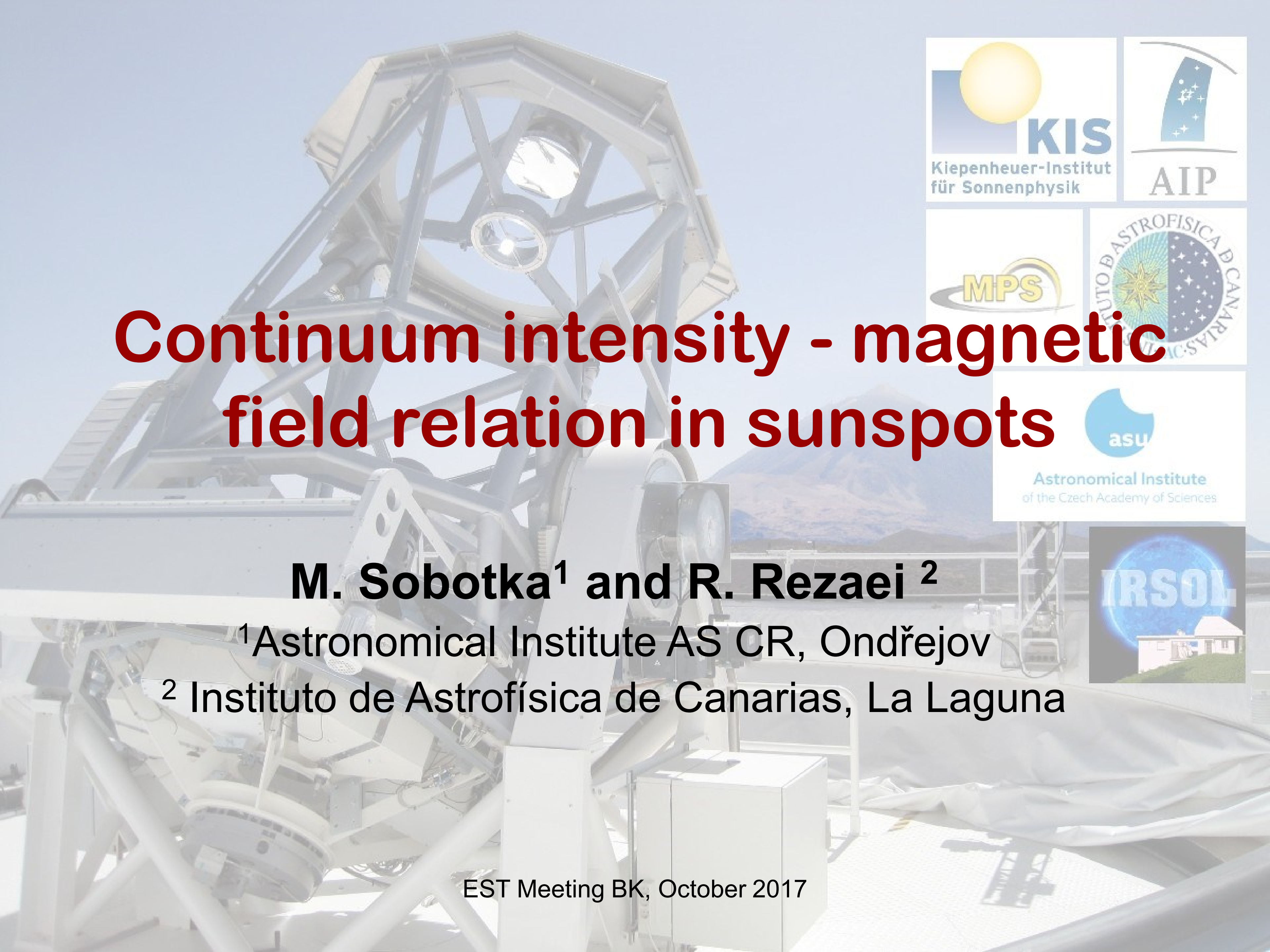


Continuum intensity - magnetic field relation in sunspots

M. Sobotka[1] and R. Rezaei [2]

[1]Astronomical Institute AS CR, Ondřejov

[2] Instituto de Astrofísica de Canarias, La Laguna

EST Meeting BK, October 2017

Introduction

The horizontal force balance in a sunspot (magnetic pressure $B^2/2\mu$) implies that I_c (or T_b) and B should be related, at least in the umbra: $T_b \sim B^2$ (Martínez Pillet & Vázquez 1990). This motivated the following works:

Kopp & Rabin (1992) used IR line Fe I 1564.9 nm in six spots to measure this relation. Advantage: Low scattered light in infrared.

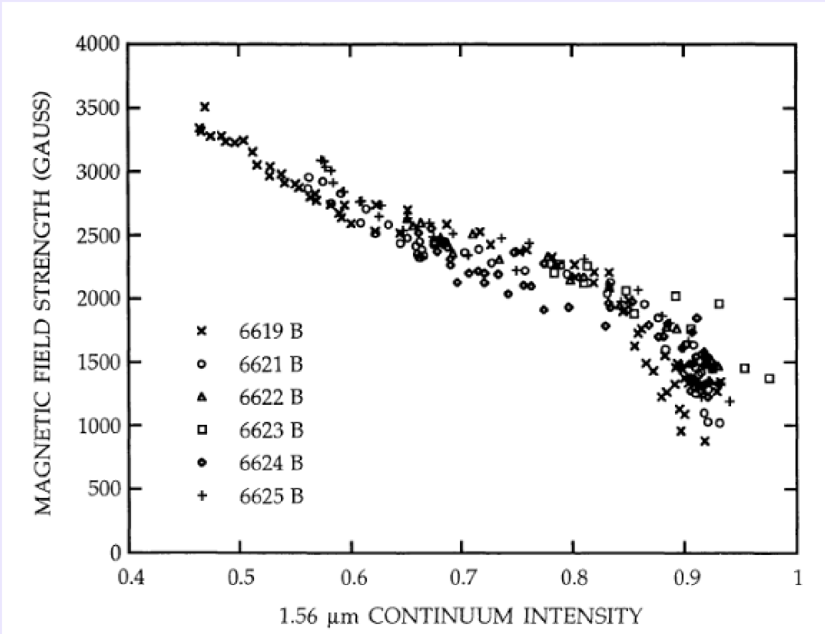
The same line was used by Solanki et al. (1993), Livingston (2002), Penn et al. (2003), Mathew et al. (2004), and Rezaei et al. (2012).

Other authors (Martínez Pillet & Vázquez 1993, Balthasar & Schmidt 1992, Stanchfield et al. 1997, Leonard & Choudhary 2008) used lines in the visible range, typically 630.3 nm.

