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VARIATIONS OF THE SOLAR INTERIOR WITH THE CYCLE: OBSERVATIONAL ASPECTS.

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Abstract

Using 3 different set of helioseismic observations, we report 3 different results all related to the variation of the solar interior with the cycle. 1) Using 15 years of observations of low degree (l=1-3) pressure (p) modes with Mark-1 intrument located at the Peak del Teide (Tenerife), we have shown how the varying activity change the properties of these modes. 2) Using 6 years of observations of the medium-l modes (l=1-99) with LOWL[4] instrument located at at Mauna Loa (Hawaii), we have analysed the variations of the shape of the tachocline (interface between the solar convection and radiative zones) during the ascending phase of the cycle. 3) Using 4 years of observations of the fundamental (f) modes (l=117-300) with the MDI[5] instrument on board SoHO[6], we have quantified the radial shear of angular velocity in the subphotospheric layers and checked for its possible variation with the cycle.

1 The frequency shift of low degree p-modes and its time dependence

We have done an analysis of the low-degree p-mode properties over more than a solar cycle (Jiménez Reyes et al., 2001). The resonant frequencies, integrated between 2.5 and 3.7mHz, present a very good correlation with the solar activity cycle (see Fig. 1) whereas the total velocity power has been found anti-correlated with the solar activity.

Moreover, the frequency shifts have been obtained as a function of frequency and degree. These studies make use of data taken from two experiments (Mark-I

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[4]LOWL is an abreviation for low degree with degree denoted by L
[5]Michelson Doppler Imager
[6]Solar and Heliospheric Observatory

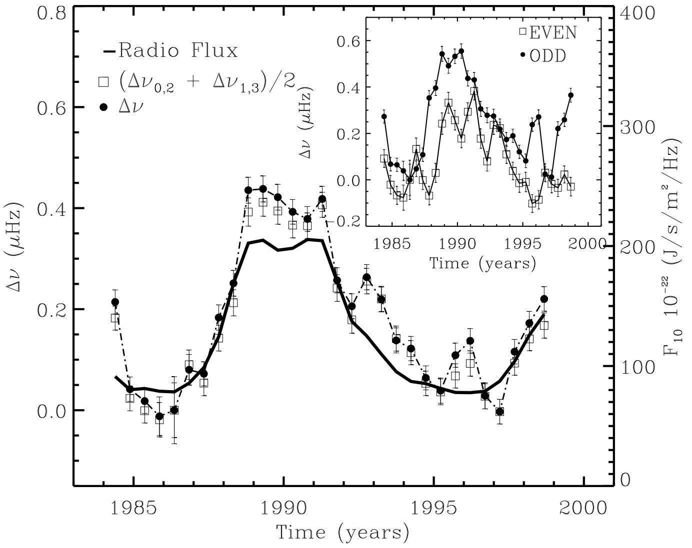

Fig. 1. Time variation of the integrated frequency shift for low-degree p-modes is plotted in the upper panel (black dots). The radio flux at 10.7 cm is also shown (full line) as a classical solar activity index.. In the sub plot, the results for the even and odd degrees separately are presented. The averages of these, are plotted in the main panel (squares)

and LOWL) which confirm each other results, when they coincide (at very low ℓ modes), and complement their findings otherwise. The freqency and l-dependences of the frequency shift being similar to those of the inverse mode mass, we conclude that the main source, of magnetic or thermic origin, for the variation of the frequencies with the cycle is located near the surface. However, interesting details such as an oscillation of the frequency shift found above 3.5mHz for the very low-ℓ p-modes and the surprisingly small frequency shift for ℓ even modes (see Fig. 1) need further investigation as they could be the signature of a secondary, deeper rooted source.

2 Prolateness of the tachocline and its time dependence

The splitting coefficients obtained for each year of LOWL observations (1994-2000) have been inverted using a 2D RLS inversion code (Corbard et al. 2001). The radial resolution obtained is about $0.12R_\odot$ at 60° and $0.10R_\odot$ at the equator. The angular resolution achieved is of about 20° at the equator. Because the radial shear doesn't exist at about 30° and because the angular resolution decrease at high latitudes, we limit our analysis to two latitudes: the equator and 60°.

The center of the tachocline is always found deeper at the equator than at 60°. The variation of this prolateness with time is shown in Fig. 2. The maximum of prolateness found is about $0.02R_\odot$. These differences and their fluctuations are

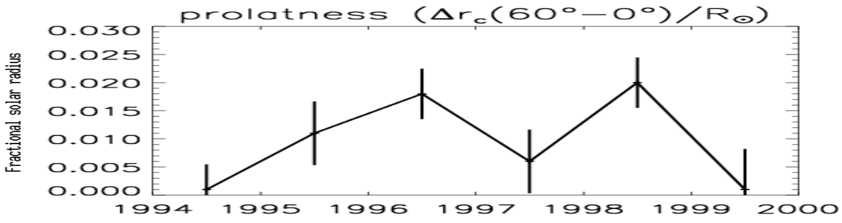

Fig. 2. Difference between the central position of the tachcline infered at 60° and at the equator, as a function of time.

nevertheless very small and are also very sensitive to the inversion parameters chosen and especially the amount of regularization used.

