# A Thermal Origin of the Sound-Speed Perturbations Below Sunspots?

Sébastien Couvidat

couvidat@stanford.edu

*W.W. Hansen Experimental Physics Laboratory, Stanford University, Stanford, CA 94305-4085*

## ABSTRACT

We apply the time-distance formalism to Doppler velocity data of 12 sunspots observed by the MDI instrument, between 1997 and 2006. Maps of the mean travel-time perturbations of acoustic waves are produced for 36 distances between source and receiver, and inverted for sound-speed perturbations below the solar surface down to 26.8 Mm. The two-region subsurface structure of a sunspot (a shallow region of sound-speed [$c$] decrease immediately below the surface followed by a region of sound-speed increase deeper inside the Sun) is observed for every active region. We study how the surface line-of-sight magnetic flux and the surface umbral temperature relate to the amplitudes of the sound-speed perturbation below the surface and to the transition depth between $\delta c/c < 0$ and $\delta c/c > 0$. These relationships are used to analyze the hypothesis that the two-region subsurface structure is mainly or only a thermal effect. We confirm that the magnetic field also directly contributes significantly to this subsurface structure.

## 1. Introduction

We study 12 sunspots observed in Hi-Res mode by MDI, and for which Doppler velocity, continuum intensity, and line-of-sight magnetic-field measurements are concurrently available. We only select sunspots composed of a single umbral core, and we apply to them the time-distance formalism (Duvall *et al.*, 1993). The first inversion of the sound-speed profile below a sunspot by Kosovichev, Duvall, and Scherrer (2000) revealed a two-region structure: immediately below the surface $\delta c/c < 0$ inside the sunspot compared to the quiet Sun, and then $\delta c/c > 0$ in deeper layers. Other inversions for various sunspots confirmed this result (*e.g.* Jensen *et al.*, 2001; Couvidat *et al.*, 2004; Hughes, Rajaguru, and Thompson, 2005; Zharkov, Nicholas, and Thompson, 2007). The physical meaning of this structure is not yet fully understood, as the separation of —among others— thermal and magnetic field effects is not done during the sound-speed perturbation inversion. Kosovichev et al. (2000) suggested that the region $\delta c/c < 0$ may be due to a lower temperature, resulting from the magnetic inhibition of convection. Similarly they interpreted the deeper region of $\delta c/c > 0$ as a region of possible increased temperature. Other physicists argue that the region of decreased sound speed might be primarily magnetic in origin (*e.g.* Crouch *et al.*, 2006).

Here we try to shed light on the nature of the regions of perturbed sound speed that inversions retrieve, by analyzing 12 sunspots. Even though this is too small a sample to allow a thorough statistical analysis, this is the first time that so many sunspots have been subjected to the same time-distance analysis code at once and are inverted with the same regularization parameters.

## 2. Data Processing

### 2.1. Datasets

We utilize a subset of the data of Couvidat and Rajaguru (2007). Contiguous Dopplergrams are stacked together to produce 3D datacubes $\phi(\mathbf{r}, t)$ of the line-of-sight (l.o.s) Doppler velocity at the solar surface, where $\mathbf{r} = (x, y)$ is the horizontal vector, and $t$ is the time coordinate. The dimensions of these cubes are $256 \times 256 \times 512$ nodes, with a spatial resolution $\delta x = \delta y = 0.826$ Mm, and a temporal resolution $\delta t = 1$ minute. The same procedure is applied to produce data cubes of the strength of the l.o.s. magnetic field $[\mathbf{B}(\mathbf{r}, t)]$ from magnetic field maps (magnetograms), and to produce datacubes of the solar continuum intensity $[I_0(\mathbf{r}, t)]$.

All our sunspots are close to disk center, with $\cos(\mu) > 0.93$, where $\mu$ is the angle between l.o.s. and the vertical direction.

Here, a sunspot is defined as a group of contiguous pixels with a l.o.s. magnetic field strength larger than 300 Gauss and that exhibits both an umbra and penumbra. The area of such a spot is the number of pixels within this spot (umbra+penumbra) multiplied by the area of a pixel $\delta x \times \delta y = 0.682$ Mm$^2$. The l.o.s. magnetic flux is the value of $\mathbf{B}(\mathbf{r}, t)$ at each pixel multiplied by the area of a pixel (we averaged $\mathbf{B}(\mathbf{r}, t)$ over a range of $t$). For each sunspot, we also take the average value of the five lowest continuum intensities measured inside its umbra, as determined on intensity maps averaged over $t$. We refer to this value as the umbral continuum intensity. Table 1 summarizes the properties of the sunspots studied.

### 2.2. Correction Of The Intensity And Magnetic Field Maps For Scattered Light

The MDI continuum intensity is contaminated by scattered light (*e.g.* Mathew *et al.*, 2007). To correct the intensity maps we perform a Wiener deconvolution based on the measured point spread function (PSF) of MDI. We work with azimuthally-averaged PSFs provided by M.C. Rabello-Soares (Rabello-Soares, Korzennik, and Schou, 2001), and also with the PSF described in Table A.1. of Mathew *et al.* (2007), which was derived from Mercury transit data. These PSFs are obtained from full-disk MDI data, while here we deal with hi-res data: we scale the full-disk PSF to account for the change in pixel size. The deconvolution by the MDI PSF makes the normalized umbral continuum intensities drop by $0.05 - 0.10$, with a somewhat larger drop for smaller sunspots (see Table 1), as expected.

