling factor

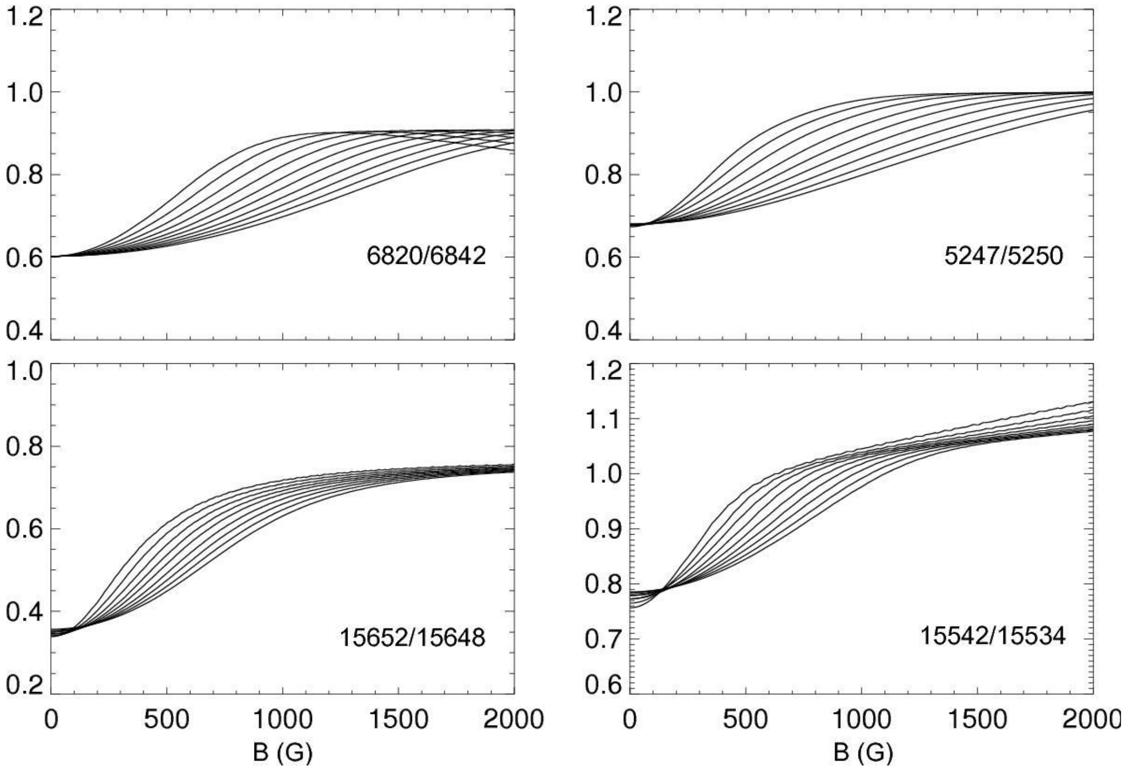


$B_{eff} = \alpha B_{real}$ - const

Quiet photosphere - MLR

- Magnetic line-ratio (MLR) is the most widely used method for the magnetic filling factor estimations

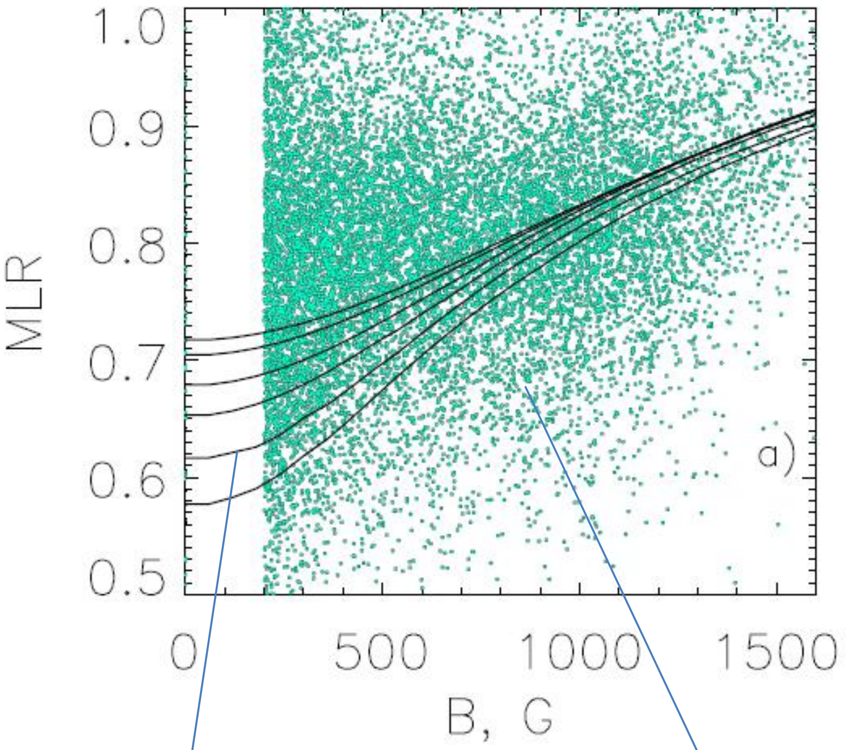
$$\mathrm{MLR} = B[\text{higher } g] \,/\, B[\text{lower } g]$$



Smitha & Solanki (2017, A&A, 608, A111)