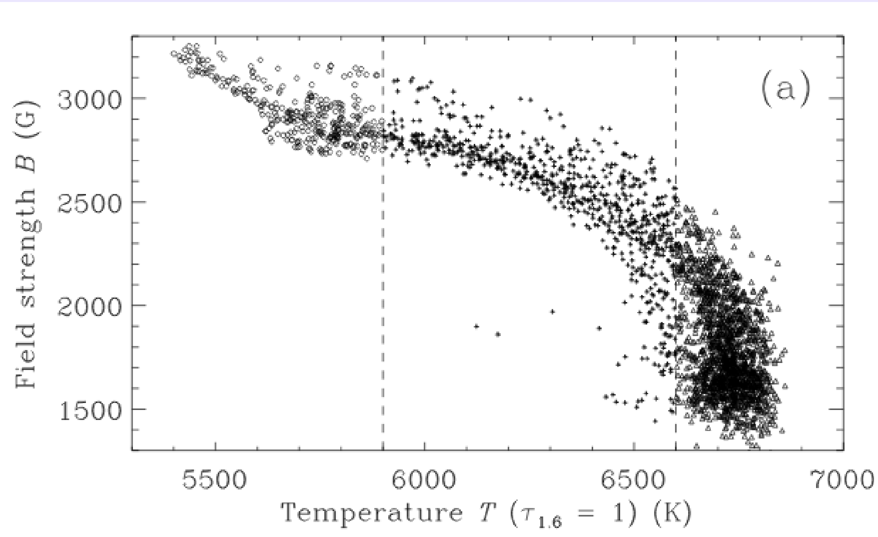
Let us make a simple exercise and compare their results with contemporary GREGOR high-resolution observations and numerical simulations.