To correct the magnetic-field maps, we assume that the solar line profile measured by MDI at a specific location on the solar disk is a linear combination of the line profile of light emitted at this specific location and of the line profile of light emitted somewhere else on

Table 1: Characteristics of the sunspots studied, for a threshold of 300 G. NOAA is the number of the active region hosting the sunspot. Cor. is for data corrected for scattered light. Area is the area in $\mathrm{Mm}^2$ of the sunspot. Flux is the l.o.s. magnetic flux in kG $\mathrm{Mm}^2$. $I_0/I_p$ is the umbral continuum intensity normalized to quiet Sun photospheric value $I_p$.

| 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 |

the solar disk but reaching the same MDI pixel because of scattering (J. Schou and Y. Liu, private communications). Under this assumption, the l.o.s. magnetic-field strength $[B_{\mathrm{MDI}}(x,y)]$ measured by MDI is related to the actual magnetic-field strength $[B_{\mathrm{exact}}]$ through the following equation:

$$B_{\mathrm{MDI}}(x,y) = \frac{\int B_{\mathrm{exact}}(x',y')\, I_{0;\mathrm{exact}}(x',y')\, \mathrm{PSF}(x-x',y-y')\, \mathrm{d}x'\mathrm{d}y'}{\int I_{0;\mathrm{exact}}(x',y')\, \mathrm{PSF}(x-x',y-y')\, \mathrm{d}x'\mathrm{d}y'} \tag{1}$$

where $I_{0;\mathrm{exact}}$ is the actual solar continuum intensity. We retrieve $B_{\mathrm{exact}}$ by performing a Wiener deconvolution. For the rest of the poster we shall use the corrected values of intensity and magnetic field strength only, unless otherwise mentioned.

# 3. Results

We invert the mean travel-time perturbation $\delta\tau_{\rm mean}(\mathbf{r},\Delta)$ maps for sound-speed perturbation using a regularized least-squares algorithm (details in Couvidat et *al.*, 2005). We invert for 36 layers in depth, with the deepest layer centered 26.8 Mm below the surface. The travel-time maps of the 12 sunspots all show an increase in $\delta\tau_{\rm mean}(\mathbf{r},\Delta)$ at short $\Delta$ (see Figure 1) and a decrease at large $\Delta$ (Figure 2). Therefore the inversion of these maps produces 3D sound-speed perturbations that show the usual two-region structure underneath the sunspots. The minimum (respectively maximum) amplitude of $\delta c/c$ in the region where $\delta c/c < 0$ (respectively $\delta c/c > 0$) varies between sunspots. Similarly, the depth at which the transition between these two regions occurs shows some variation.

## 3.1. Relationships Between Surface Area Of Sunspots, Their l.o.s. Magnetic Fluxes, And Their Minimum Continuum Intensities

Following Norton and Gilman (2004), we determine the temperatures corresponding to the umbral continuum intensities of each sunspot by using a Planck function. Upper panel of Figure 3 shows the umbral continuum intensity (normalized to the quiet-Sun photospheric intensity) as a function of the l.o.s. magnetic flux $[F]$. The umbral continuum intensity seems to vary more or less as $1/F$ as suggested by Figure 2 of Livingston (2002).

The saturation effect on MDI magnetograms (Liu, Norton, and

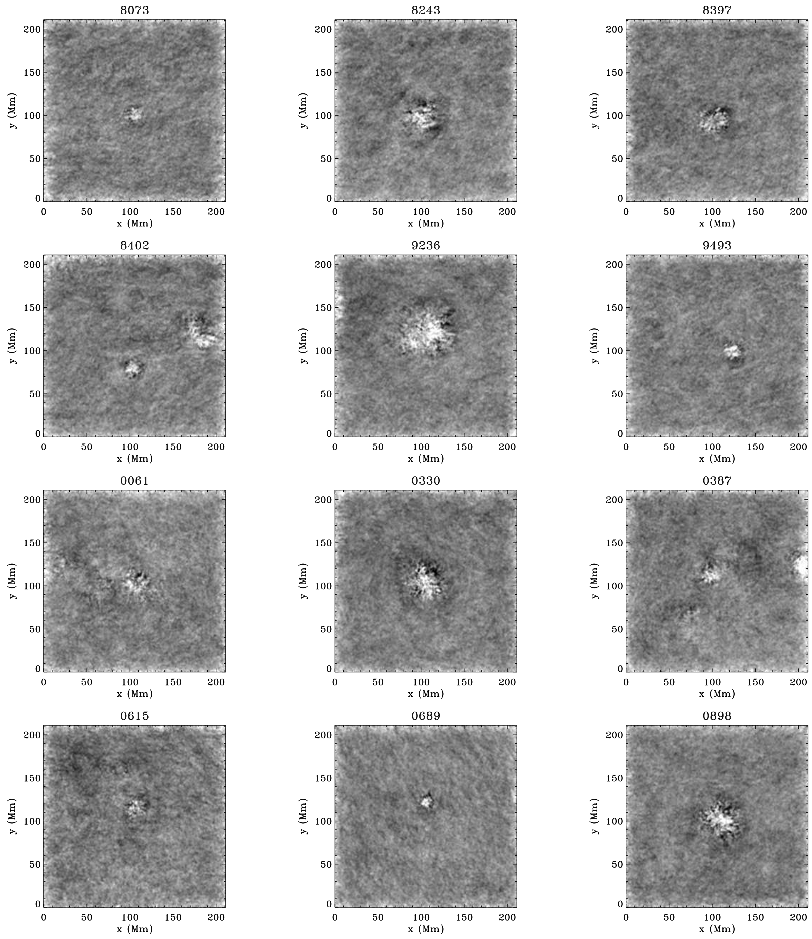


Fig. 1.— Mean travel-time perturbations $\delta\tau_{\rm mean}(\mathbf{r},\Delta)$ maps for $\Delta = 10$ Mm and for the 12 sunspots studied in this paper (NOAA number above each panel). The greyscale is the same for all panels, it is linear and has been truncated to $[-30, +30]$ seconds.