Quiet photosphere – 6301/6302

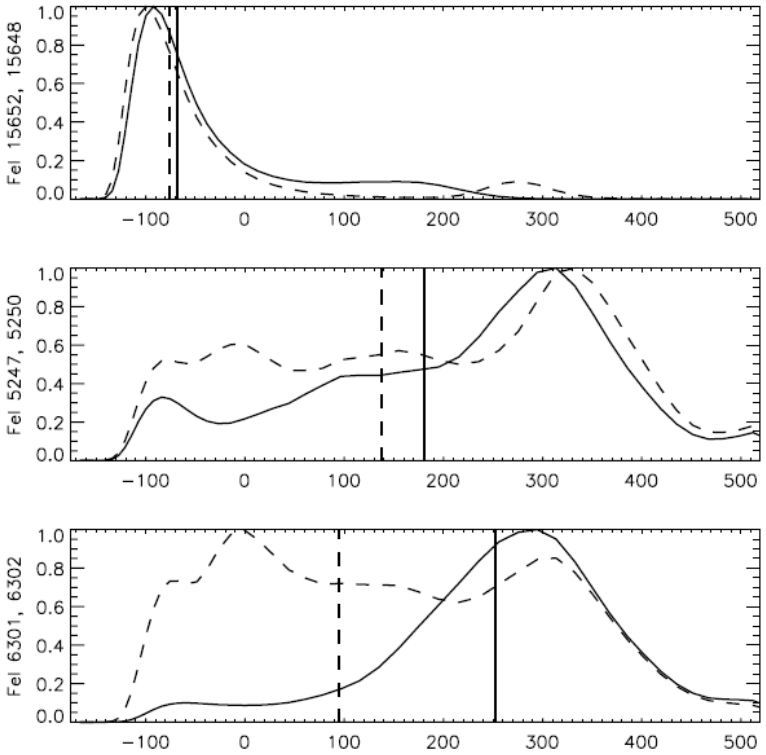
MLR with 6301/6302 pair



callibration

data from MHD MC

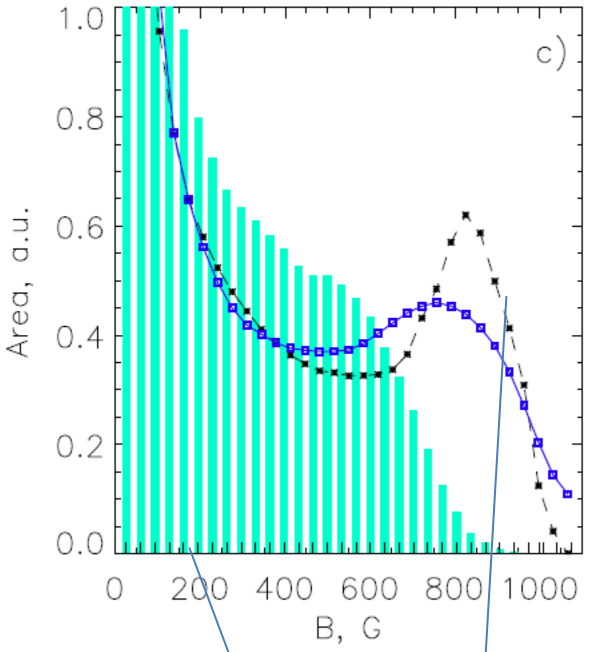
Contribution functions from Khomenko & Collados (2007)