Results of previous works, low spatial resolution

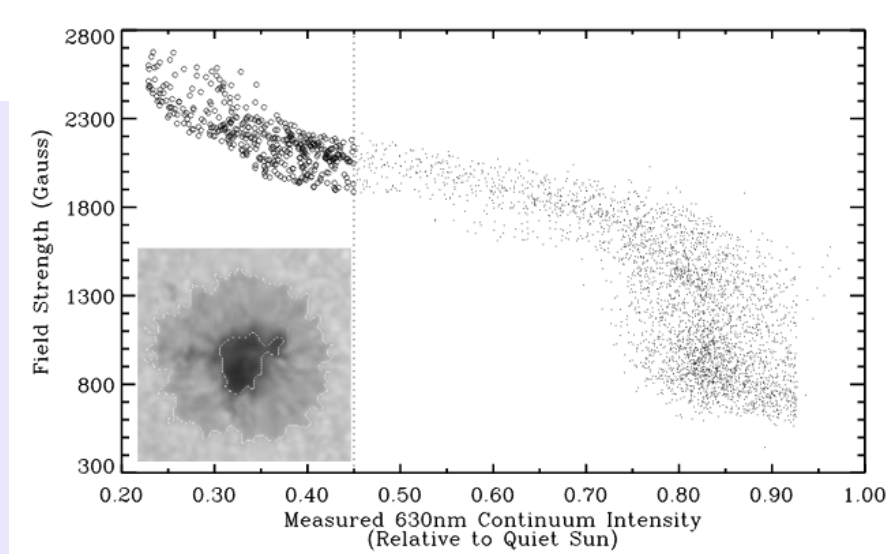
Kopp & Rabin 1992



Mathew et al. 2004

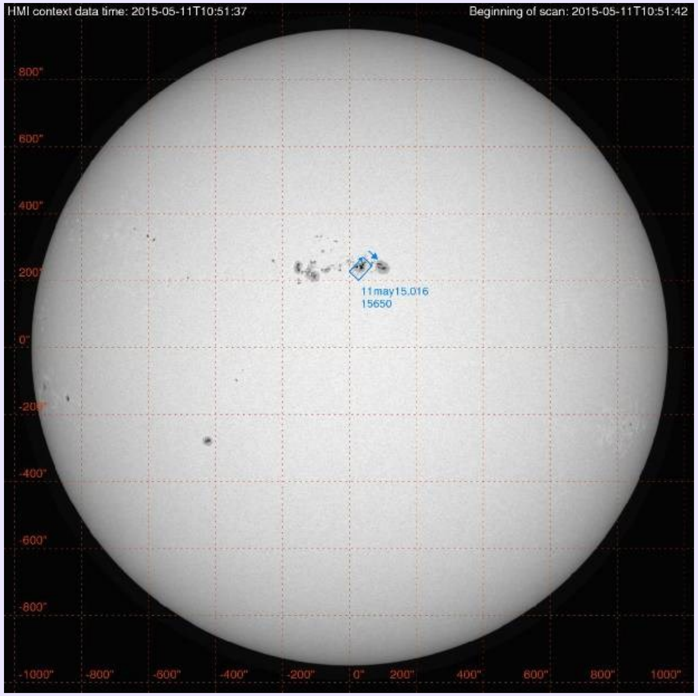


Stanchfield et al. 1997



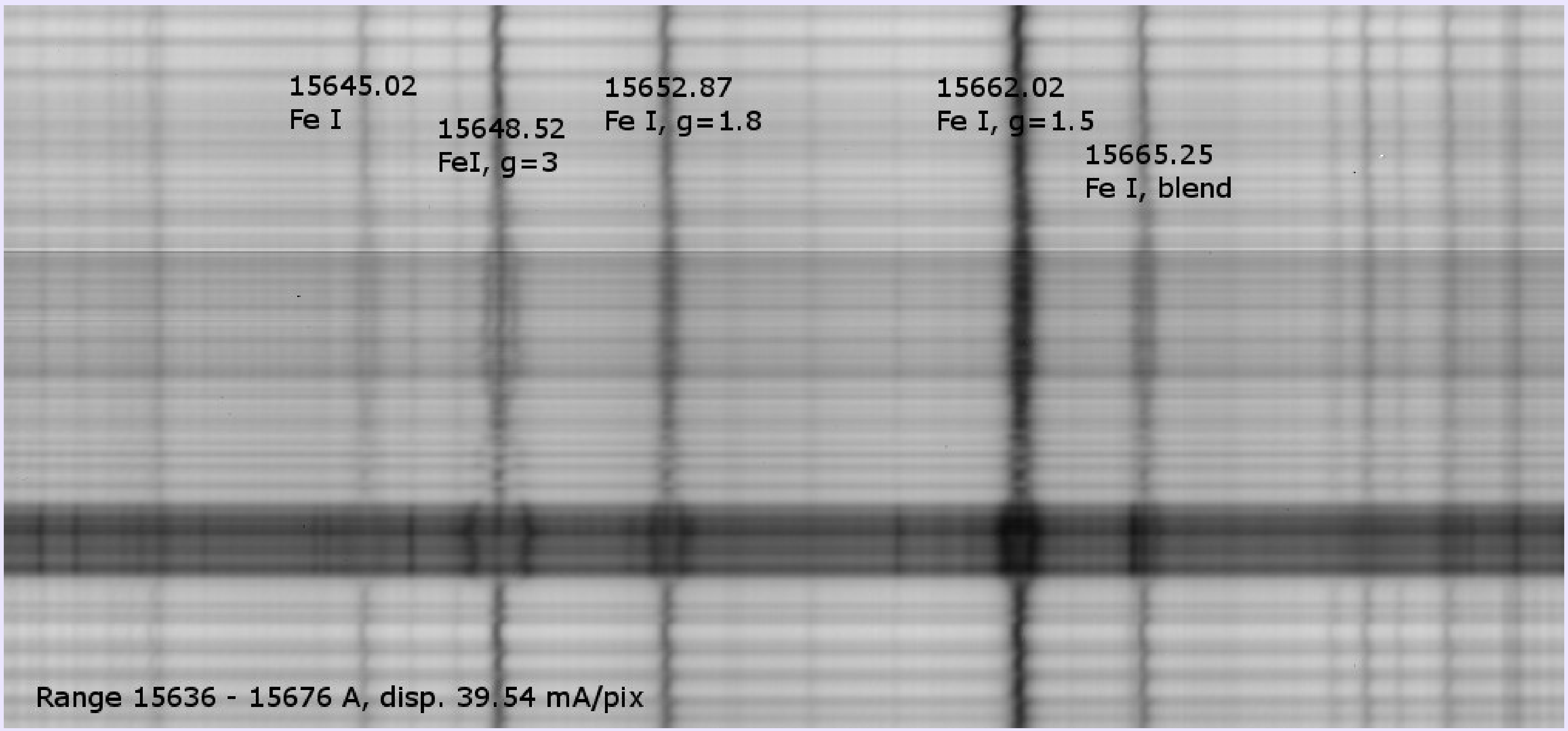
Umbra, penumbra, and
u - p transition

Observations

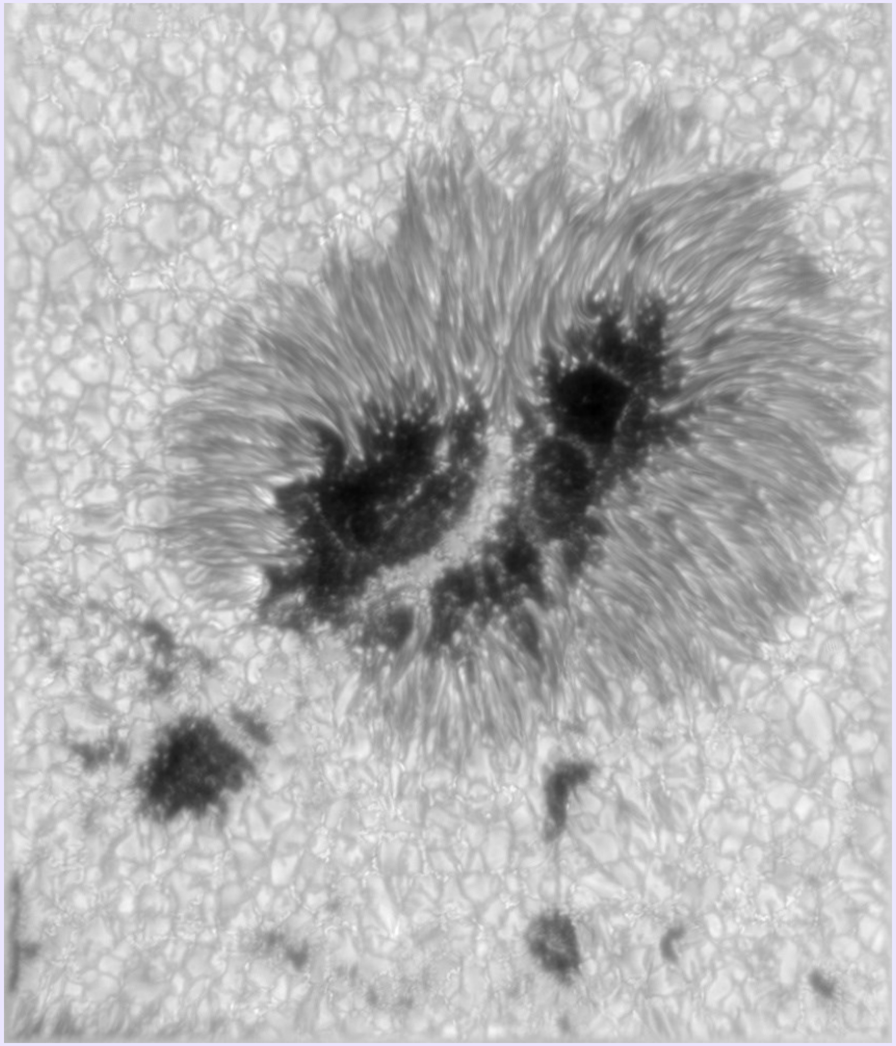


- Sunspot group NOAA 12339,
  11 May 2015, 09:31 – 11:26 UT
- 3 large spots selected, all at θ = 15°
- GREGOR (D=1.5 m, AO), **GRIS** in the 1.5 μm range, full-Stokes polarimetry, calibration with the standard pipeline by M. Collados. Image rotator compensation.
- Spatial scale 0.135"/pixel, dispersion 3.95 pm/pixel, approx. scan duration 30 minutes, line 1564.9 nm.
- Context **imaging** in red continuum 630.4 nm, speckle reconstruction.

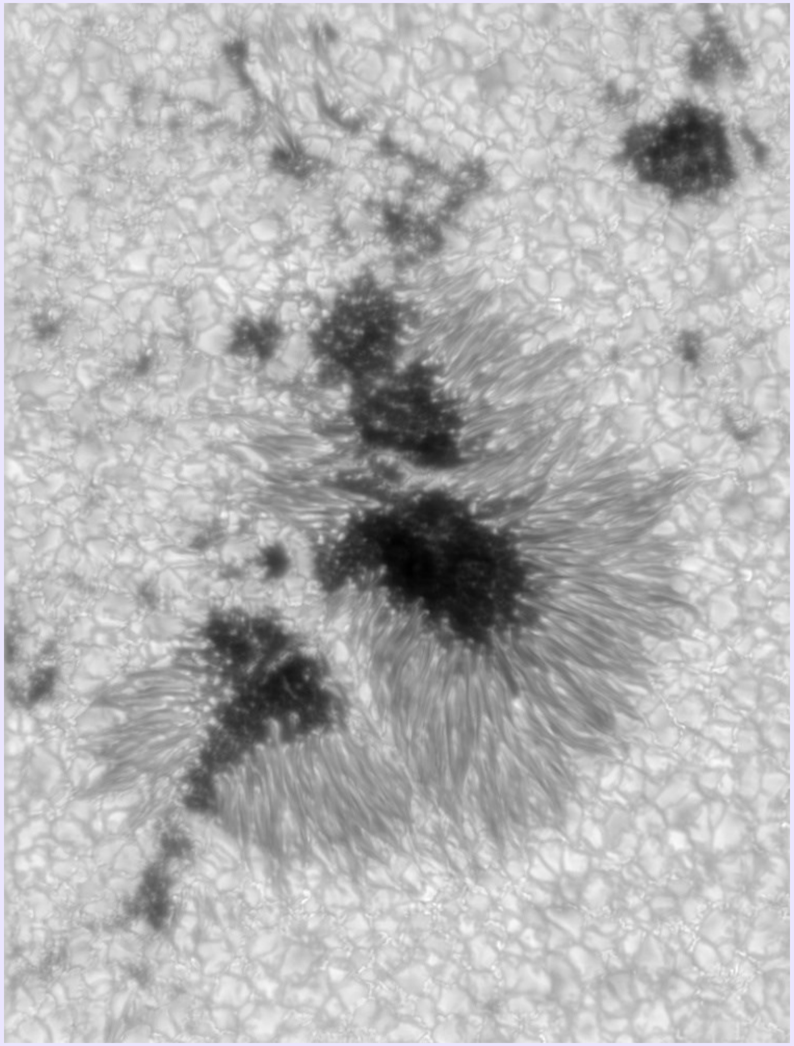
GRIS spectrum: Line Fe I 1564.9 nm, g=3 triplet, split completely for B > 1400 G, linear response for B > 500 G. It originates around z = 110 km. The continuum I_c around 1564.2 nm is formed at z = –30 km.



