July 28-31, 2008

Magnetic Flux, Umbral Temperature, and the Sound-Speed Perturbations Below Sunspots

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Datasets

Sound-Speed Perturbations Below Sunspots

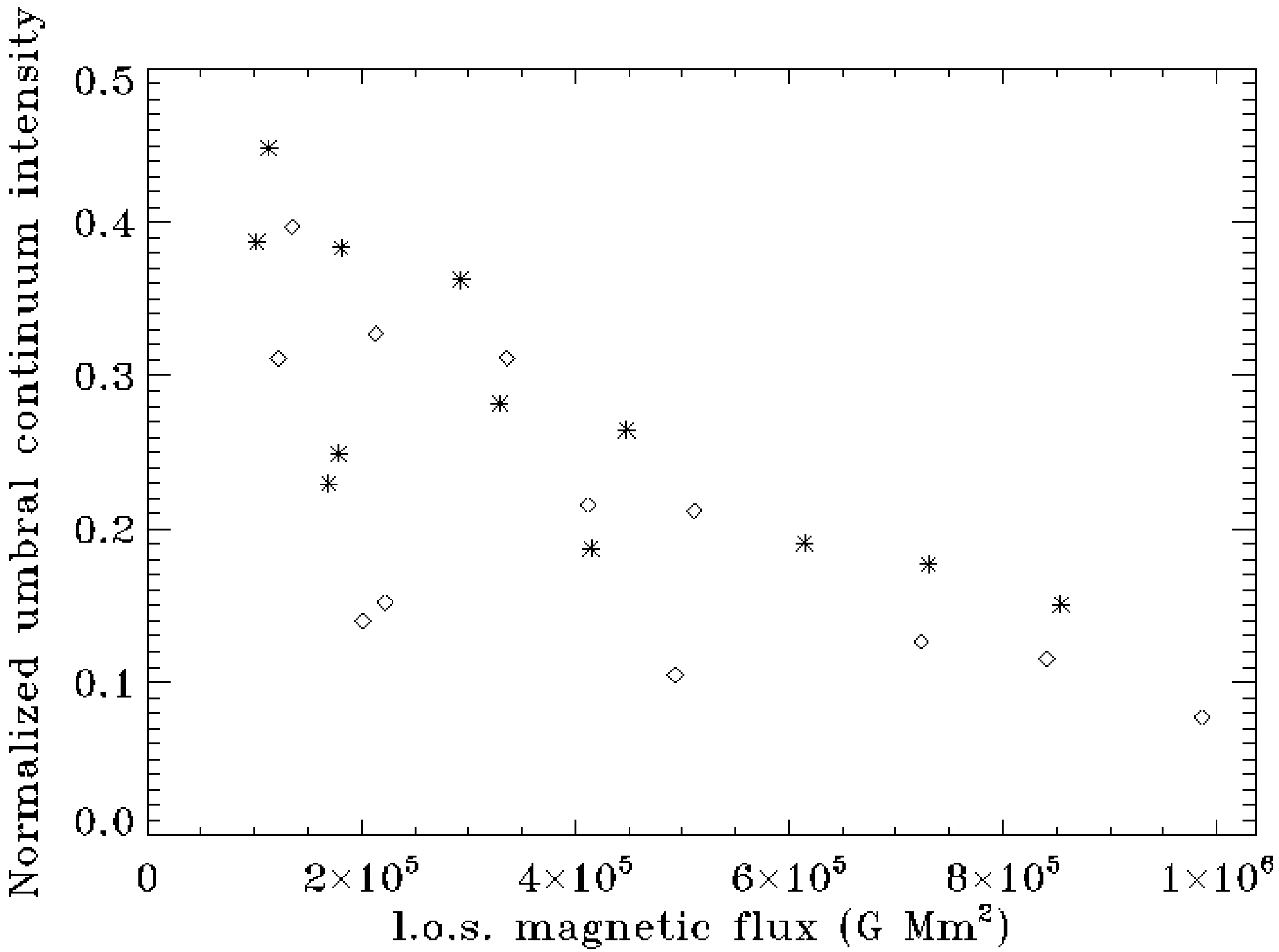
Table 1. Characteristics of the sunspots studied, for a threshold of 300 G. NOAA is the active region number hosting the sunspot, as provided by NOAA. Area and Area Corr. are the area in Mm^2 of the sunspot before and after the magnetograms and intensity maps have been corrected for scattered light. Flux and Flux Corr. are the l.o.s. magnetic flux in kG Mm^2 before and after correction. I_0/I_p and I_0/I_p Corr. are the umbral continuum intensity normalized to quiet Sun photospheric value I_p, before and after correction. NOAA numbers come from the website of the Institute for Astronomy of the University of Hawaii.

NOAA	Date	Area	Area Corr.	Flux	Flux Corr.	I_0/I_p	I_0/I_p Corr.
8073	17 Aug 97	152.8	150.8	113.4	135.4	0.448	0.397
8243	18 Jun 98	517.2	511.7	414.9	493.8	0.187	0.104
8397	04 Dec 98	545.8	536.9	447.9	511.4	0.264	0.212
8402	05 Dec 98	212.9	208.1	169.1	201.6	0.229	0.140
9236	24 Nov 00	1101.9	1061.7	854.3	986.6	0.151	0.078
9493	12 Jun 01	217.0	214.9	178.9	222.3	0.249	0.152
0061	09 Aug 02	420.3	455.1	329.1	412.4	0.282	0.215
0330	09 Apr 03	904.7	888.4	730.8	840.9	0.177	0.115
0387	23 Jun 03	429.2	423.0	293.0	335.8	0.362	0.311
0615	21 May 04	253.1	251.8	181.2	213.3	0.383	0.327
0689	27 Oct 04	145.3	140.6	102.2	122.5	0.387	0.311
0898	03 Jul 06	814.7	826.3	614.7	723.4	0.191	0.126

12 sunspots observed with MDI Hi-Res between 1997 and 2006

Intensity and l.o.s. magnetic field maps have been corrected for scattered light (Wiener deconvolution with PSFs of Mathew et al. (2007) and Rabello-Soares, Korzennik, and Schou (2001); Correction of magnetic field maps based on conversation with J. Schou)