Height, km

Quiet photosphere – Stokes V widths

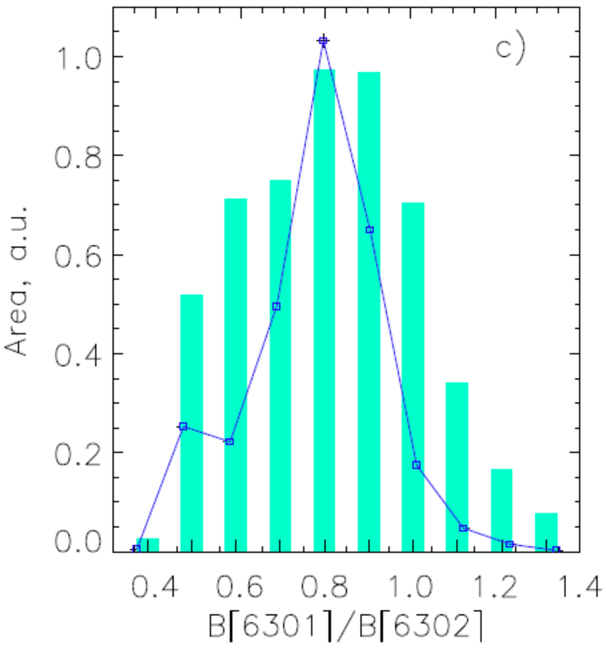
Histograms of B_{eff}



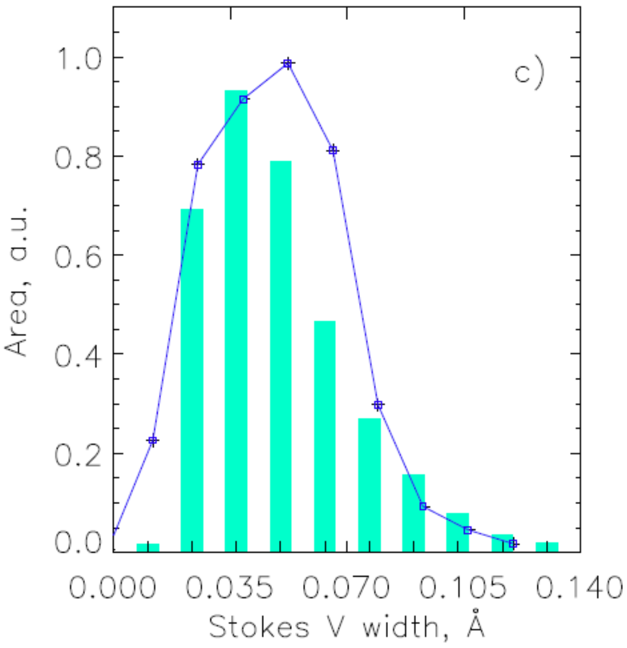
High-res

Low-res

Histograms of MLR

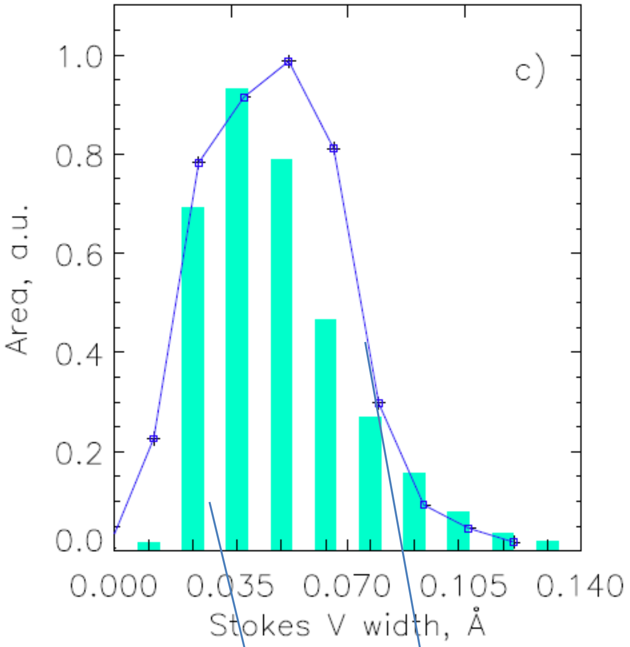


Histograms of SVW



Quiet photosphere – Stokes V widths

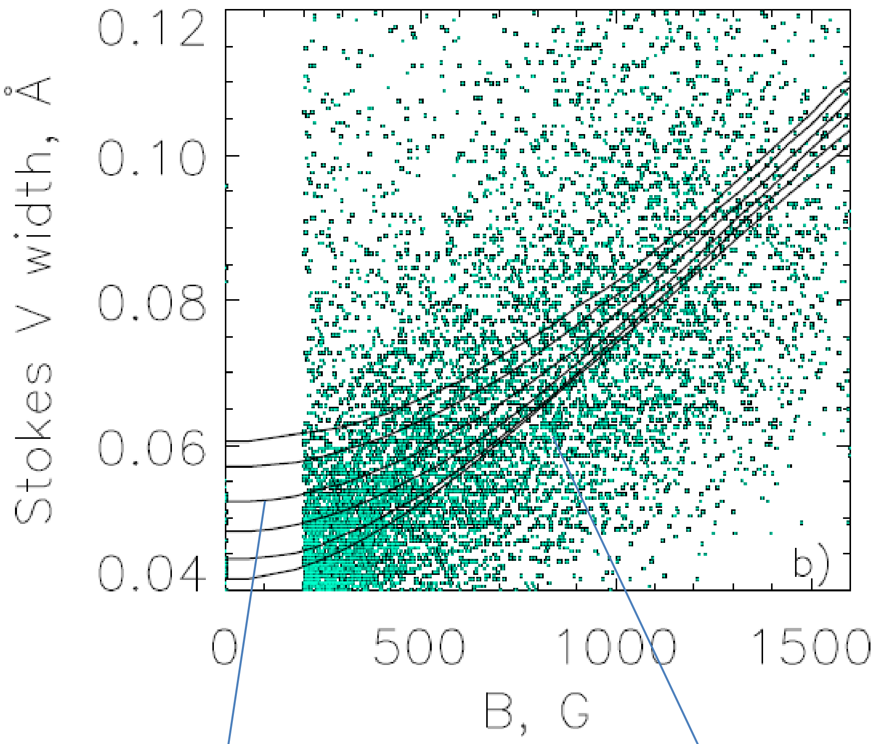
Histograms of SVW



High-res

Low-res

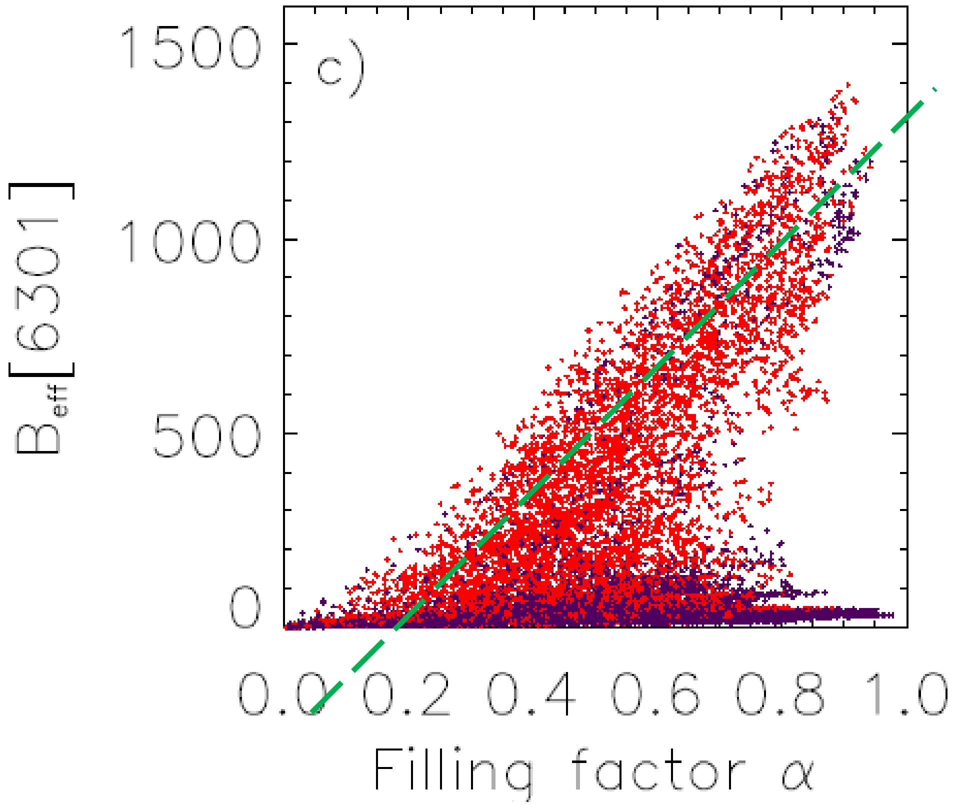
SVW with 6301/6302 pair



callibration

data from MHD MC

Quiet photosphere – “statistical”