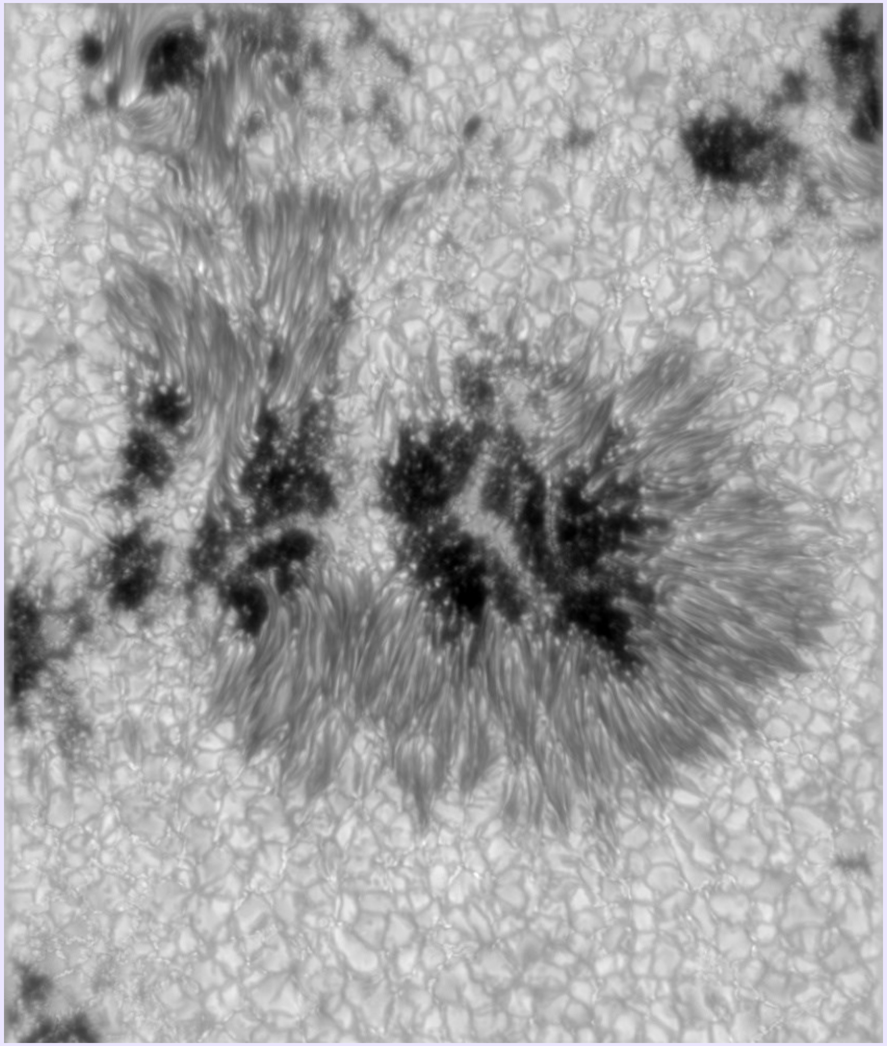
Reconstructed red-continuum (630 nm) images



1 (scan 007)



2 (scan 016)



3 (scan 018)

All the three spots have a very rich fine structure with strong and faint light bridges, umbral dots, and penumbral filaments and grains.

Magnetic field measurement

Circular polarization:

$$cp = \frac{1}{I_c}\left(\int_{\lambda 1}^{\lambda 0} V(\lambda)\, d\lambda - \int_{\lambda 0}^{\lambda 1} V(\lambda)\, d\lambda\right)$$

Linear polarization:

$$lp = \frac{1}{I_c}\int_{\lambda 1}^{\lambda 2} \underbrace{\boxed{\sqrt{Q^2(\lambda) + U^2(\lambda)}}}_{QU}\, d\lambda$$

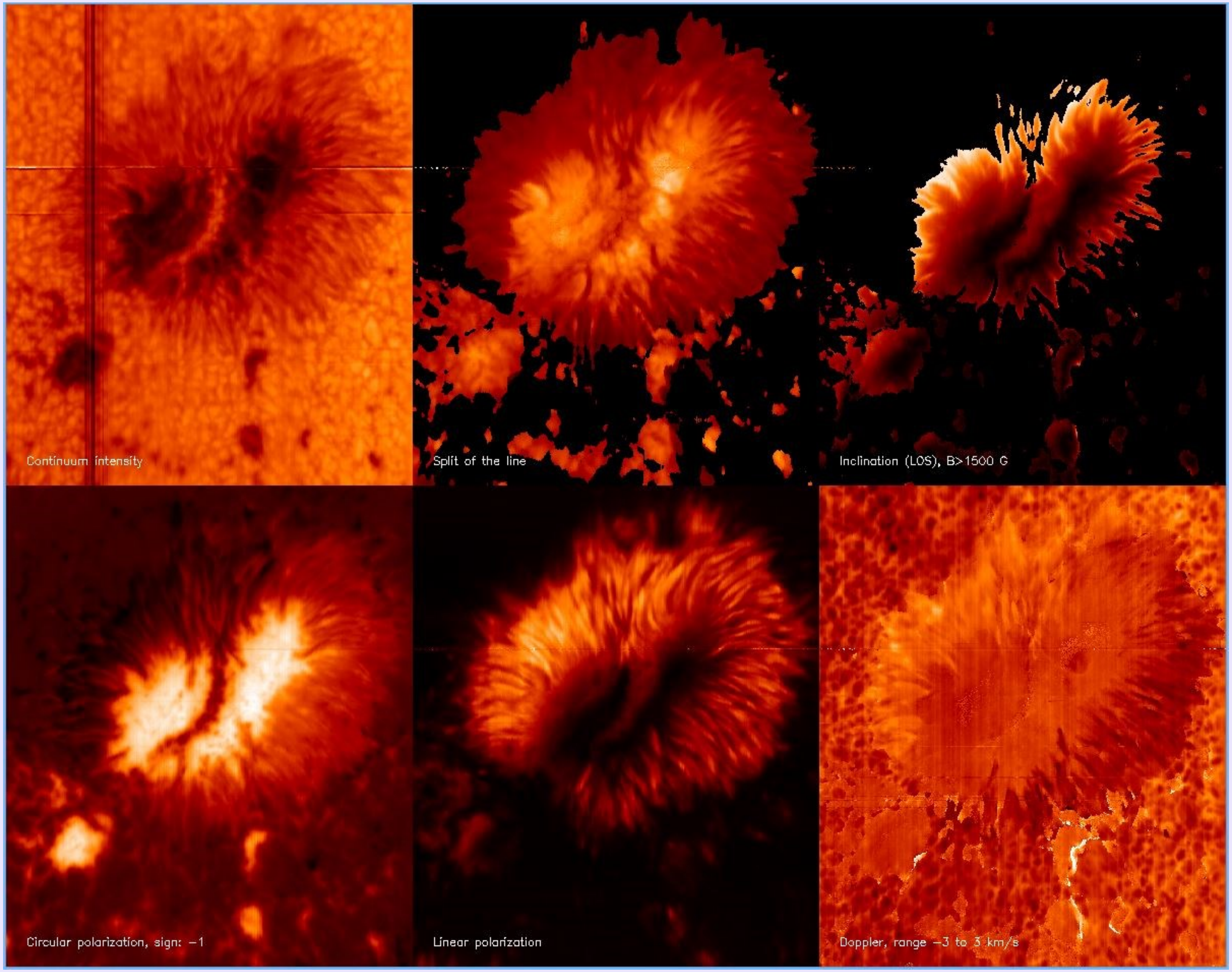
Field strength *B* :