Scherrer, 2007) might artificially decrease the value of $F$ for large sunspots. However lower panel of Figure 3 shows the relation between surface area of the sunspot and its l.o.s. magnetic flux, and as expected (*e.g.* Solanki, 2003) this is very close to a linear relationship: with our sample of sunspots, the saturation effect on the magnetograms is probably not too significant (even though present).

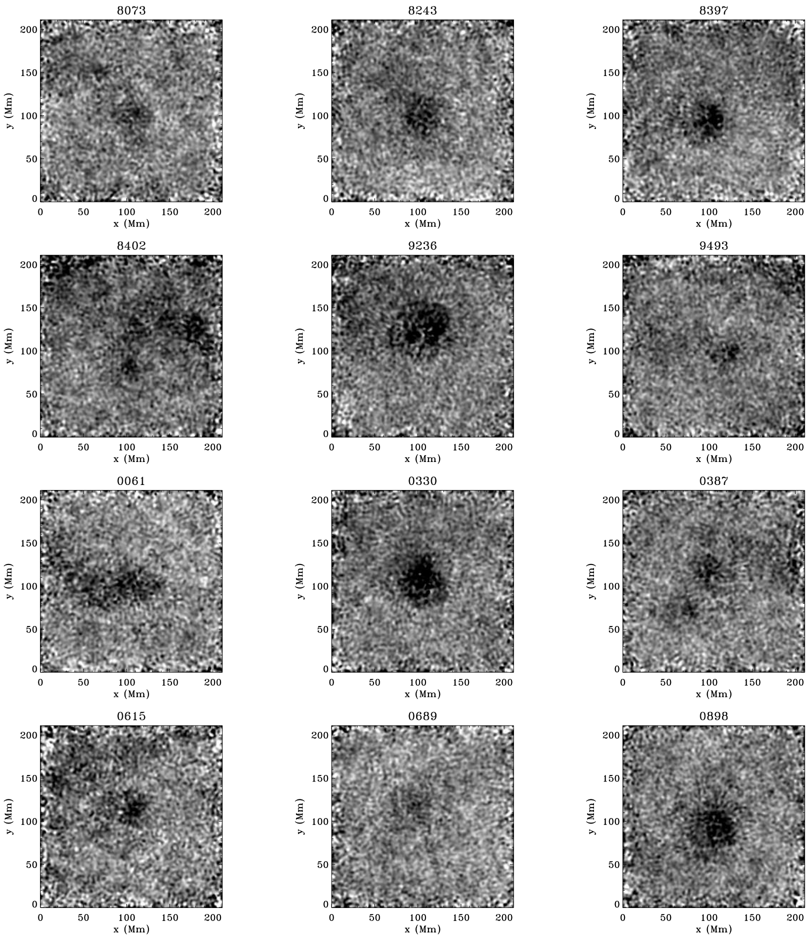


Fig. 2.— Mean travel-time perturbations $\delta\tau_{\rm mean}(\mathbf{r},\Delta)$ maps for $\Delta = 22$ Mm and for the 12 sunspots studied in this paper (NOAA number above each panel). The greyscale is the same for all panels, it is linear and has been truncated to $[-30,+30]$ seconds.

### 3.2. Amplitude Of The Sound-Speed Perturbation In The Region Where $\delta c/c < 0$

Figure 4 shows that there is a strong relationship between the l.o.s. magnetic flux at the solar surface and the minimum amplitude of the sound-speed perturbation in the subsurface region $\delta c/c < 0$. An increased magnetic field acts at different levels: it enhances the inhibition of convection in the shallow layers underneath the sunspot,

