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Comparison of subsurface sound-speed structures of three active regions

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Abstract. We analyze three solar active regions observed with the MDI instrument onboard SoHO (Scherrer *et al.* 1995). We apply the time-distance helioseismology formalism to derive the travel times of acoustic waves propagating through these active regions. The inversion of these acoustic travel times gives us access to the 3D sound-speed structure below the sunspots. We compare the main characteristics of these inversion results as a function of the active region size and magnetic field strength.

The methodology and assumptions applied here for deriving the travel times of acoustic waves and performing their inversion is described in detail in Couvidat *et al.* (2005; 2006) and references therein. We study the following active regions: NOAA 8243 of June 18, 1998 (Kosovichev *et al.* 2000; Couvidat *et al.* 2006), NOAA 8555 of June 1, 1999 (data provided by Tom Duvall), and NOAA 9236 of Nov. 24, 2000 (provided by Junwei Zhao).

More sunspots need to be studied and here we only present preliminary results. Figure 1 shows a vertical cut in the inverted squared sound-speed perturbation $\delta c^2/c^2$ for these regions (lower panels). All three sunspots exhibit the well-known two-region structure:

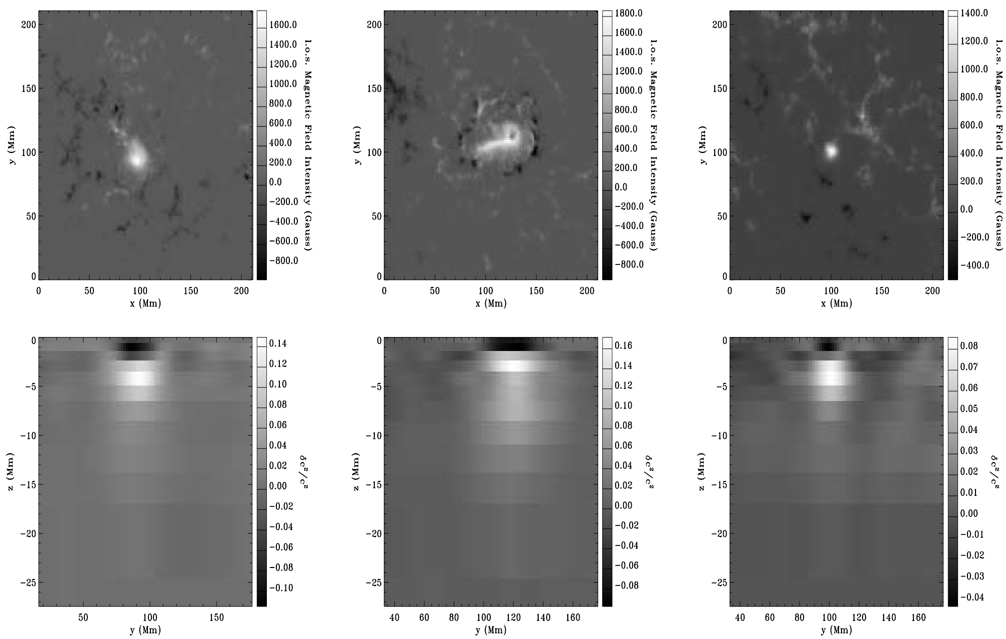

Figure 1. Lower panels: vertical cuts in the inverted $\delta c^2/c^2$ cubes for AR 8243 (left panel), AR 9236 (middle panel), and AR 8555 (right panel). Upper panels: corresponding magnetograms from MDI.

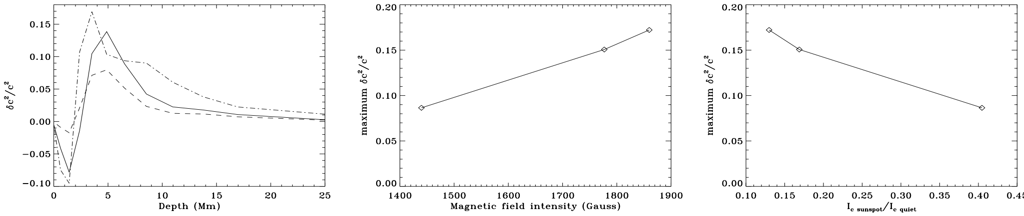

Figure 2. Left panel: $\delta c^2/c^2$ profile for the three active regions studied: NOAA 8243 (solid line), NOAA 8555 (dashed line), and NOAA 9236 (dash-dotted line). These profiles are averages over a small region centered on the different spots. Middle panel: peak positive value of $\delta c^2/c^2$ as a function of the maximum magnetic field strength in the active region. Right panel: peak positive value of $\delta c^2/c^2$ as a function of the minimum continuum intensity in the active region—as measured by MDI—divided by the continuum intensity in the quiet Sun.

near the solar surface the sound speed is reduced compared to the quiet Sun ($\delta c^2/c^2 < 0$), while in deeper layers the sound speed is increased. There seems to be a strong correlation between the active region surface area—as measured on the Doppler velocity maps, on the magnetograms, or on the inverted $\delta c^2/c^2$ cubes—and the $|\delta c^2/c^2|$ maximum amplitude near the surface: AR 8555 has a surface area roughly estimated to 215 Mm^2, AR 8243 to 730 Mm^2, and AR 9236 to 1600 Mm^2. For the layer $z = -0.62$ to $z = 0$ Mm, the amplitudes of the sound-speed perturbation at the center of the spot are respectively: $\delta c^2/c^2 = -0.024$, -0.053, and -0.075. Therefore, a larger active region produces a larger sound-speed perturbation in the shallow subsurface layers. There is also a correlation between the extent of the $\delta c^2/c^2 \neq 0$ region and the size of the active region: larger regions have a $\delta c^2/c^2 \neq 0$ region that extends deeper (see left panel of Figure 2). The depth at which $\delta c^2/c^2$ reaches its peak negative value appears independent of the active region: it is always in the layer $z = -1.5$ to $z = -0.62$ Mm. This effect might be real or might be due to lack of vertical resolution in the inversion. However, the depth at which $\delta c^2/c^2$ reaches its peak positive value varies with the sunspot, even though there is no apparent correlation with the sunspot size or magnetic field strength. The peak positive value is related to the active region maximum magnetic field strength, and to the intensity reduction (see middle and right panels of Figure 2). Both positive and negative peak values are correlated: the larger the negative peak value the larger is the positive one. However the ratio of peak negative $\delta c^2/c^2$ and peak positive $\delta c^2/c^2$ does not seem to be correlated with the active region size: from the smallest spot to the largest this ratio is worth -0.51, -0.77, and -0.68. The transition between $\delta c^2/c^2 < 0$ and $\delta c^2/c^2 > 0$ occurs between $z = -1.5$ and $z = -2.5$ Mm. The absolute value of the amplitude of the sound-speed perturbation appears to be always larger in the region of positive $\delta c^2/c^2$ than in the region of negative $\delta c^2/c^2$.

Globally, larger active regions produce stronger and deeper sound-speed perturbations. This was expected from the correlation between surface area of an active region and its magnetic field: larger sunspots usually have a larger magnetic field strength, and therefore they produce a larger gas temperature, pressure, and density perturbations.

References

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