$$B = \frac{4\pi m_e c^2}{e g \lambda_0^2}\Delta\lambda = \frac{4\pi m_e c^2}{e g \lambda_0^2}\,\frac{cp\,.\,V_{split} + lp\,.\,QU_{split}}{2(cp + lp)}$$

LOS inclination γ :

$$\gamma = \mathrm{atan}\frac{QU_{max}}{V_{max}}$$

Line positions are measured using a parabolic fit of *I, QU, V* extrema.


Continuum intensity
Split of the line
Inclination (LOS), B>1500 G
Circular polarization, sign: −1
Linear polarization
Doppler, range −3 to 3 km/s

1 (scan 007)

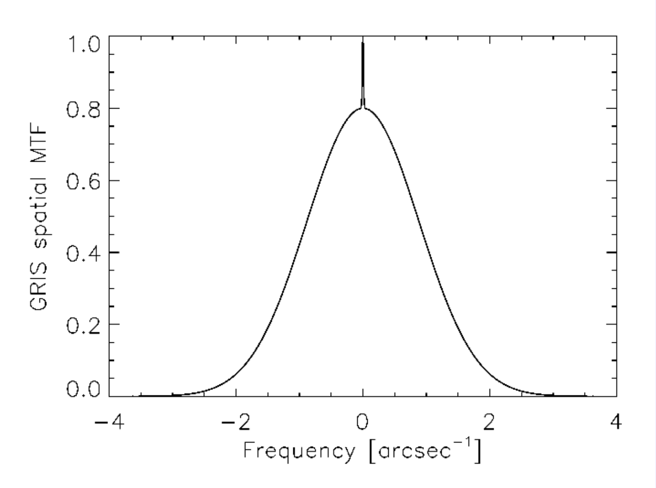
Stray light

GRIS instrumental scattered light (Borrero et al. 2016)

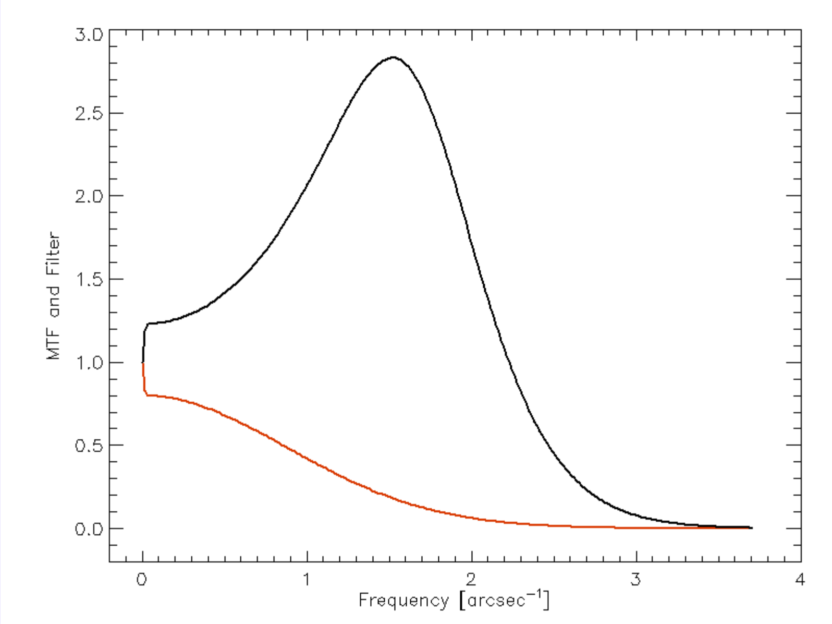
Spectral scattered light – it influences line depths in *I*. Not important for line splitting, shifts, and *I*-continuum intensity.

Spatial scattered light – derived under the assumption that when ***B*** is in the LOS direction, the central (π) absorption in the full-split line is completely caused by the scattered light. Borrero found a PSF composed of two Gaussians with σ_1 = 0.18” and σ_2 = 20”. The first describes the scattering in the spectrograph, the second in the telescope optics.

$$\mathrm{MTF} = \mathfrak{F}\,(\mathrm{PSF})$$



Deconvolution of the spatial scattered light from the continuum maps by means of the Wiener filter and normalization to the local mean quiet-Sun intensity.



$$I_{corr} = \mathscr{F}^{-1}(\mathscr{F}(I_{obs}) \cdot \text{Filter})$$

Filter = (c+1) MTF / (c MTF^2 +1),
c = 30 (depends on the noise)

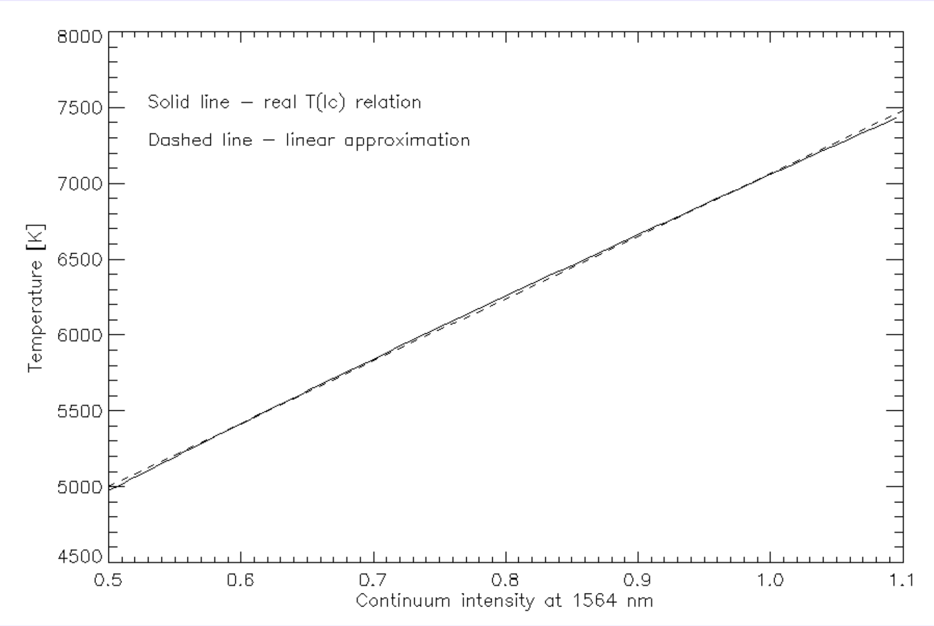
An alternative attempt was made with parameters derived by M. Collados from the Mercury transit of 9 May 2016. These parameters, obtained with a very bad seeing, led to an overcorrection and were not used.