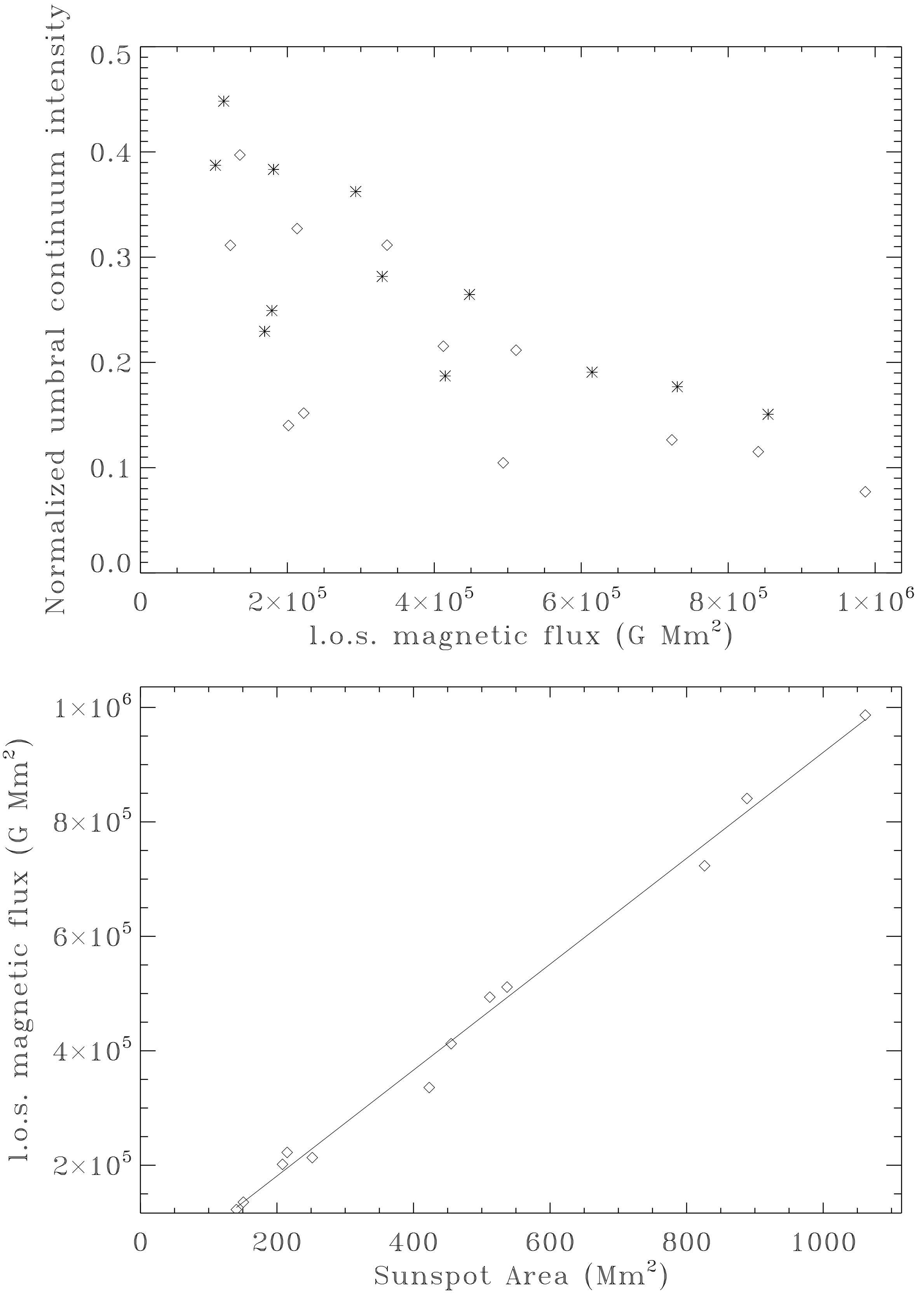


Fig. 3.— Upper panel: Umbral continuum intensity normalized to the quiet-Sun photospheric value as a function of the l.o.s. magnetic flux. Diamonds are for the intensity maps and magnetograms corrected for scattered light, while the stars are for uncorrected data. Lower panel: L.o.s. magnetic flux as a function of the surface area of sunspots. The solid line is a linear fit.

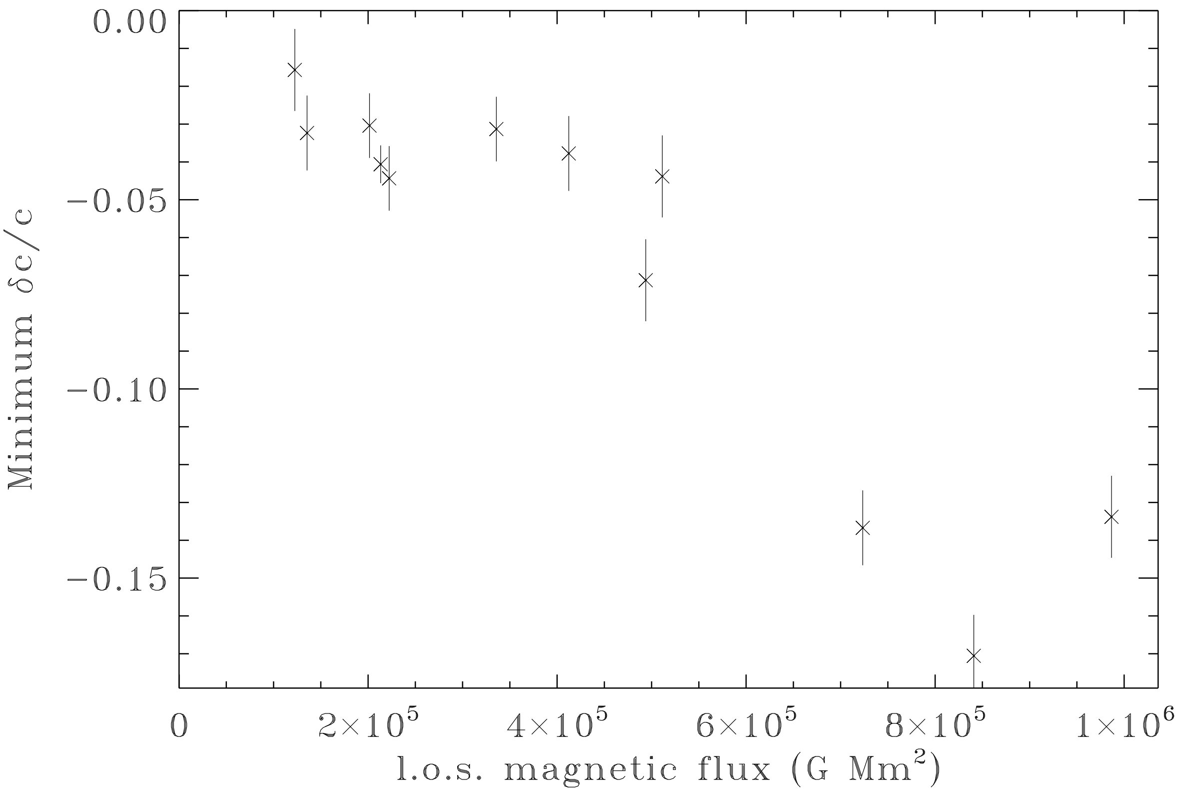


Fig. 4.— Minimum value of the inverted sound-speed perturbation in the region of decreased $\delta c/c$ as a function of the l.o.s. magnetic flux of the sunspots.

it increases the mode conversion that occurs in the region where the Alfvén speed is close to the sound speed (fast-slow MHD mode conversion, *e.g.* Cally, 2000), it increases the upward loss of energy to Alfvén waves, and more basically it reduces the gas pressure inside the magnetic region. Therefore a relationship between surface magnetic field and sound-speed perturbation underneath the sunspots was expected. Upper panel of Figure 5 shows a similar relation between minimum value of $\delta c/c$ and the umbral continuum intensity (normalized to the quiet-Sun photospheric value). Lower panel