Impact of scattered light correction



Similar to Livingston (2002) ?

diamonds=corrected data, stars=uncorrected data

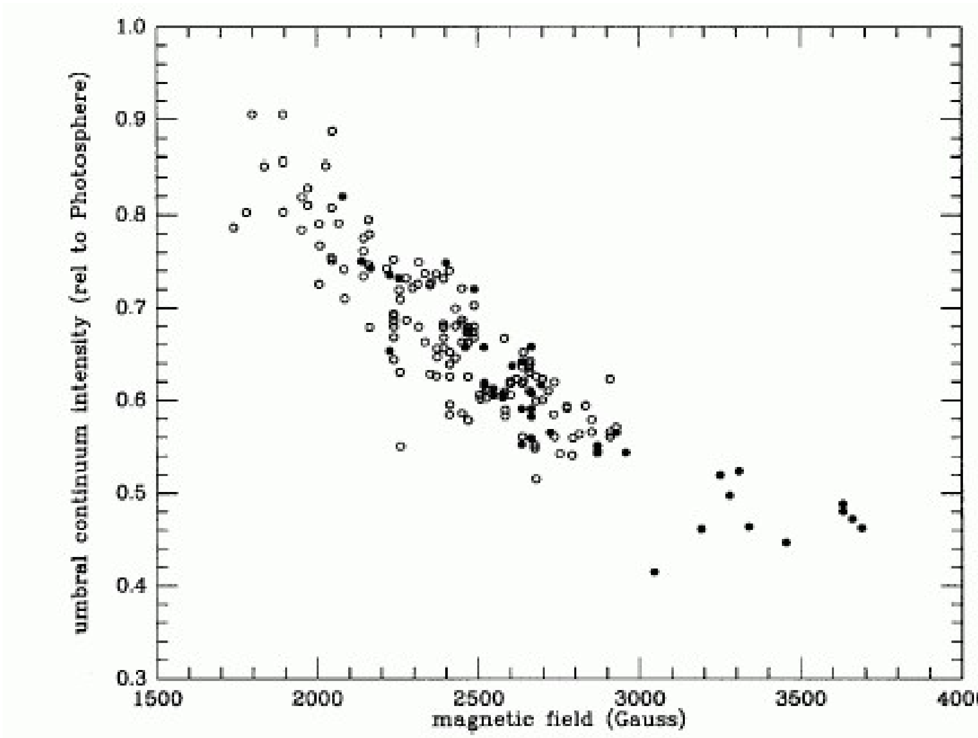


Figure 2. Peak magnetic field vs. umbral continuum intensity. *Filled circles* are for cycle 22 (1[…] 1991); *open circles* for cycle 23 (2000–2001). Each point represents an individual spot.

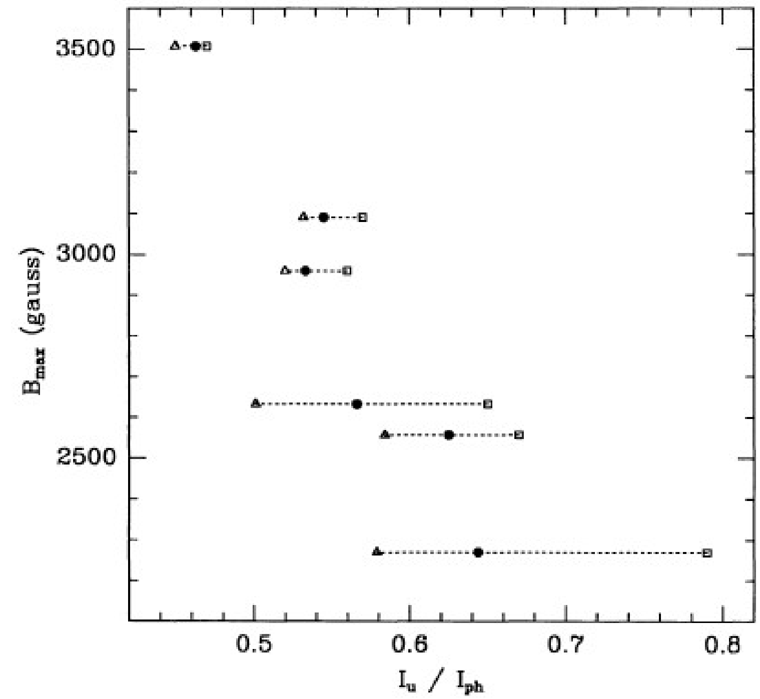
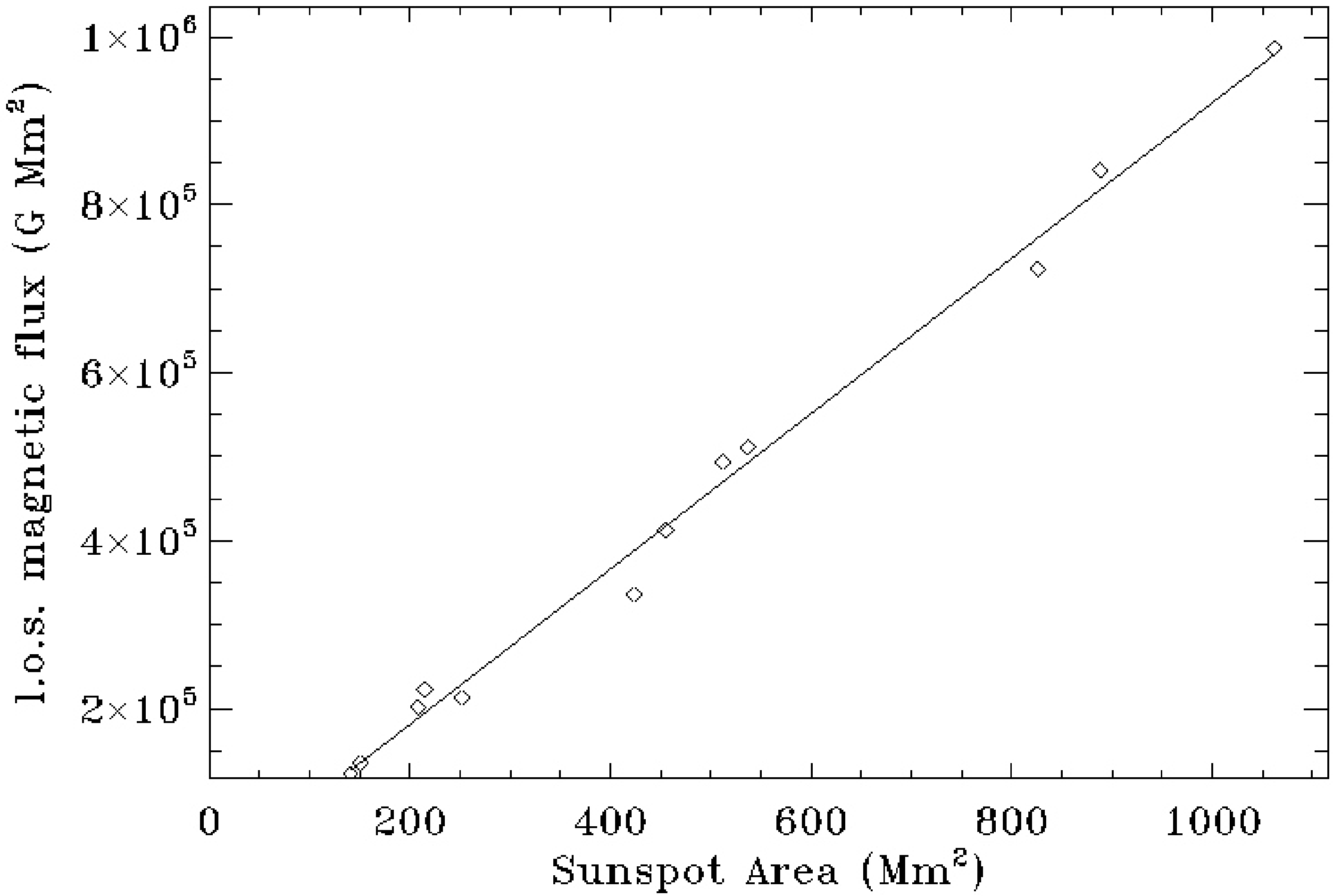