Temperature

The **brightness temperature** T_b is calculated from the corrected continuum intensity (Mathew et al. 2016) by solving the equation

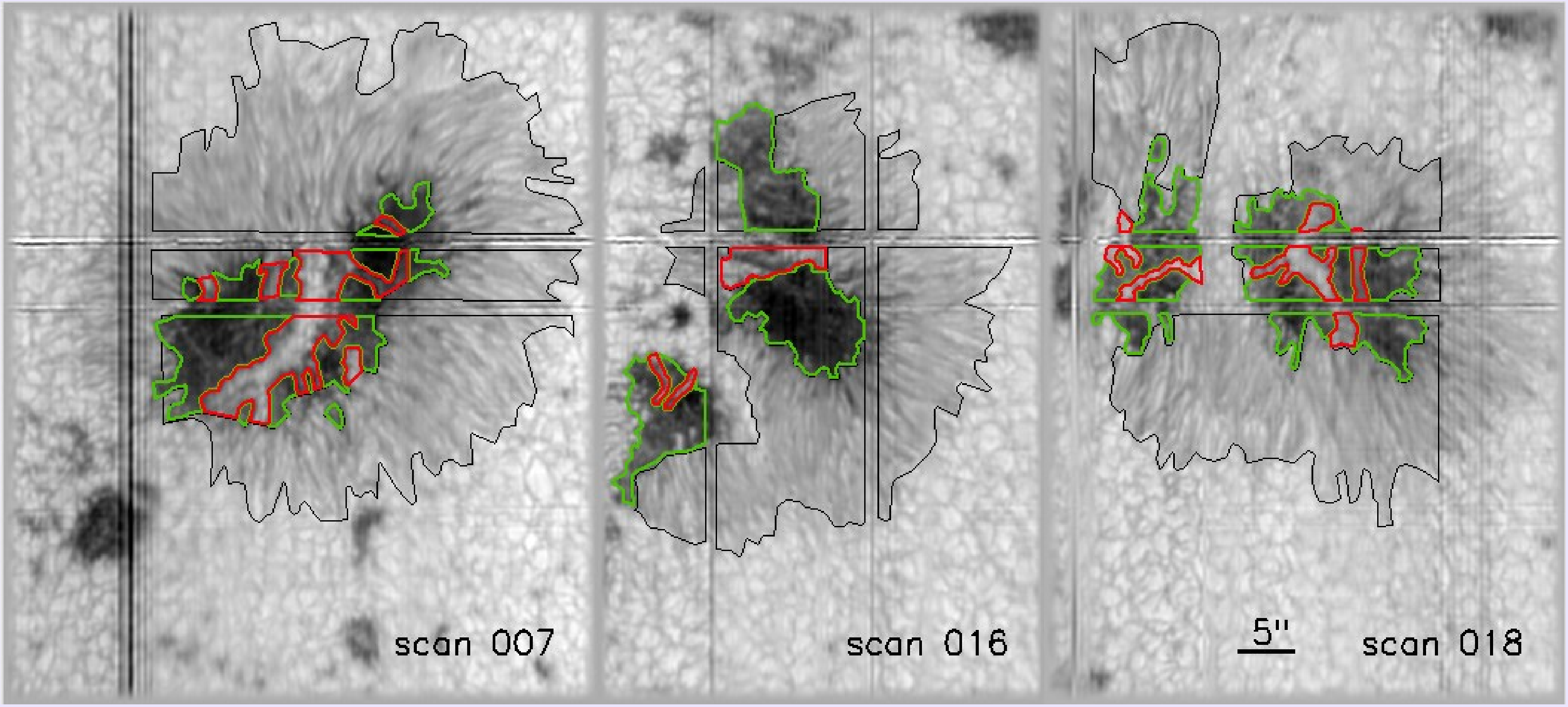
$$I_c / I_{QS} = \mathcal{B}(\lambda, T_0) / \mathcal{B}(\lambda, T_b)$$

T_0 = 7058 K (λ = 1564 nm) is the quiet-Sun temperature at $\tau_{1.6} = 1$



Masks

In contrast to previous studies, we took advantage of the high spatial resolution and separated the umbra, penumbra, and light bridges using hand-drawn masks (shown together with continuum images corrected for stray light).