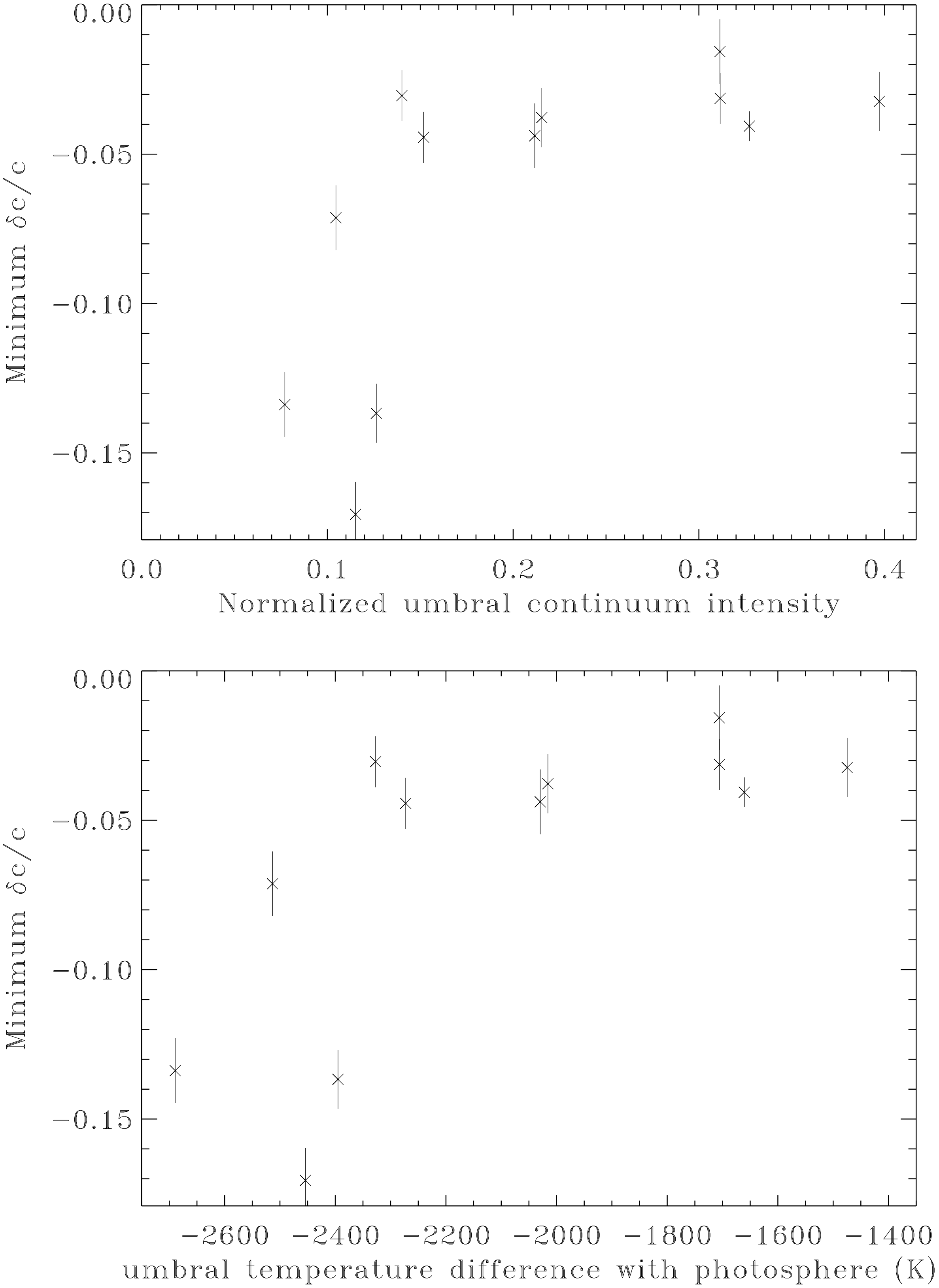


Fig. 5.— Minimum value of the inverted sound-speed perturbation in the region of decreased $\delta c/c$ as a function of the normalized umbral continuum intensity (Upper panel) and the umbral temperature difference with the quiet-Sun photospheric value (Lower panel).

of Figure 5 shows the same but as a function of temperature difference inside the umbra (difference with the photospheric temperature). The correlation coefficient between l.o.s. surface magnetic flux and minimum value of $\delta c/c$ is about $r_1 = 0.91$ (for both corrected and uncorrected magnetograms), while the correlation coefficient between umbral temperature and minimum value of $\delta c/c$ is about $r_2 = 0.71$ (corrected intensity maps) and $r_2 = 0.76$ (uncorrected maps). The decrease in $r_2$ when intensities are corrected may be due to the corresponding increase in the dispersion of umbral continuum intensities as visible on Figure 3. The one-standard-deviation [$\sigma$] uncertainty on these correlation coefficients is given by (Pearson and Filon, 1899):

$$\sigma = \frac{1 - r^2}{\sqrt{n}} \tag{2}$$

where $r$ is the value of the correlation coefficient and $n$ is the size of the sample. Because of our small sample (12 sunspots), $\sigma = 0.05$ for $r = 0.91$, $\sigma = 0.14$ for $r = 0.71$, and $\sigma = 0.12$ for $r = 0.76$. Therefore, it cannot be ruled out that we actually have $r_1 = r_2$.