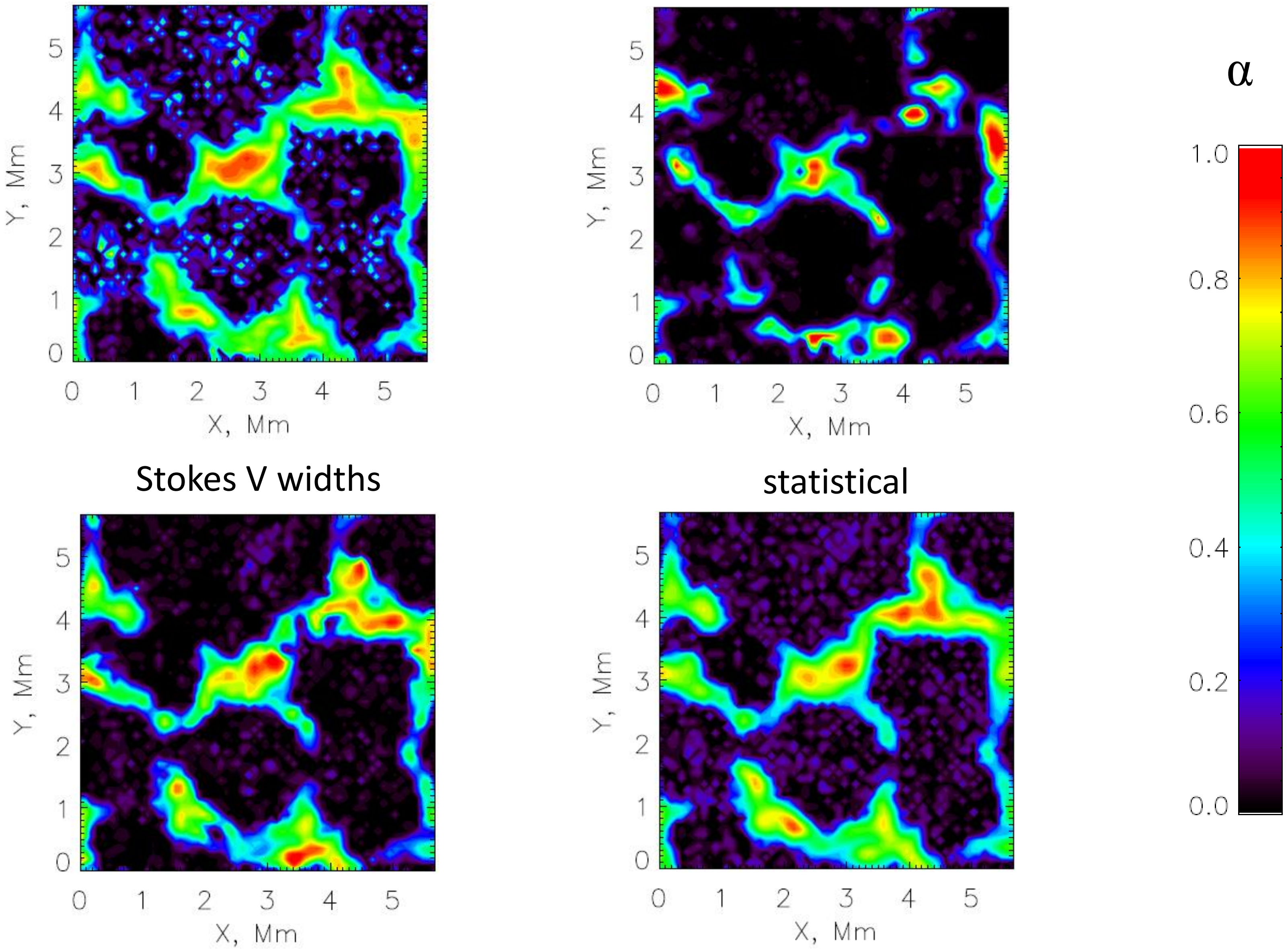


$$\alpha \approx \frac{\kappa_0}{B_{\mathrm{eff,meanmax}}} B_{\mathrm{eff}} + \alpha_0$$

α_0=0.21 (should be close to 0)

κ_0=0.78 (should be close to 1)