Fig. 6. Maximum magnetic field strength vs corresponding umbral intensity (in units of mean quiet Sun intensity) for the six sunspots. Three intensity values are shown for each spot: observed values (open squares); best-estimate stray light corrected values using the nominal blurring parameters (b_1, b_2, f_1, f_2) plus scattered light (see text) (filled circles); and worst-guess blurring parameters ($\tilde{b}_1, \tilde{b}_2, \tilde{f}_1, \tilde{f}_2$) plus scattered light (triangles).

Livingston (2002)

Kopp & Rabin (1992)

Impact of scattered light correction (2)

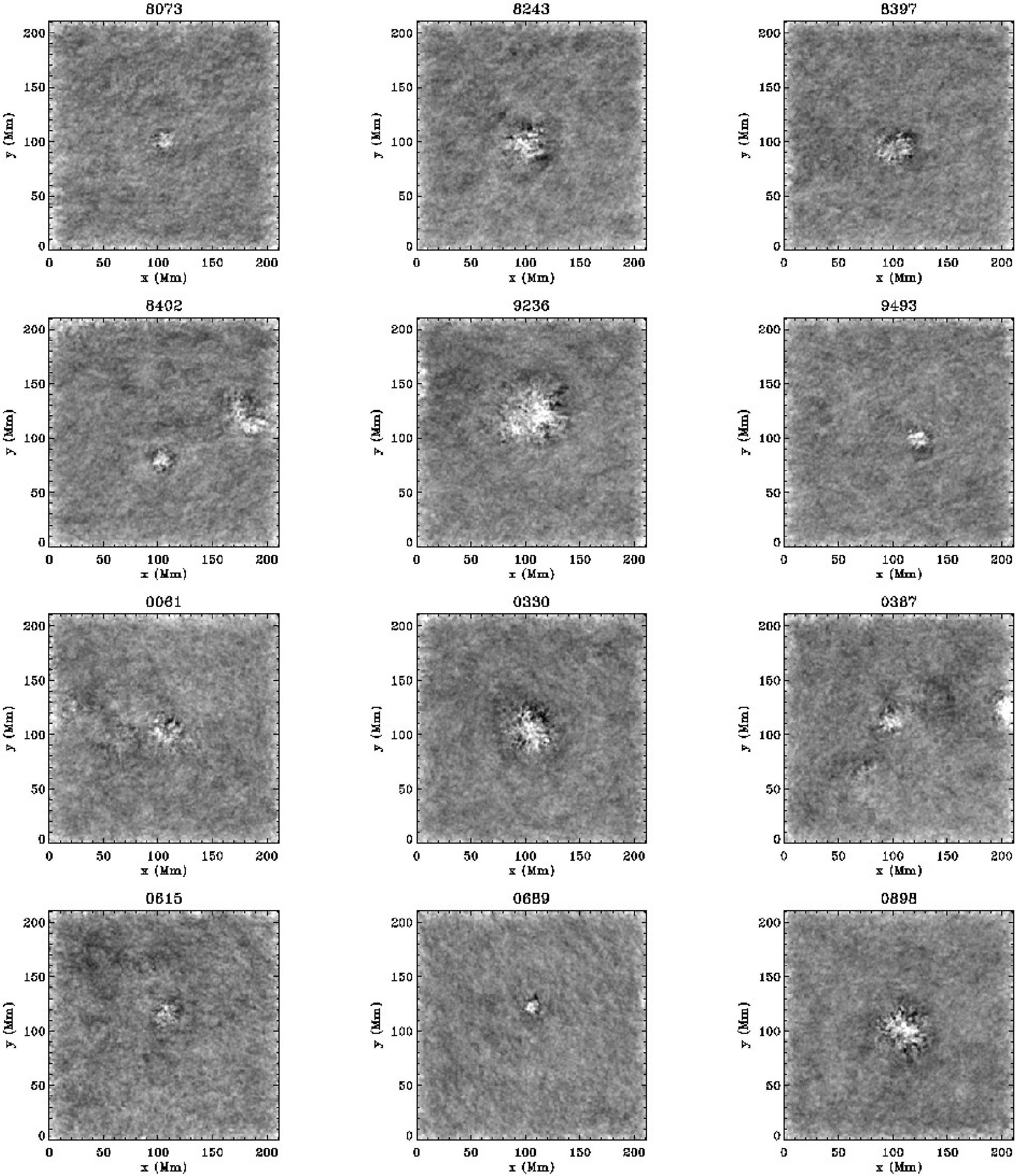


Linear relation as reported in Solanki (2003)