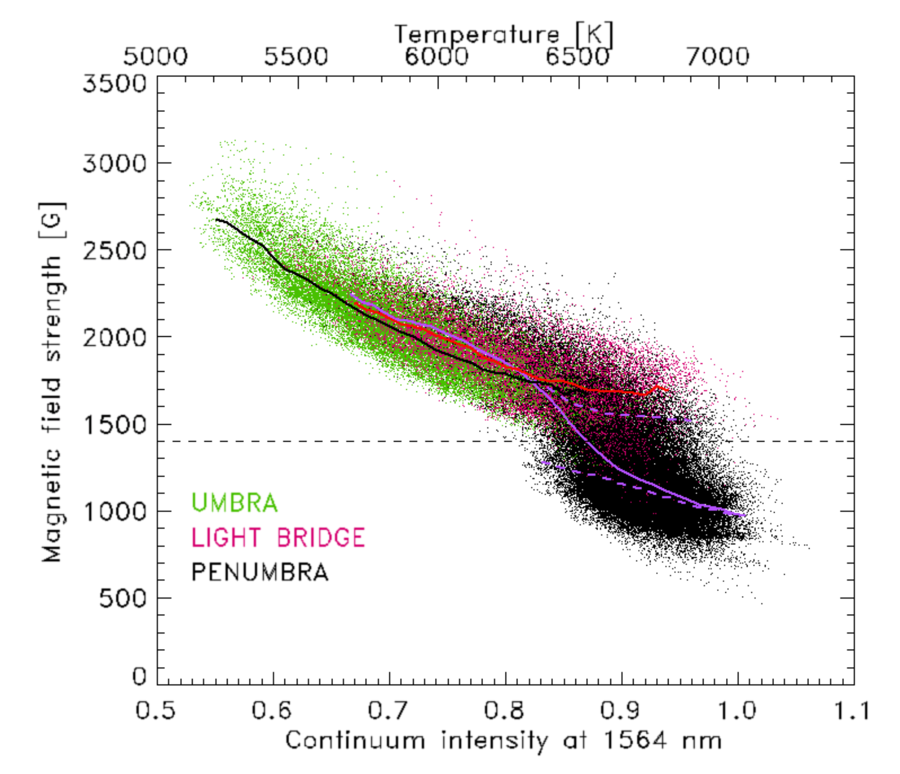


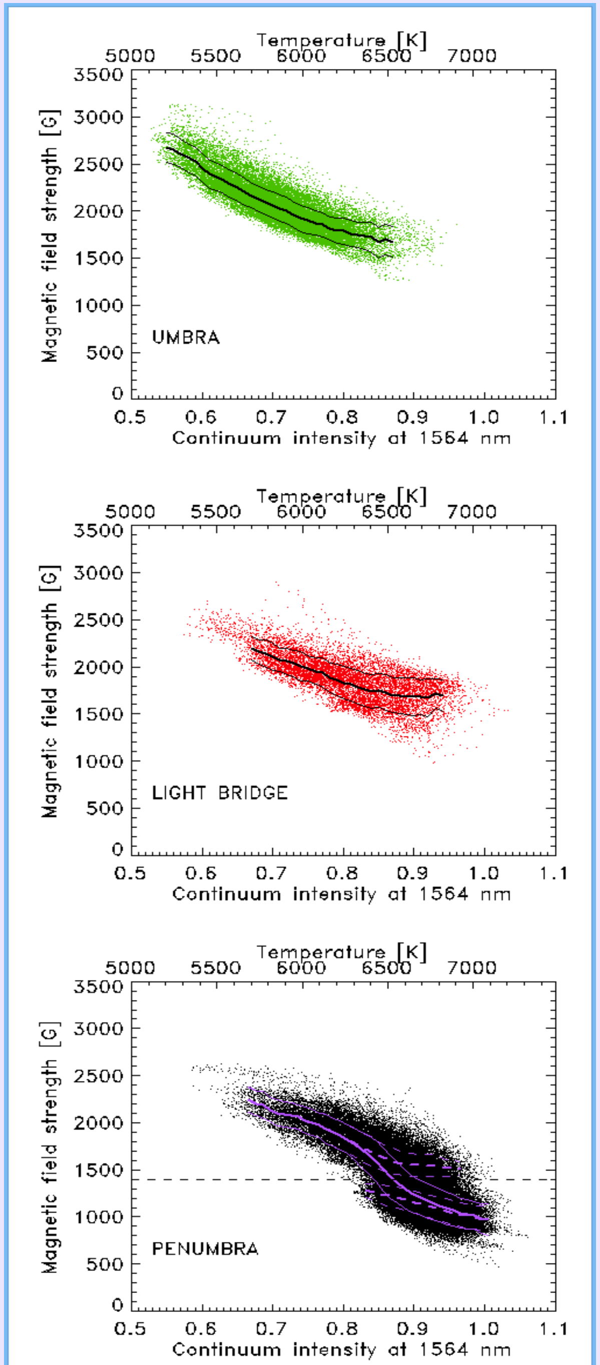
Results

A scatter plot of B vs. I_c and T_b for the three studied sunspots together.

The shape is consistent with previous studies (in a very good agreement with Livingston (2002)), but a larger scatter.

Lines represent mean values of B falling into 0.01-wide bins of I_c.





All 3 spots together. Umbra, penumbra, and light bridges are separated.

- **Umbra**: A non-linear relation, also for $B^2 - T_b$. Scatter due to resolved fine structures and B variations inside umbral cores.

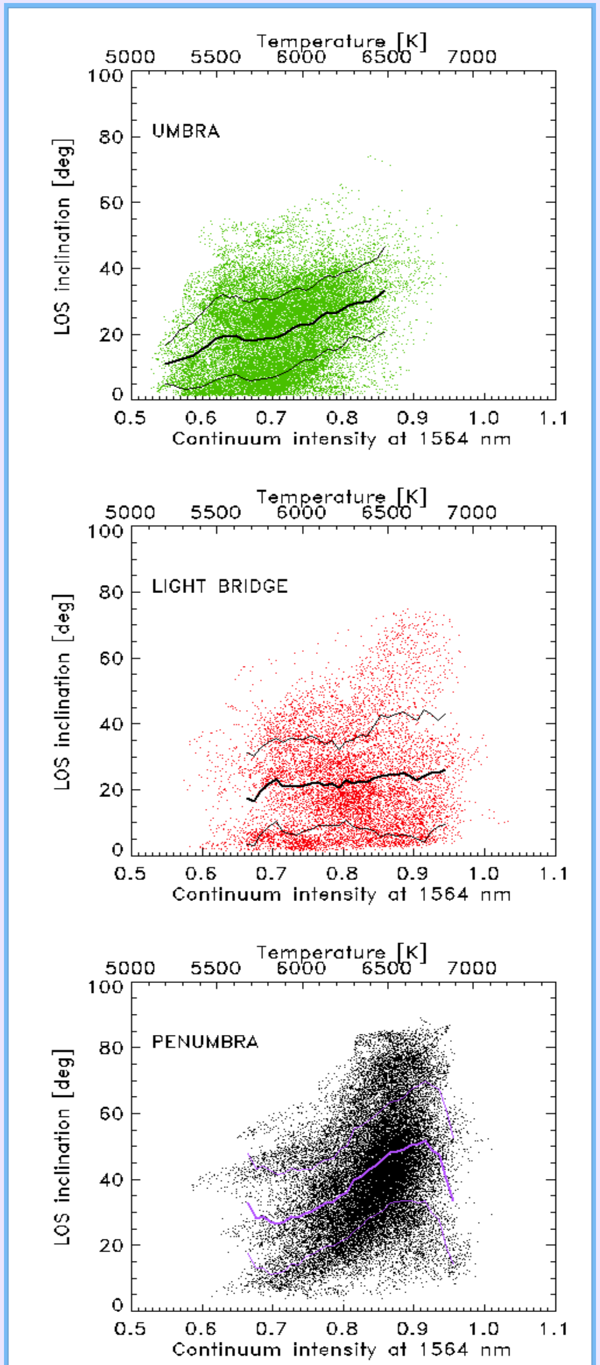
- **Light bridges**: *Similar to umbra*, but brighter and B < 2500 G. In bright parts, higher B than in the inner penumbra.

- **Penumbra**: Large scatter of I_c – bright and dark filaments. Two populations, divided at 1400 G:

Upper pop.: ***Inner penumbra*** – The $B - I_c$ relation is *similar to those of umbra and light bridges*; effect of a less inclined and stronger ***B***.

Lower pop.: ***Outer penumbra*** – A strong decrease of *B,* by 400 G on average.

These results support the “interlocking comb” model (e.g., Thomas & Weiss 2008):
1. Less-inclined field extending high in atmosphere
2. Low-lying nearly horizontal field (in outer p.)



Magnetic field **LOS inclination**
at heliocentric angle of 15°.
Limited to areas with B > 1500 G.