Quiet photosphere – comparison



actual

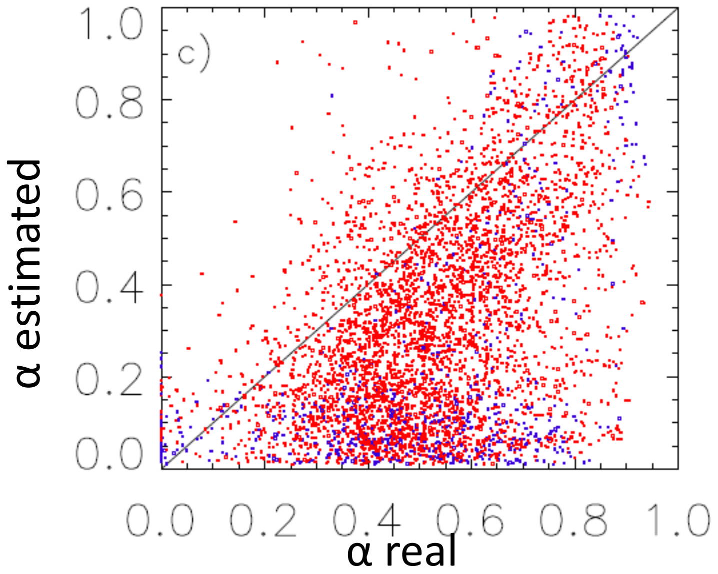
MLR

Stokes V widths

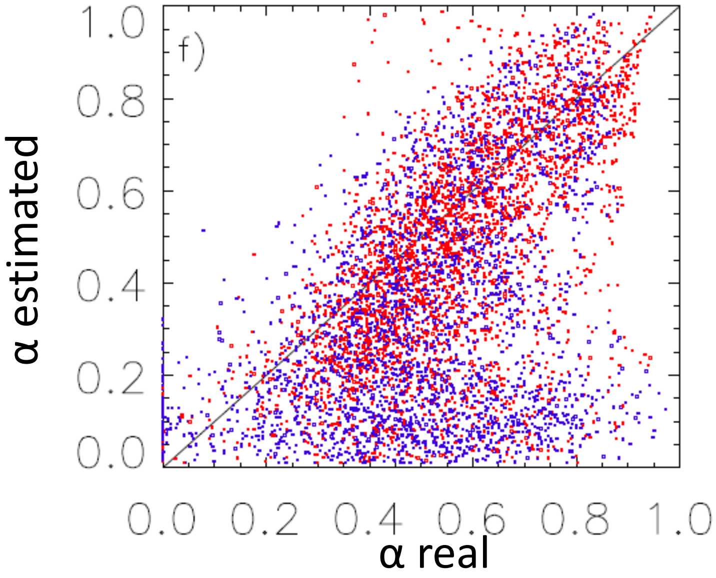
statistical

Quiet photosphere – comparison

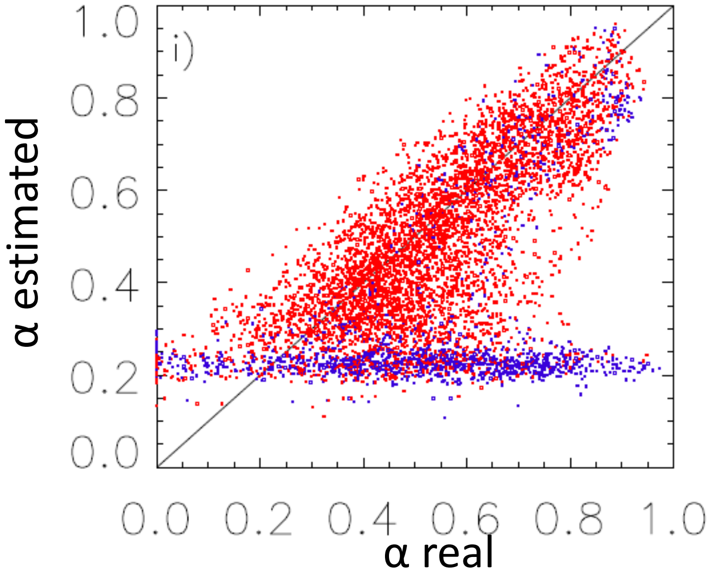
MLR



Stokes V widths



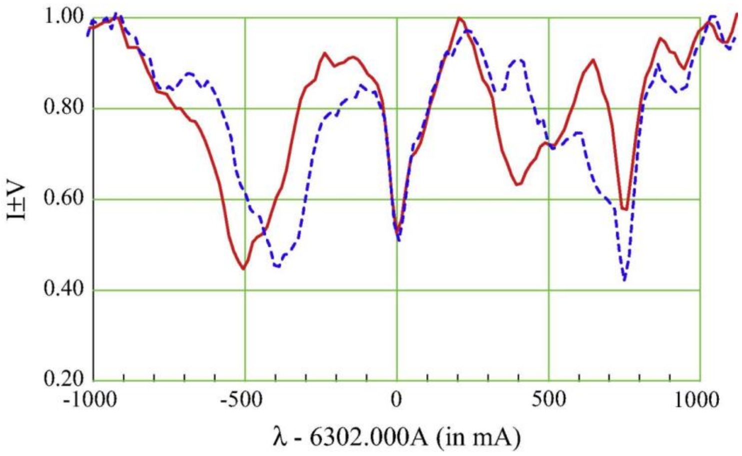
statistical



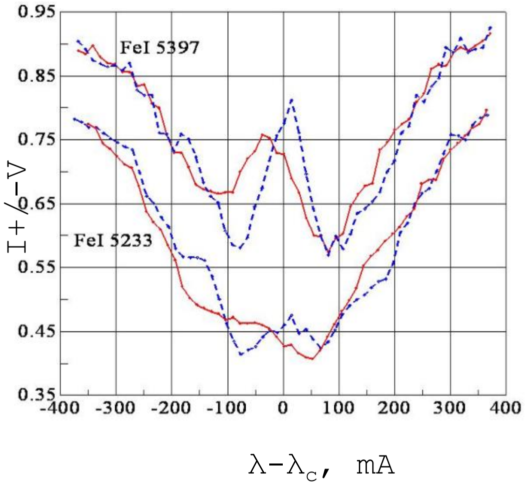
Flaring photosphere

⇒ In flares spectral lines often have abnormal profiles, with several components with different widths, Zeeman splitting, Doppler shift and, most importantly, emission

6301/6302 pair in X flare on 29/10/2003 (Hinode SOT/SP), from Lozitsky (2017)



5233 and 5397 lines in X1.4/1B flare on 02/04/2001 (Kiev HST, from Lozitsky (2009)