A straigthforward interpretation of the difference between $r_1$ and $r_2$ (assuming that this difference is real) is that the increase in $\delta\tau_{\text{mean}}(\mathbf{r}, \Delta)$ for short $\Delta$ distances (here interpreted as a decrease in $\delta c/c$), is less due to the temperature drop in the umbra than to the strong umbral magnetic field. However, we only know the values of the magnetic field and temperature close to the solar surface, not where $\delta c/c$ is minimum. If we assume that the magnetic field and temperature at the surface are a good proxy for the magnetic field and temperature at a depth of $1 - 2$ Mm, then Figures 4 and 5 do not support the interpretation of increased mean travel times as being ONLY due to the decrease of temperature inside the sunspot: considering the large value of $r_2$ a temperature drop resulting from inhibition of convection is probably the main reason for a travel-time increase at short $\Delta$, but the magnetic field also directly impacts on this travel-time increase (on top of its indirect impact through magnetic inhibition and thus temperature change). This direct impact might be the mode conversion championed by, *e.g.* Cally (2000), Schunker and Cally (2006), and Crouch *et al.* (2006). The combination of both the direct and indirect impacts could explain why $r_1 > r_2$.

### 3.3. Amplitude Of The Sound-Speed Perturbation In The Region Where $\delta c/c > 0$

As shown on Figure 6, the relationship between maximum amplitude of the sound-speed increase in the deeper layers and magnetic field strength at the solar surface is not as strong as for the shallow layers. This is probably because: *i)* the magnetic field impacts less in deeper layers than close to the solar surface due to a larger value of $\beta = P_{\rm gas}/P_{\mathbf{B}}$, the ratio of gas to magnetic pressure; and/or *ii)* the magnetic field strength in deeper layers is less closely related to the surface field strength. The correlation coefficient between l.o.s. magnetic flux at the solar surface and maximum value of $\delta c/c$ is about 0.77 (for both corrected and uncorrected magnetic-field maps), which is equal to the correlation coefficient between umbral temperature

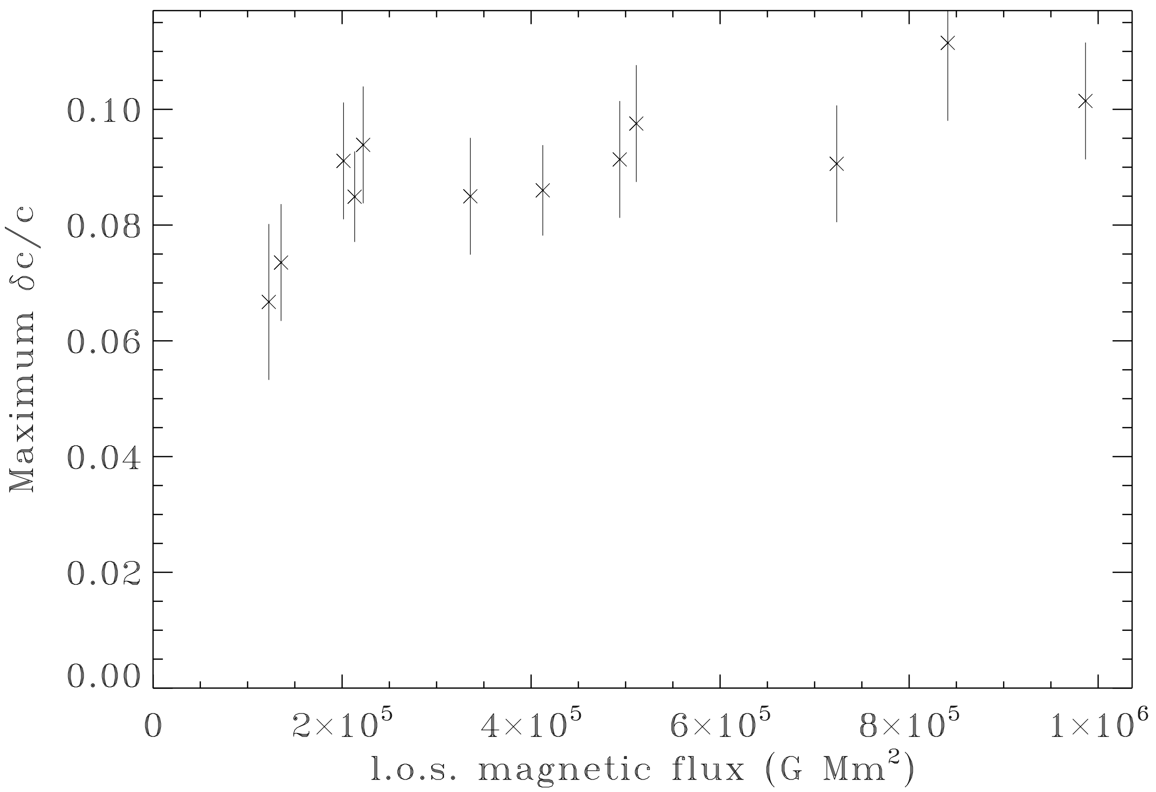


Fig. 6.— Maximum value of the inverted sound-speed perturbation in the region of increased $\delta c/c$ as a function of the l.o.s. magnetic flux of the sunspots.

and maximum value of $\delta c/c$ (also measured here at 0.77, but reaching 0.81 on uncorrected intensities). Therefore, unlike the region $\delta c/c < 0$, it can be argued that the region $\delta c/c > 0$ is completely explained by an increase in temperature.

### 3.4. Location Of The Transition Region

The depth at which the transition from $\delta c/c < 0$ to $\delta c/c > 0$ occurs increases when the l.o.s. magnetic flux decreases (Figure 7).