Methodology

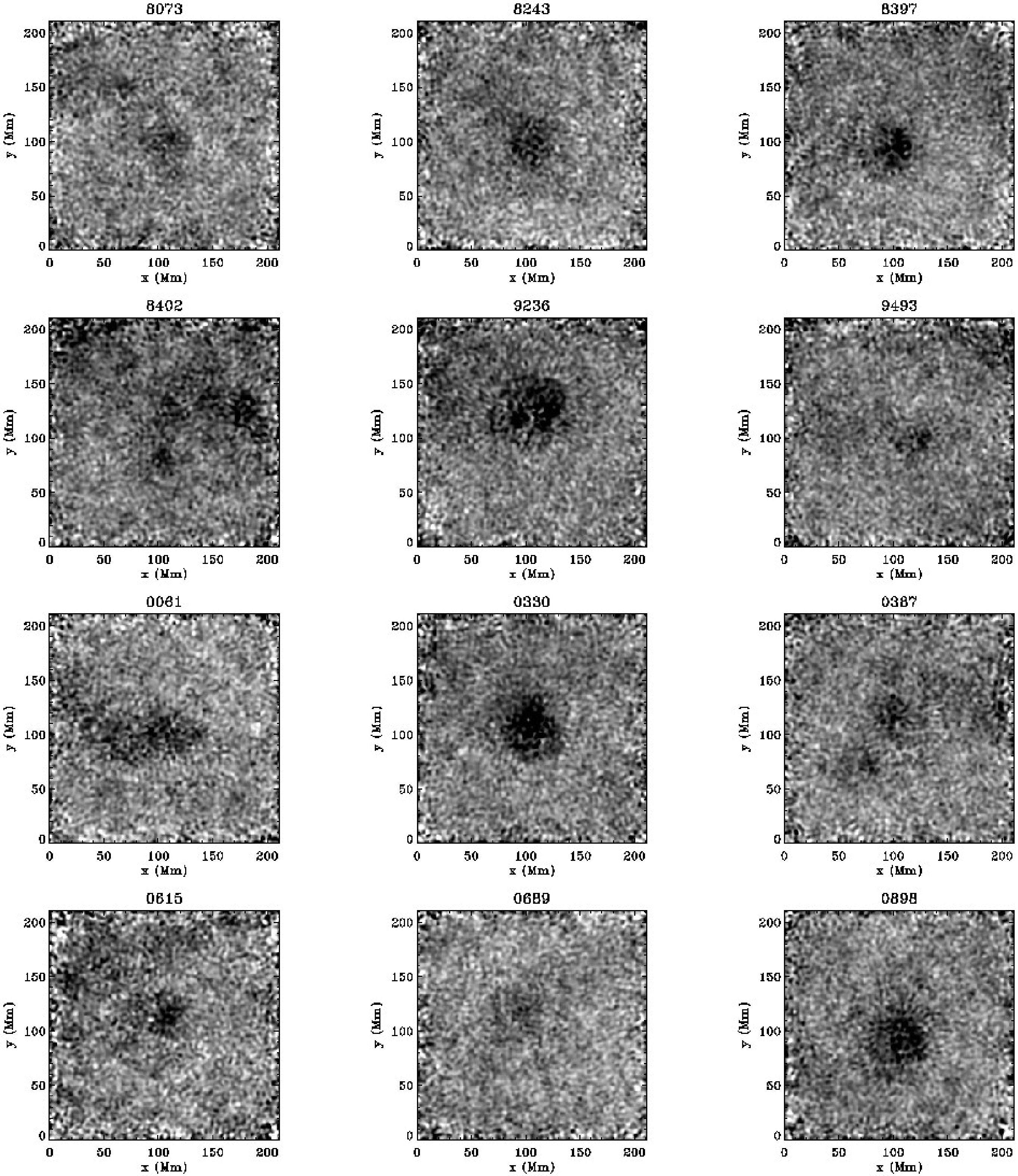
- Time-distance analysis (Duvall et al. 1993): mean-travel time perturbations for 36 distances source-receiver (from 6.2 to 66.7 Mm). Gabor wavelet fit
- MCD inversion (Jensen, Jacobsen, & Christensen-Dalsgaard 1998): modified with horizontal regularization (Couvidat et al. 2005)
- Sensitivity kernels: Born-approximation kernels (Birch, Kosovichev, & Duvall 2004) provided by Aaron
- Caveats: we make the assumption that mean-travel time perturbations are entirely due to sound-speed perturbations below the solar surface; we use Born kernels with Gabor wavelet fit; we assume linear approximation is valid

Results



Mean travel-time perturbations at 10 Mm

Results (2)