Flaring photosphere - MLR

⇒ “MLR” possible, but using series of lines

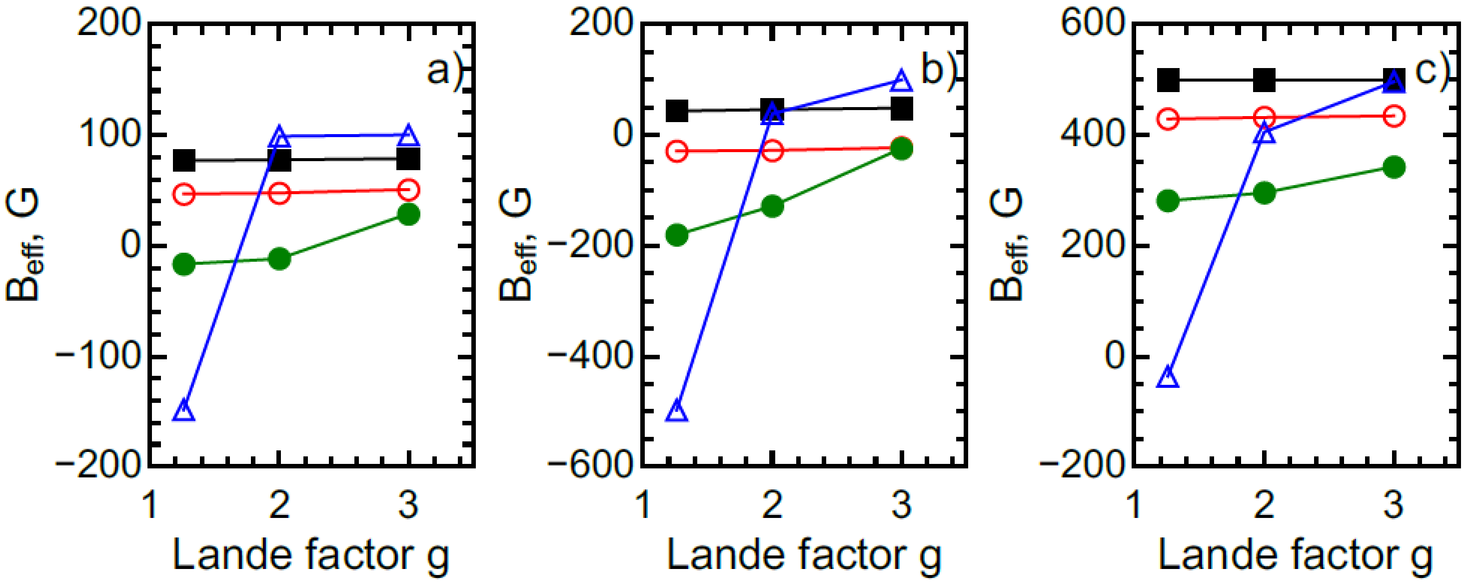


Figure 13. Effective magnetic field strengths $B_{\rm eff}$ as functions of Lande factor g derived from synthetic line profiles of Fe I 5233 Å ($g = 1.26$), 5247.1 Å ($g = 2.00$) and 5250.2 Å ($g = 3.00$) based on the two-component field model with C2 component in emission. Panel a is for the case with $B_{\rm back} = 100$ G and $\Delta\lambda_{C2} = 0.25\Delta\lambda_{C1}$; panel b is for the case with $B_{\rm back} = 100$ G and $\Delta\lambda_{C2} = 0.5\Delta\lambda_{C1}$; panel c is for the case with $B_{\rm back} = 500$ G and $\Delta\lambda_{C2} = 0.5\Delta\lambda_{C1}$ The field strength in C2 component is 500 G (black lines with solid squares), 1 kG (red with circles), 2 kG (green with solid circles), and 4 kG (blue with triangles).

Flaring photosphere - bisectors

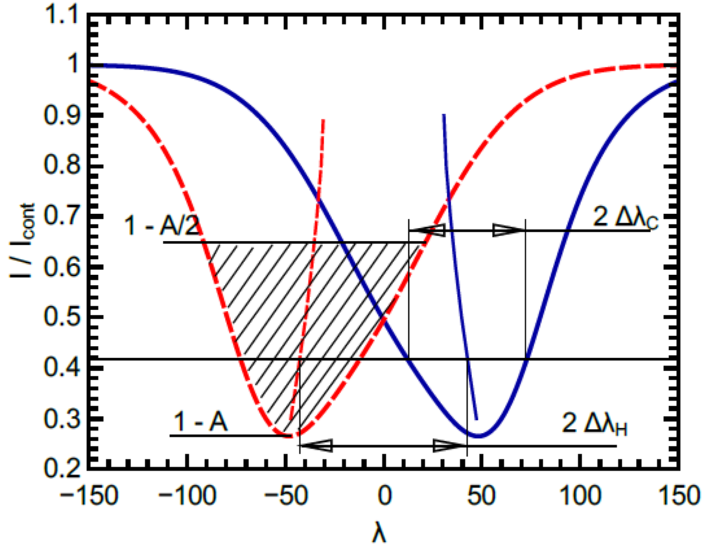


Figure 4. The scheme demontrates geometrical meaning of $\Delta\lambda_c$, $\Delta\lambda_H$ and $B_{\rm eff}$. Blue solid and red dashed lines denote $I+V$ and $I-V$ components, respectively. Thin blue solid and thin red dashed lines denote bisectors corresponding to $I+V$ and $I-V$ Stokes profiles, respectively. Hatched area within one of the components shows the part of a profile used to determine its centre-of-mass position, which, in turn, used to deduce the value of $B_{\rm eff}$ (see Section 3.1).

Flaring photosphere - bisectors

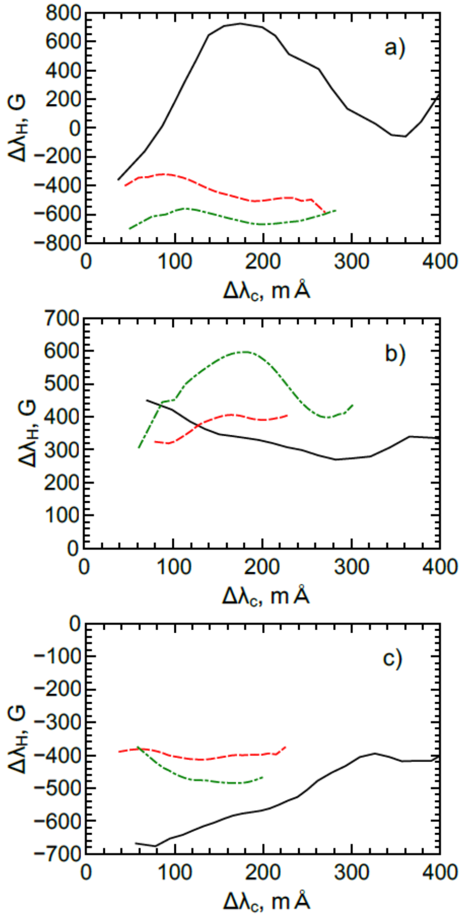
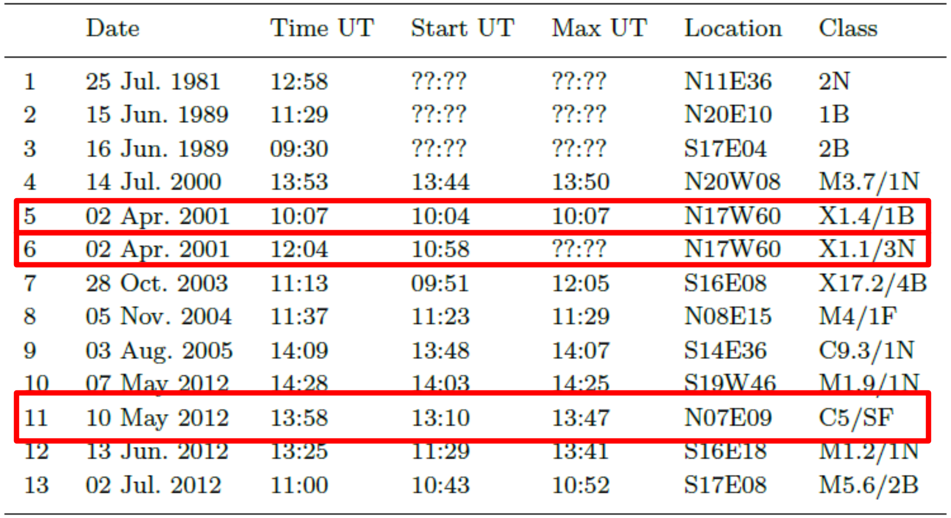