A precise location of this region is difficult to reach due to a coarse grid in depth, with a sampling rate of $0.5 - 0.6$ Mm, and also due to broad averaging kernels when the inversion is performed. The change in depth of the transition region is most likely not due to the inversion procedure, since the same regularization parameters were applied to all sunspots. If the trend observed on Figure 7 is real, it confirms that the increase in the mean travel-time perturbations we measure at small distances $\Delta$ inside a sunspot cannot be interpreted only as a decrease in $c$ immediately below this sunspot due to inhibition of the convection by the magnetic field. Indeed, if this inhibition producing a decrease in $c$ were to be responsible for the totality of the travel-time increase, then the sunspots with a larger magnetic flux would have the transition layer occuring deeper and not shallower as observed, as can be shown by applying the convective stability criterion developed by Gough and Tayler (1966) (Figure 8):

$$\frac{B^2}{\gamma(P+B^2)} > \frac{1}{\gamma} - \frac{P}{\rho}\frac{\mathrm{d}\rho}{\mathrm{d}P} \tag{3}$$

where $B$ is the vertical magnetic-field strength, $P$ is the gas pressure, $\gamma$ is the adiabatic exponent, and $\rho$ is the gas density. This approximate criterion states that if the inequality holds, then the magnetic field is strong enough to inhibit convection. Figure 7 supports the idea that: *i)* the mean travel-time increase observed inside sunspots for short $\Delta$ distances cannot be totally due to a decrease in sound-speed, and/or *ii)* this decrease in sound speed cannot be explained by inhibition of convection alone (*i.e.* this is not a thermal

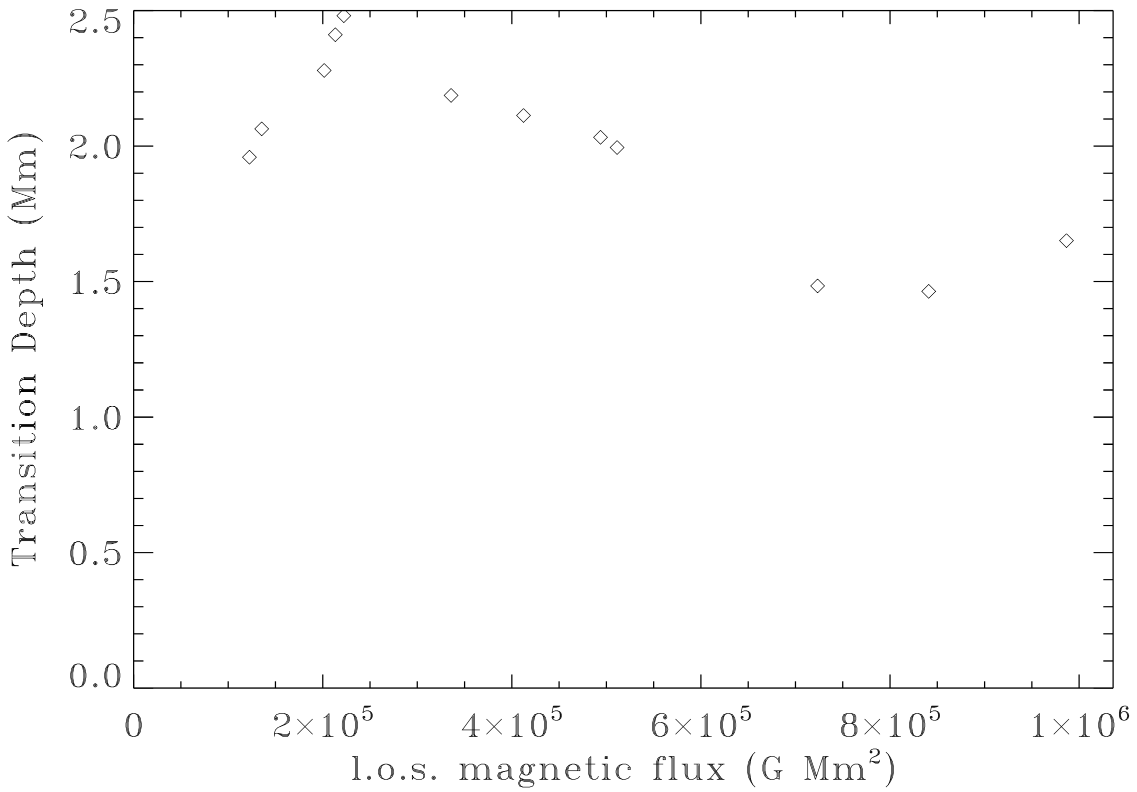


Fig. 7.— Depth at which the transition from $\delta c/c < 0$ to $\delta c/c > 0$ occurs as a function of the l.o.s. magnetic flux. The precise depth was obtained by linear interpolation between sampling points.

effect only). This shows that the magnetic field probably has a direct impact on the wave travel times. It could be that there is a balance between mode conversion — specifically the conversion of acoustic waves into fast MHD waves (*e.g.* Crouch and Cally, 2005) — which probably reduces the wave travel time, and magnetic-field inhibition of the convection, which increases the travel time. As the magnetic field strength increases, mode conversion becomes increasingly significant and pushes the transition region from $\delta c/c < 0$ to $\delta c/c > 0$