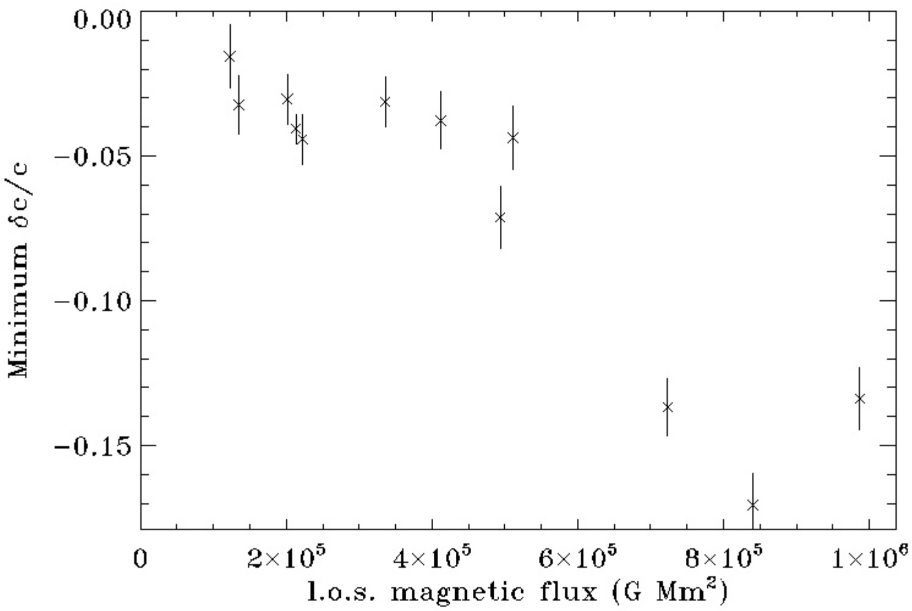


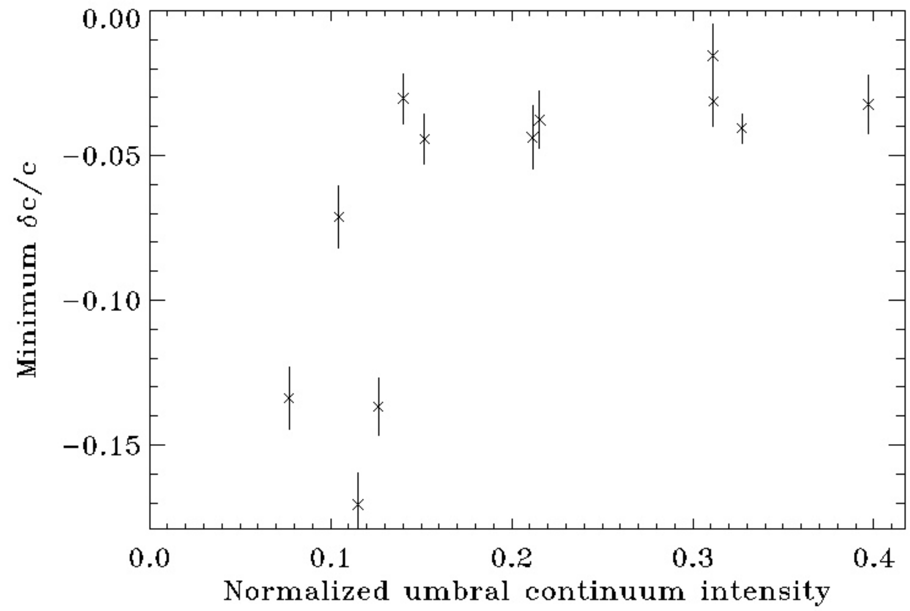
Mean travel-time perturbations at 22 Mm

Results (3)