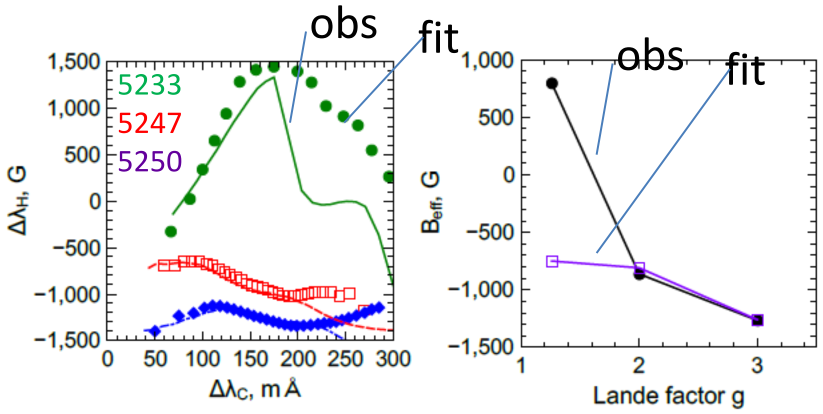
Figure 8. Bisector splitting functions for Fe I 5233 Å (solid black lines), 5247.1 Å (red dashe lines) and 5250.2 Å (green dot-dashed lines) for flares 5 (panel a), 6 (panel b), and 11 (pan c).



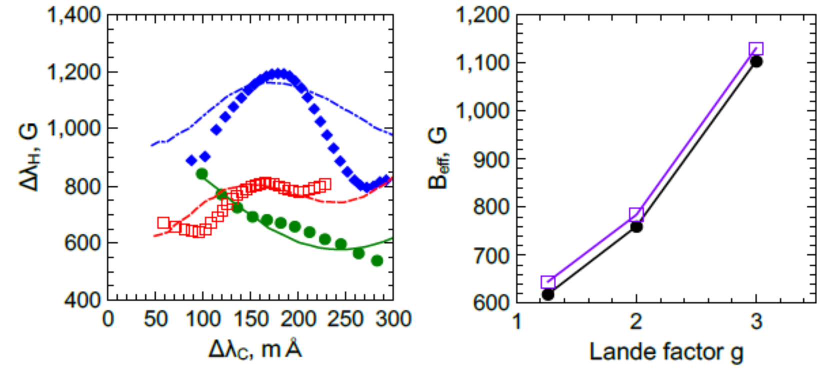
	Date	Time UT	Start UT	Max UT	Location	Class
1	25 Jul. 1981	12:58	??:??	??:??	N11E36	2N
2	15 Jun. 1989	11:29	??:??	??:??	N20E10	1B
3	16 Jun. 1989	09:30	??:??	??:??	S17E04	2B
4	14 Jul. 2000	13:53	13:44	13:50	N20W08	M3.7/1N
5	02 Apr. 2001	10:07	10:04	10:07	N17W60	X1.4/1B
6	02 Apr. 2001	12:04	10:58	??:??	N17W60	X1.1/3N
7	28 Oct. 2003	11:13	09:51	12:05	S16E08	X17.2/4B
8	05 Nov. 2004	11:37	11:23	11:29	N08E15	M4/1F
9	03 Aug. 2005	14:09	13:48	14:07	S14E36	C9.3/1N
10	07 May 2012	14:28	14:03	14:25	S19W46	M1.9/1N
11	10 May 2012	13:58	13:10	13:47	N07E09	C5/SF
12	13 Jun. 2012	13:25	11:29	13:41	S16E18	M1.2/1N
13	02 Jul. 2012	11:00	10:43	10:52	S17E08	M5.6/2B

Flaring photosphere - fitting

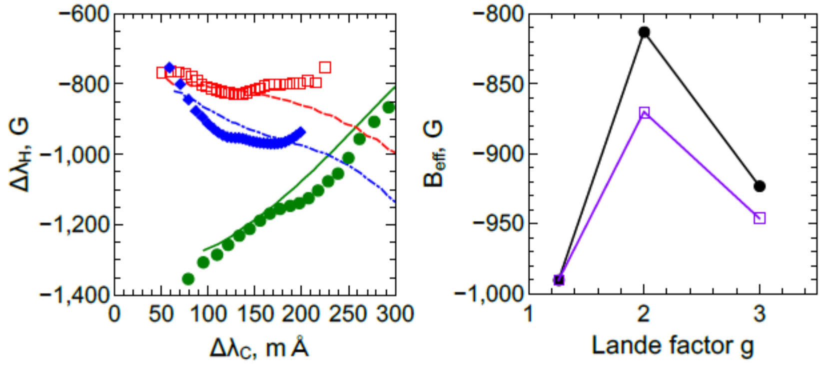
Flare 5



Flare 6



Flare 11



Flaring photosphere – fitting results

Indicates width of the spectral component (i.e. thermal + microturb. width)

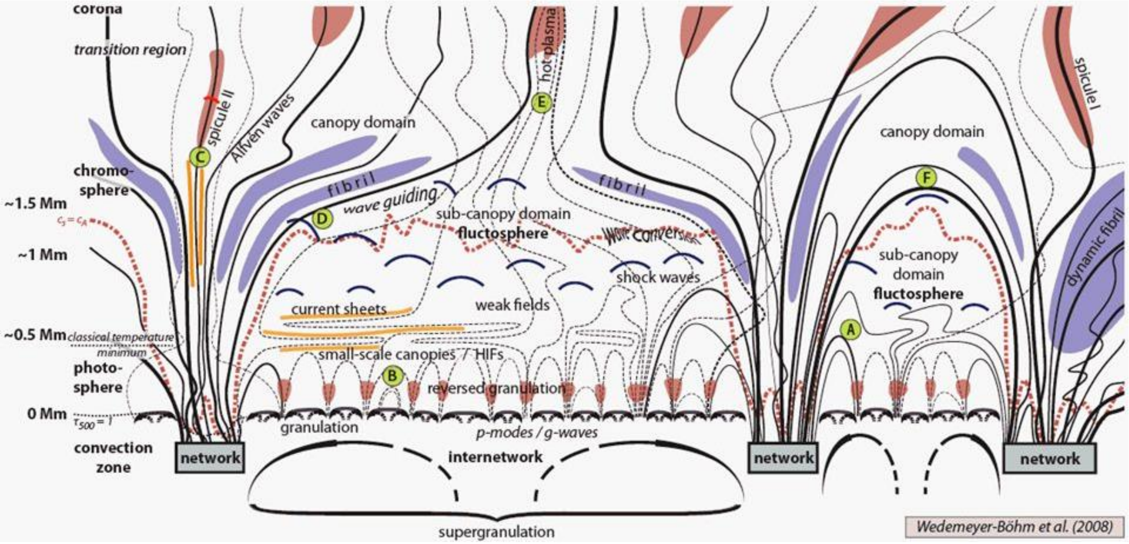
Filling factor (normally α)