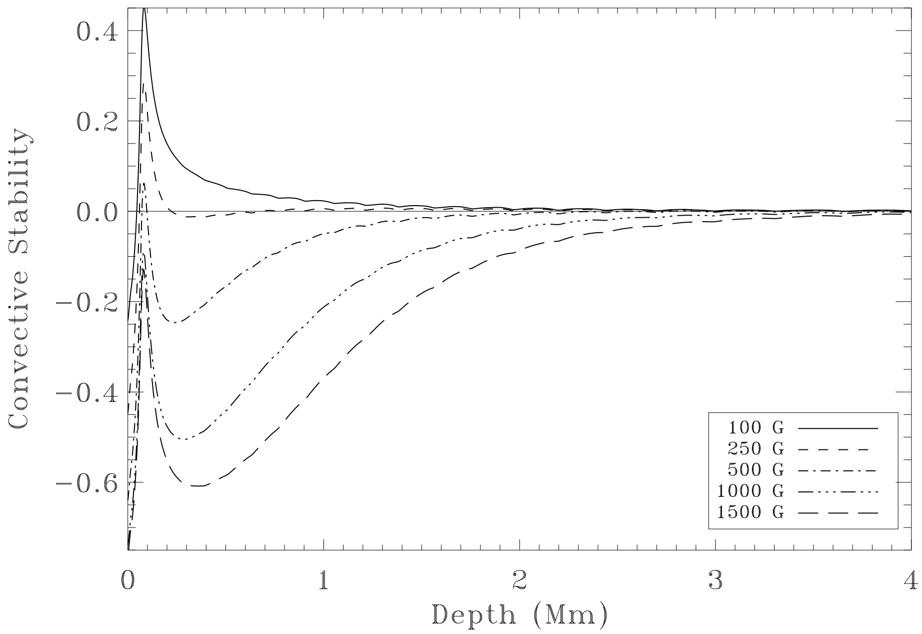


Fig. 8.— Convective stability criterion as a function of the depth and for several vertical magnetic field strengths. When the convection stability is negative, the magnetic field inside the sunspot is strong enough to totally inhibit convection.

closer to the photosphere.

## 4. Conclusion

An increase in $\delta\tau_{\rm mean}$ for short $\Delta$ distances, and a decrease for large $\Delta$ distances, are general features of the mean travel-time perturbations maps of sunspots. The explanation of the travel-time increase as being ONLY produced by a temperature drop immediately below the solar surface, due to magnetic inhibition of convection, shows its limits: if we assume that the travel-time increase can be entirely interpreted as a sound-speed decrease, then we find a larger correlation between l.o.s. magnetic flux and amplitude of $\delta c/c$ in the region where $\delta c/c < 0$, than between the umbral temperature and $\delta c/c$. Moreover, the depth at which the transition between $\delta c/c < 0$ and $\delta c/c > 0$ occurs seems to increase when the magnetic field decreases, in contradiction to what is expected from inhibition of convection by the magnetic field. Therefore, it seems that a temperature drop — in the shallow subsurface layers — alone cannot completely explain the increase in travel times, and that direct magnetic field effects advocated by, *e.g.* Lindsey and Braun (2003); Cally (2000); Crouch *et al.* (2006), also play a non-negligible role. This corroborates the results of, *e.g.*, Braun and Birch (2006) and Couvidat and Rajaguru (2007) emphasizing the role of the magnetic field on the region of increased $\delta\tau_{\rm mean}$. Nevertheless, the large correlation between surface umbral temperature and minimum value of $\delta c/c$ shows that the temperature drop underneath the sunspot is probably the main (not the unique) source of these increased travel times. Moreover, the deeper region $\delta c/c > 0$ could probably be explained by a thermal effect alone.

**Acknowledgments**

This work was supported by NASA grants NNX07AK36G (MDI) and NNG05GM85G (LWS). I thank J. Schou for his valuable help regarding the correction of intensity and magnetic field maps from scattered light and M. C. Rabello-Soares for providing me with her very useful MDI PSFs. Finally I also thank T. L. Duvall for very useful comments on this work.

## REFERENCES

Braun, D.C., and Birch, A.C.: 2006, ApJ, 647, 187.

Cally, P.S.: 2000, Solar Phys., 192, 395.

Couvidat, S., Birch, A.C., Kosovichev, A.G., and Zhao, J.: 2004, ApJ, 607, 554.

Couvidat, S., Gizon, L., Birch, A.C., Larsen, R.M., and Kosovichev, A.G.: 2005, ApJ, 158, 217.

Couvidat, S., and Rajaguru, S.P.: 2007, ApJ, 661, 558.

Crouch, A.D., and Cally, P.S.: 2005, Solar Phys., 227, 1.

Crouch, A.D., Cally, P.S., Charbonneau, P., Braun, D.C., and Desjardins, M.: 2006, Solar MHD Theory and Observations: A High Spatial Resolution Perpective, APS Conference Series, 354, 161.

Duvall, T.L., Jr., Jefferies, S.M., Harvey, J.W., and Pomerantz, M.A.: 1993, Nature, 362, 430.

Gough, D.O., and Tayler, R.J.: 1966, MNRAS, 133, 85.

Hughes, S.J., Rajaguru, S.P., and Thompson, M.J.: 2005, ApJ, 627, 1040.

Jensen, J.M., Duvall, T.L., Jr., Jacobsen, B.H., and Christensen-Dalsgaard, J.: 2001, ApJ, 553, 193L.

Kosovichev, A.G., Duvall, T.L., Jr., and Scherrer, P.H.: 2000, Solar Phys., 192.

Lindsey, C., and Braun, D.C.: 2003, SoHO 12/GONG+ 2002 Workshop, ESA publications, 23.

Liu, Y., Norton, A.A., and Scherrer, P.H.: 2007, Solar Phys., 241, 185.

Livingston, W.: 2002, Solar Phys., 207, 41.

Mathew, S.K., Martínez Pillet, V., Solanki, S.K., and Krivova, N.A.: 2007, A&A, 465, 291.

Norton, A.A., and Gilman, P.A.: 2004, ApJ, 603, 348.

Pearson, K, and Filon, L.N.G.: 1899, Philosophical Transactions of the Royal Society, A, 191, 229.

Rabello-Soares, M.C., Korzennik, S.G., and Schou, J.: 2001, Helio- and asteroseismology at the dawn of the millennium, (ESA SP-464), ESA, Noordwijk, Netherlands, p.129-136.

Schunker, H., and Cally, P.S.: 2006, MNRAS, 372, 551.

Solanki, S.K.: 2003, A&A Review, 11, 153.

Zharkov, S., Nicholas, C.J., and Thompson, M.J.: 2007, Astron. Nachr., 328, 240.

This preprint was prepared with the AAS LATEX macros v5.2.