All sunspots show two-region structure in sound-speed

Region of decreased sound-speed



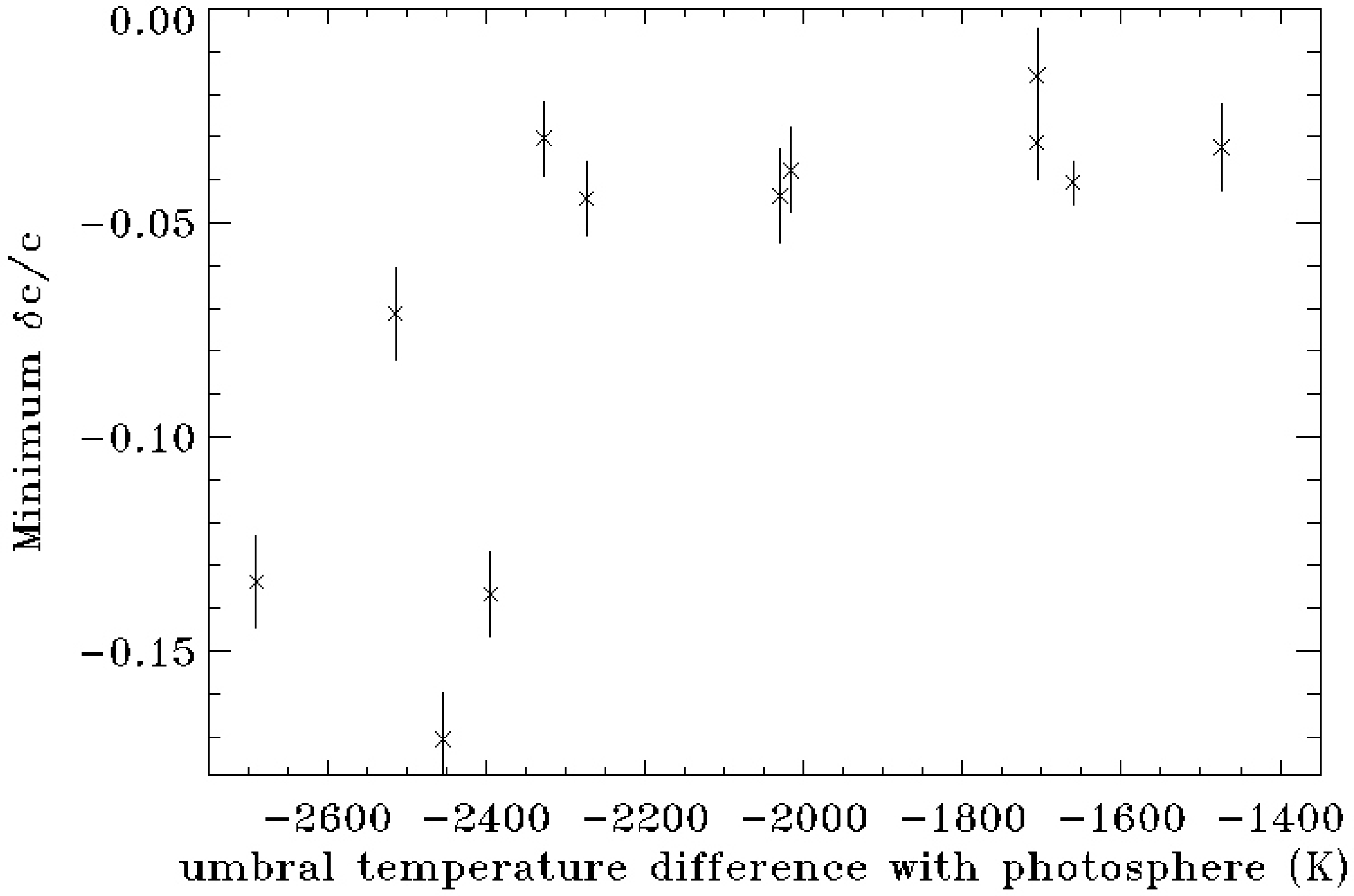


Correlation coefficient r1
= 0.91 (±0.05)

Correlation coefficient r2
= 0.71 (±0.14)

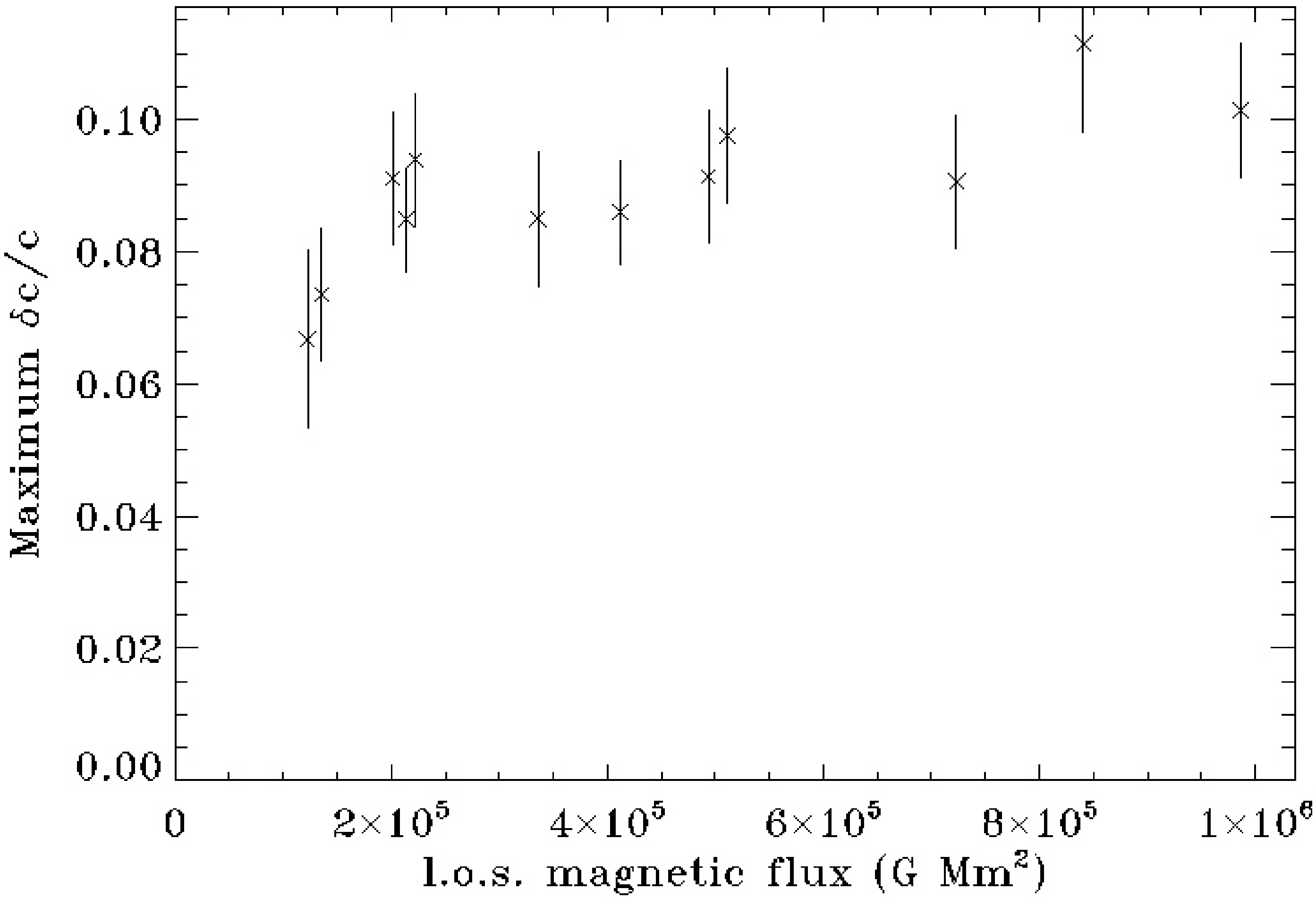
Magnetic inhibition of convection explains r2 (?)
while r1 >r2 shows significance of direct impact of B on wavefield (?)