Flare 5	B_{back}, G	B_{sub}, G	$\mathcal{F}$	$\Delta\lambda_{\text{LOS}}$, km s^{-1}	T_{sub}, 10^3 K
5233.0 Å	-700	-5500	-0.09	-20	10
5247.1 Å	-700	-2700	-0.09	-20	10
5250.2 Å	-890	-2500	-0.08	-18	8

Flare 6					
5233.0 Å	480	3000	-0.04	-60	23
5247.1 Å	480	3000	-0.04	-40	11
5250.2 Å	600	2750	-0.05	-18	10

Flare 11					
5233.0 Å	-680	-1500	-0.12	-50	30
5247.1 Å	-650	-1750	-0.12	-25	20
5250.2 Å	-670	-1750	-0.12	-30	18

Flaring photosphere

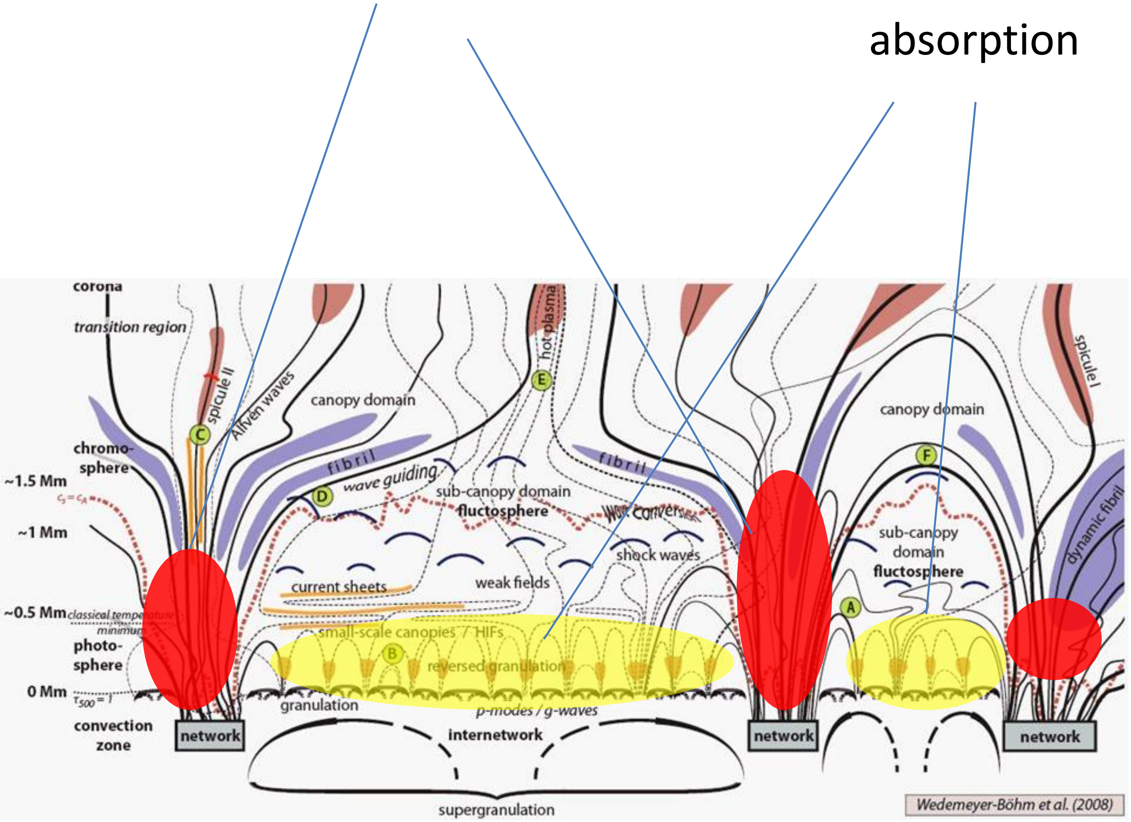


(Wedemeyer-Bohm et al., 2008)

Flaring photosphere

emission

absorption



(Wedemeyer-Bohm et al., 2008)

Summary

- Photospheric magnetic field is very inhomogeneous at small scales. What we measure using magnetographs is ~flux/pixel
- Magnetic field can have discrete components
- In addition to widely-used MLR, the intrinsic field can be estimated using Stokes V widths or “statistically”.
- The Stokes V widths method (a) requires only one line and (b) does not saturate for stronger fields
- Magnetographic field measurements in flares are dangerous because the lines profiles are very different…
- Flares show two-component structure. “Strong field” elements are connected to the corona and are responsible for the energy transport from the corona. The weak ambient field forms low-level canopy

- What about sizes?

  - Speckle-interferometry in Fe I 5250 (*Keller 1992, Keller & von der Luhe 1992*) – few kG fluxtubes with diameters ~100-200 km
  - Observations in Fe I 15648 and 16652 (*Lin 1995*) – two populations of strong fluxtubes, one with 1.5kG and 100-1000 km, another with 500G and <100 km
  - Indirect estimations (e.g. *Wiehr 1978, Lozitsky & Tsap 1989, Sanchez Almeida 1998*) – 50-500 km
  - IBIS observations of C flare (*Kleint, 2012*) – less than 250 km (resolution of instrument)
  - CRISP observations of ‘coronal rain’ in flares (*Antolin & Rouppe van der Voort 2012*) – around 300 km

  - We need direct observations: high spatial resolution + (preferably) Stokes components
  - Current: Hinode, DST/ROSA/FIRS
  - Future: DKIST, ALMA(?)

- Why not MLR with different lines? (if 6301/6302 are not good enough)

- Why not Stokes inversion?

- Implications for the “magnetic transients” in solar flares