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HELIOSEISMIC MEASUREMENTS OF SOLAR RADIUS CHANGES FROM SOHO/MDI

S. Lefebvre[1,2], A.G. Kosovichev[3] and J.P. Rozelot[4]

Abstract. The sub-surface of the Sun is much more complex than it does appear up to now. Analysing the SOHO/MDI (SOlar and Heliospheric Observatory/Michelson Doppler Imager) f-mode frequencies and their temporal variation for the last 9 years, we computed the variation of the radius in the subsurface layers of the Sun by applying helioseismic inversions. We have found a variability of the "helioseismic" radius in antiphase with the solar activity, with the strongest variations of the stratification being just below the surface around $0.995R_\odot$. In addition, the radius of the deeper layers of the Sun, between $0.975R_\odot$ and $0.99R_\odot$ changes in phase with the 11-year cycle. These results imply a non-homogeneous variation of the radius with depth and time and may explain discrepancies in ground-based observations.

1 Introduction and results

For the last few decades, the measurements of temporal solar radius variations have been a debated issue due to inconsistent results. Here, we proposed helioseismic inversions to infer the "seismic" radius (Schou *et al.*1997). We used the frequencies of f-modes sensitive to physical changes below the photosphere: these frequencies are issued from MDI observing runs[1]. Common modes during the period 1996-2005 have been extracted. For further inversions, only modes whose l ranges from 150 to 250 have been selected. Dziembowski & Goode (2004) established a relation between the relative frequency variations $\delta\nu/\nu$ for f-mode frequencies and the relative radius variations $\delta r/r$ of subsurface layers, $\left(\frac{\delta\nu}{\nu}\right)_l = -\frac{3l}{2\omega^2 I}\int dI\,\frac{g}{r}\frac{\delta r}{r}$, where l is the degree of the f-modes, I is the moment of inertia, ω the eigenfrequency and g the gravity acceleration. Lefebvre & Kosovichev (2005) used this equation and the Regularized Least-Squared technique to invert the seismic radius; updated results are shown in Fig. 1. Our main results are: (i) the variation of solar radius is non-uniform and confined between $0.97R_\odot$ and the surface; (ii) the inner layers (below $0.99R_\odot$) move up during the increase of activity, and so vary in phase with the solar cycle whilst the outer layers (above $0.99R_\odot$) move down, so varying in antiphase with the solar cycle; (iii) the near-surface layers are in antiphase with the solar cycle, with an amplitude of the order of 2 km.

2 Perspectives and conclusion

These results point out a cyclic modification of the physical structure just beneath the photosphere, that could be described as a very thin double-structure transition layer, the seat of the solar radius variability. This confirms previous conclusions that solar-cycle variations in the solar radius are confined to the outermost layers of the Sun (Dziembowski & Goode, 2005).

A perspective is to look for asphericities in 2D. The search for asphericities is of great interest since Rozelot *et al.* (2003) and Lefebvre *et al.* (2006a) have observed asphericities at the solar surface thanks to Pic du Midi and Mount Wilson measurements. To better understand these observations, it is important to investigate the

[1] SAp/DAPNIA/DSM CEA Saclay, L'Orme des Merisiers Bât. 709, 91191 Gif sur Yvette cedex, France
[2] UMR 7158 CEA-CNRS-Université Paris VII, 91191 Gif sur Yvette cedex, France
[3] W.W. HEPL, Stanford University, Stanford, CA 94305-4085, USA
[4] OCA/GEMINI, Avenue Copernic, 06130 Grasse, France

[1]These files are available on url: http://quake.stanford.edu/∼schou/anavw72z/

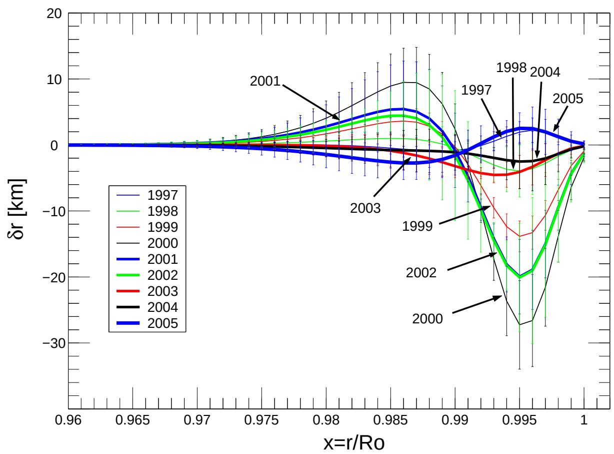

Fig. 1. Radial variation $\langle \delta r \rangle$ by reference to 1996, as a function of the fractional radius $x = r/R_\odot$, obtained as a solution of the inversion of f-mode frequencies. Note the behavior of the curves near $x = 0.99$. The error bars are the standard deviation after averaging over a set of random noise added to the relative frequencies.

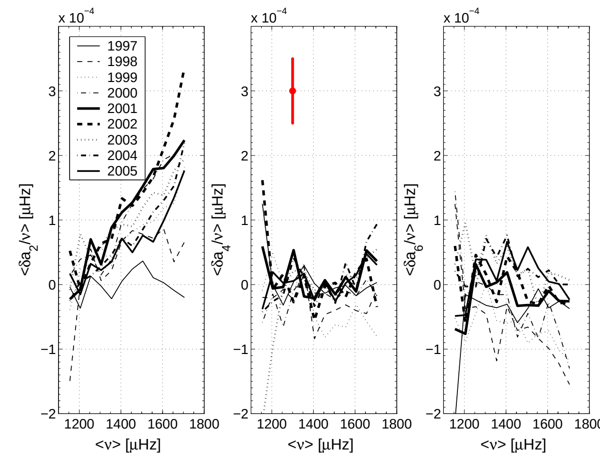

Fig. 2. Average relative differences $\langle \delta a_{2k}/\nu \rangle$ for the first 3 even-a coefficients of f-modes ($k = 1, 2, 3$) for each year by reference to the year 1996, as a function of $\langle \nu \rangle$, average frequencies binned every 50 μHz. For the sake of clarity, we only plot a mean errorbar in red in the middle panel.

subsurface layers to see if the observations at the surface propagate in the subsurface layers. This study is in progress and very preliminary results have been presented in Lefebvre *et al.* (2006b). These first results are very interesting and puzzling. Fig. 2 presents the relative variations of the first even-a a_{2k} coefficients of f-modes, $\delta a_{2k}/\nu$, and they have all different behavior with the frequency and the cycle. Moreover, the amplitude of these variations are of the order of 10^{-4}, which is 10 times bigger than the amplitude of the relative variation of the centroid frequency $\delta\nu/\nu$, which is only of the order 10^{-5}. This would mean that the relative variations in asphericities are bigger than the relative changes in the mean behavior, that is the spherical one studied in the first section, in the subsurface layers. In addition, the different behaviors of these a_{2k} coefficients show variations of asphericities both with depth and with the cycle. For the time being, these first results remain preliminary and we need to push our investigations further to better understand the physical conditions in this particular layer called "*leptocline*" (Rozelot *et al.*2006).

These results could lead to a deeper understanding of this transition zone, where complex physical processes act such as partial ionisation of the light elements, opacities changes, superadiabaticity, strong gradient of rotation and pressure. A better knowledge of this zone is necessary to understand (i) the dynamics of the solar cycle and (ii) the Sun-Earth relationships. SDO and PICARD, scheduled to be launched in 2008, then DynaMICS in a next future, will provide further observations and constraints of this zone.

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