Temperature at the surface obtained by Planck function



Results (4)

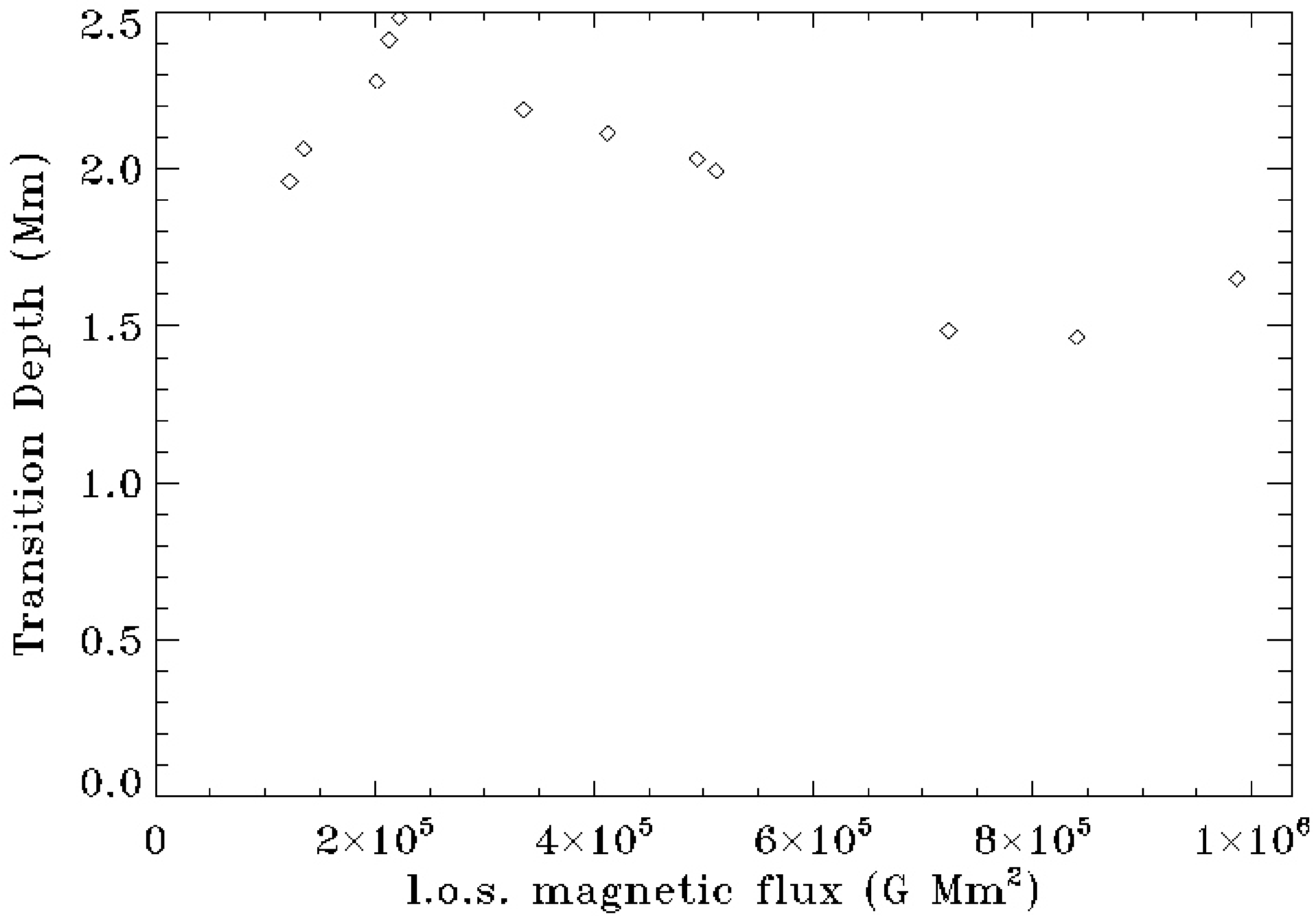
Region of increased sound-speed



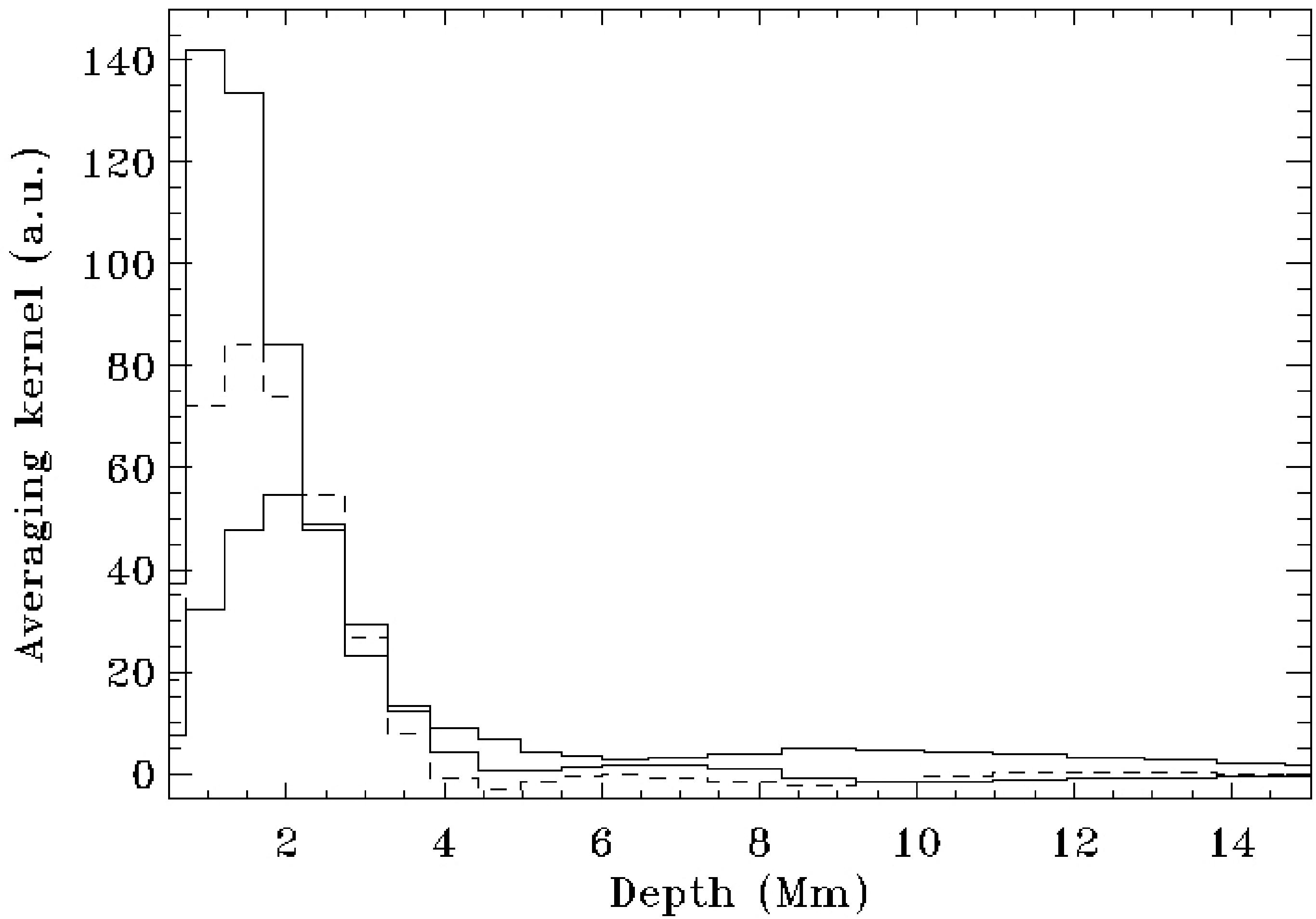
Correlation coefficient r1 = r2 = 0.77 (±0.12)