Generally speaking, we do not find from this analysis evidence of any general trend or significant oscillation in the tachocline parameters during the ascending phase of the actual solar cycle. Nevertheless, a prolateness of the layer is observed every year which allow us to, at least, exclude an oblate tachocline. The amount of prolateness found between the equator and 60° is however of the same order of magnitude than the uncertainties on the width of the layer. We can therefore only set an upper limit for the prolateness which is around $0.03R_\odot$. In the frame of the shallow-water model of the solar cycle (Dikpati & Gilman, 2001), this would correspond to a toroidal magnetic field strength of about 0.1MG if it is located in the overshoot layer or about 0.6MG if it is located in the radiative interior. If the toroidal field is concentrated in bands migrating towards the equator during the ascending phase of the cycle, one would expect, from the shallow water model, a decreasing prolateness for the period of LOWL observations. This general trend cannot be excluded but is not observed from our preliminary analysis of LOWL data.

3 The radial shear of the sub-surface layers and its time dependence

To look for possible temporal variations of the subsurface shear, we have analyzed 23 72-day MDI datasets individually and derived the mean slope of angular velocity in a layer of $\sim$ 15Mm for latitudes up to 75° (Corbard & Thompson, 2001). From this analysis, we found large-scale variations in the extrapolated surface rate that correspond very well to migrating banded zonal flows (or torsional oscillations, see left column of Fig. 3). The slope shows no significant corresponding variations, implying that the torsional oscillations raise and lower the rotation rate across the whole depth of the layer without changing the shear gradient. There are indications of annual variations in the inferred values of the slope (most strikingly at 30°, see Fig. 3), which are almost certainly an artifact: such artifacts can conceivably arise from annual variations in SoHO's orbit. However, these should not affect the time-averaged values which constitute the main result of our study as it is, we

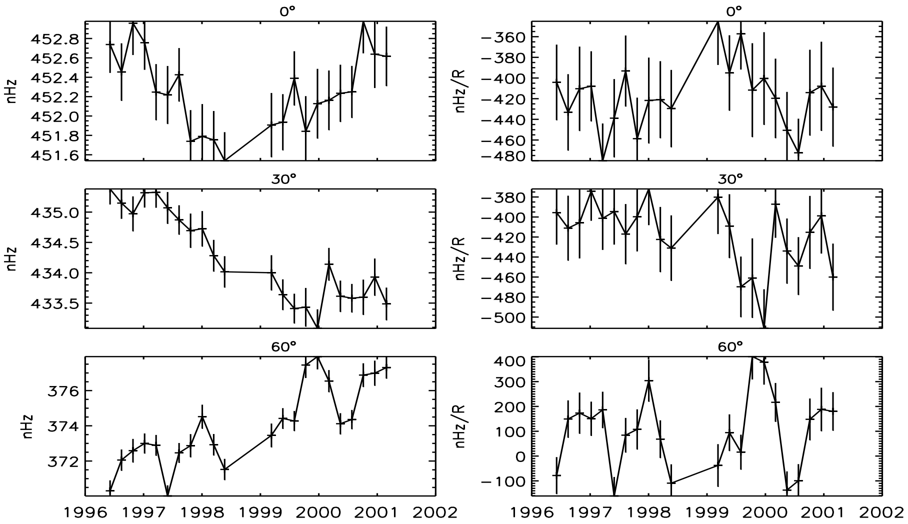

Fig. 3. Extrapolated surface values (left column) and slope (right column) of subsurface angular velocity at the equator, 30° and 60° of latitude (from top to bottom) and depth down to 15Mm.

believe, the first reliable and quantitative analysis of the subsurface radial shear. In time average, a negative outward gradient of around $-400\mathrm{nHz}/R_\odot$, equivalent to logarithmic gradient of the rotation frequency with respect to radius which is very close to -1, is found to be remarkably constant between the equator and 30° latitude. Above 30° it decreases in absolute magnitude to a very small value at around 50°. At higher latitudes the gradient may reverse its sign: if so this reversal takes place in a thin layer extending only 5 Mm beneath the visible surface, as evidenced by the most superficial modes (with degrees $l > 250$).

4 Conclusion

These first results from long term helioseismology are very encouraging and demonstrate, we think, the potential and importance of these studies in order to obtain observational constraints on the different theories of the solar cycle that are not relying only on direct surface activity observations.

References

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