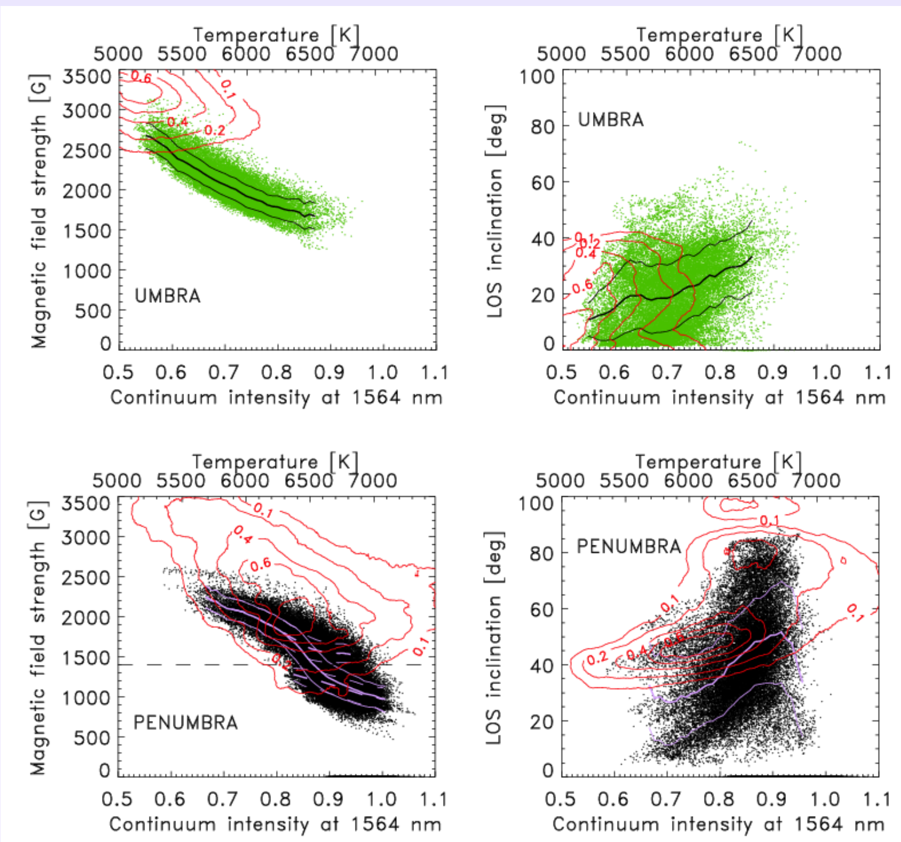
- Umbra: The average inclination increases with brightness, an effect of increasing inclination towards the edge of the umbra and in umbral dots.

- Light bridges: Similar to that in the umbra. The line origins at h = 110 km in the low photosphere, below the LB magnetic canopy, so that the average inclination is still small.

- Penumbra: Only inner penumbra due to the 1500 G limit. The average inclination increases with increasing I_c. The spread of points is consistent with the results of Mathew et al. (2004).

Comparison with synthetic data

Full-Stokes synthetic profiles, computed by Borrero et al. (2014) from a snapshot of a sunspot simulation by Rempel (2012), were analyzed in the same way as the observed ones. Red contours show densities of scatter-plot points of the synthetic data with spatial resolution 30x finer than in our observations.

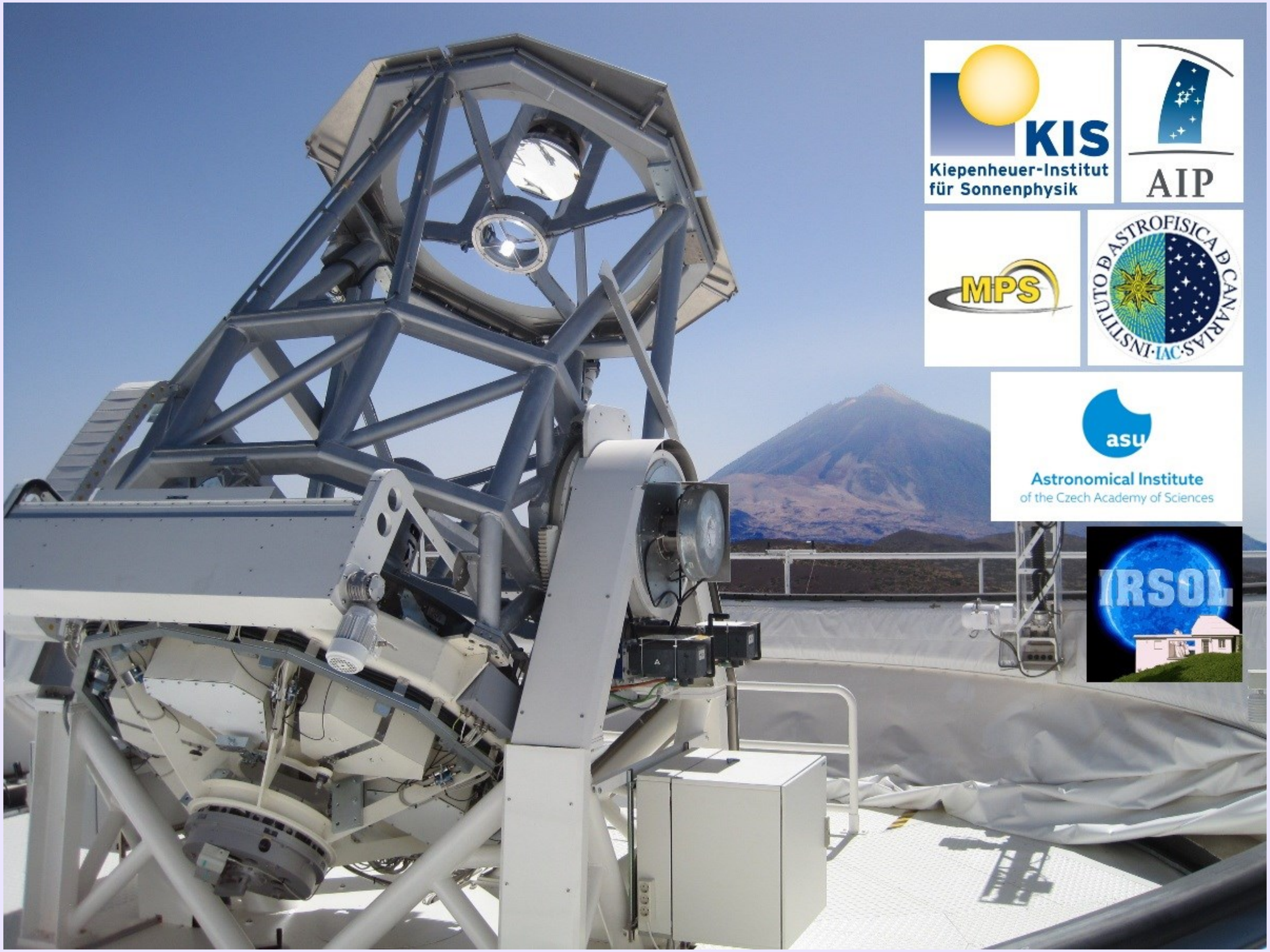


- **Umbra**: Synthetic *B* high and I_c low: blends in the line reduce observed *B*; residual scattered light. Reasonable match in inclination.
- **Penumbra**: Numerous synthetic points with high *B*; *missing outer-penumbra synthetic points*. Observed low-inclination points probably due to projection effect (LOS 15°).

- Simulated highly magnetic features are too small to be detected.
- Scatter of points increases with increasing spatial resolution.

Discussion

- Our results are consistent with the previous works, showing a larger scatter of points due to higher spatial resolution.
- The “umbra-penumbra transition” is in fact a mixture of contributions from the inner penumbra, light bridges, and bright parts of the umbra.
- There is a strong similarity of $B - I_c$ relations in the umbra, light bridges, and the inner penumbra.
- The difference between the inner and outer penumbra (B < 1400 G) can be explained in terms of the interlocking comb magnetic structure.
- The nearly horizontal field system in the outer penumbra is probably not correctly reproduced by numerical simulations (missing part of lower-population $B - I_c$ points in the synthetic data).



Thank you for attention