Results (5)

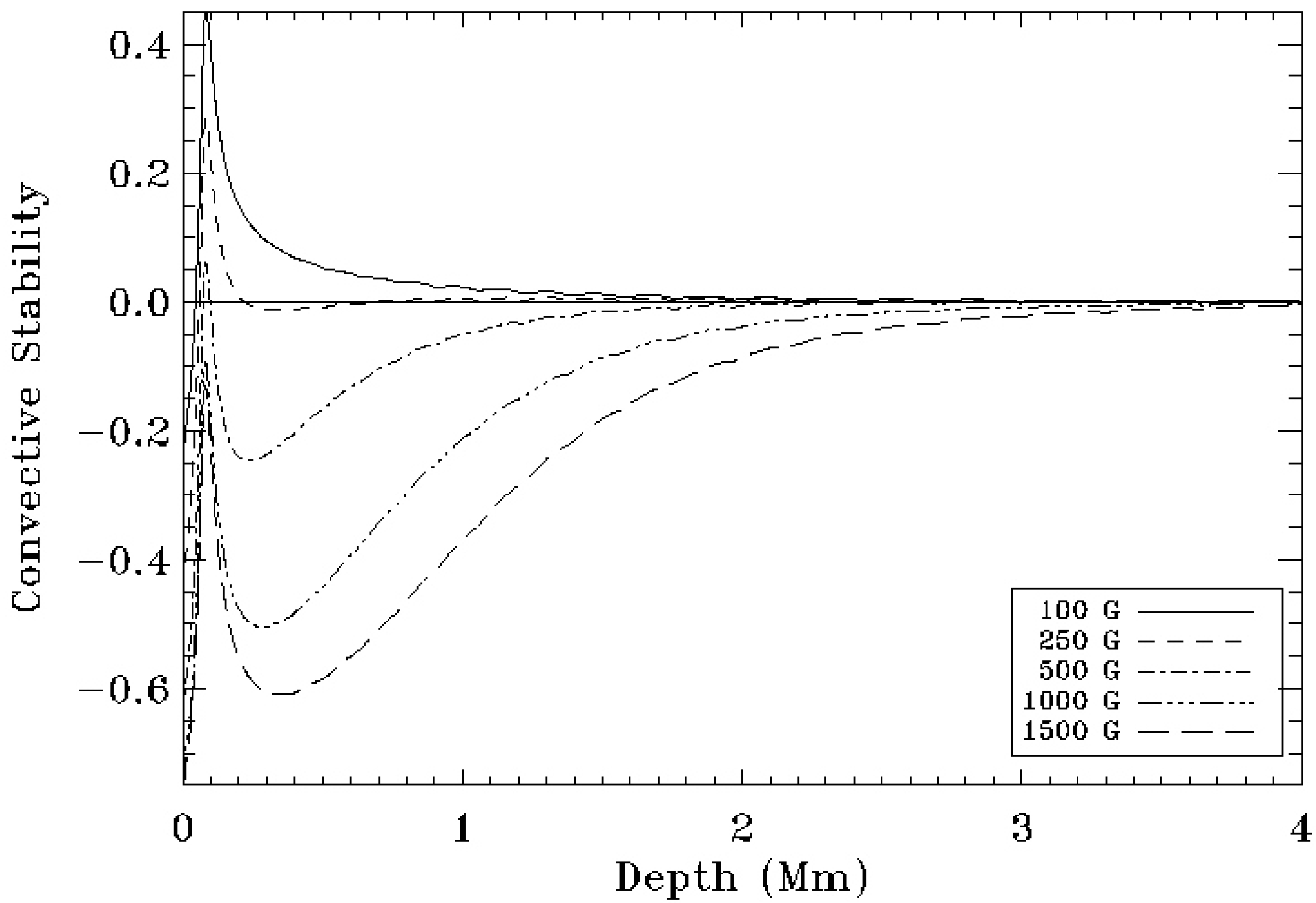
Transition zone between dc/c <0 and dc/c >0 seems shallower when magnetic flux increases



Averaging kernels at 3 target depths (1.21-1.69 Mm; 1.69-2.22 Mm; 2.22-2.75 Mm)



Convective stability criterion (Gough & Tayler 1966)



$$B^2/[\gamma(P+B^2)] > 1/\gamma - P/\rho \, d\rho/dP$$

Conclusions

- Caveat: strong assumption regarding $\delta c/c$ and $\delta\tau$
- Increase in mean travel time at short distances, decrease at large distances, is general feature of sunspots
- Region of decreased sound speed: temperature drop cannot **completely** explain the decrease in sound speed, because r1>r2 and transition zone is shallower for stronger magnetic fields => probably shows the significance of direct effects of the magnetic field (corroborating, e.g., Lindsey and Braun (2003), Cally (2000), Crouch et al. (2006), Braun and Birch (2006), Couvidat and Rajaguru (2007)...
- Nevertheless, temperature drop could be the main source of decreased sound speed