The solar core rotation from LOWL and IRIS or BiSON data

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ABSTRACT

The solar core rotation is investigated by means of a 2D regularized least square inversion. A reliable rotation rate above $0.4R_\odot$ is obtained by using the rotational splittings measured between 1994 and 1996 with the data of the LOWL instrument which can observe both low and intermediate degree p-modes. For sounding the deeper layers, we have alternately added the most recent published splittings of the IRIS and the BiSON network groups. These two sets have been known to be inconsistent at more than a 3-sigma level. The consequences of this difference on the behaviour of the rotation rate inside the solar core, seen by the global inversion, are studied and discussed in this poster.

1. Observed rotational splitting frequencies

An observable consequence of the solar rotation is that the azimuthal degeneracy of global modes of oscillation is raised. The rotational splitting is defined by $\Delta\nu_{nlm} = \frac{\nu_{nlm}-\nu_{nl0}}{m}$, where ν_{nlm} denotes the frequency of the mode of degree l, radial order n and azimuthal order m. Recent results obtained by various groups for the low degree rotational splittings have been used here.

The IRIS measurements cover a total of 19 months of observation with 4 time series obtained in 1989, 1990, 1991, 1992. The splittings are weighted averages of the results obtained by different methods applied on the same averaged spectra (Lazrek et al. 1996).

The BiSON data have been collected between 05/01/93 and 08/23/94. The splittings and their errors are obtained for each mode (n,l) by Chaplin et al. (1996) from the 16-month power spectrum.

The LOWL data contain 1102 modes (n,l) with degrees up to $l = 99$ and frequencies lower than $\nu = 3500\mu Hz$. For each mode, individual splittings are given by, at best, three a-coefficients of their expansion on orthogonal polynomials defined by Schou et al. (1994). LOWL values have been calculated from the data covering 2 years of observation between 2/26/94 and 2/25/96 (communicated by Steven Tomczyk). Individuals splittings have been built from the given a-coefficients and their uncertainties have been calculated by assuming that the splittings are uncorrelated and independent of m for each (n,l) and such that they lead at best (in least-squares sense) to the quoted errors given on the a-coefficients.

2. The 2D RLS inversion method

For low rotation the frequency shifts are given by:

$$\Delta\nu_{nlm} = \int_{-1}^{1}\int_{0}^{1} K_{nlm}(r,\mu)\Omega(r,\mu)drd\mu \qquad (1)$$

where $\Omega(r,\mu)$ is the unknown rotation rate versus depth and latitude, $\mu = \cos(\theta)$, θ is the colatitude and r the normalized solar radius. The kernels $K_{nlm}(r,\mu)$ depend on the model and the eigenfunctions of the mode which are assumed to be known exactly.

We search for the unknown rotation as a linear combination of piecewise polynomials, projected on a tensorial product of B-spline basis. A complete description of the method and the choice of the parameters used for inverting LOWL data can be found in Corbard et al. (1996). The inferred rotation $\tilde{\Omega}(r_0,\mu_0)$ at a point (r_0,μ_0) is obtained as a linear combination of the data $\Delta\nu_{nlm}$. Thus from Eq.(1) it follows that averaging kernels $\kappa(r_0,\mu_0,r,\mu)$, which are a linear combination of rotational kernels K_{nlm}, exist such that:

$$\tilde{\Omega}(r_0,\mu_0) = \iint \kappa(r_0,\mu_0,r,\mu)\ \Omega(r,\mu)drd\mu \qquad (2)$$

The radial and latitudinal full widths at mid height (Δr and $r\Delta\theta$) of these kernels provide an estimation of the spatial resolution of the inversion at a point (r_0,μ_0). It increases with lower regularizing term, at the expense of larger errors on the solution.

3. Results and discussion

Figure 1 shows the inferred rotation rate for four latitudes $(0, 30, 60, 90^\circ)$ obtained by inverting LOWL data, LOWL+IRIS data and LOWL+BiSON data. The 3 solutions differ only at radius smaller than 0.2 $R_\odot$ and show no latitudinal dependencies below this depth. The solution obtained between 0.4 and $0.95R_\odot$ is discussed in Corbard et al. (1996). These results show that the different values given by observers for the low l splittings lead to different behaviours of the inferred rotation rate in the core. Therefore the inversion is sensitive to the actual observational differences.

The LOWL data are in favor of a core that rotates slower than the radiative interior. The solutions with IRIS and BiSON data are compatible and show that

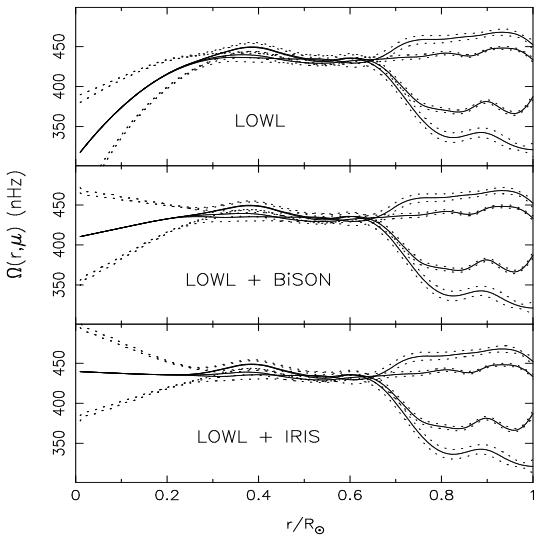

Figure 1: Rotation rate versus solar radius for latitudes $0, 30, 60, 90^\circ$ obtained with three sets of data.

an extension to the solar core of the rather uniform rotation found in the outer radiative interior could explain the observed splittings. The differences between LOWL and IRIS or BiSON data (especially for $l = 1$) are sufficient to produce solutions that are not identical. Nevertheless all the available observations argue against theories for angular momentum transport which predict a rotation rate at $0.2R_\odot$ much higher than the equatorial rotation rate. However solar core layers are intrinsically not well constrained so that little variation in the data could produce important variation in the solution. Although the 1σ error bars shown on the figure are large below $0.2R_\odot$, we can not insure that the true rotation rate lies inside these error bars. In fact these bars represent the uncertainties on a weighted averaged of the rotation rate. In an attempt to have a best interpretation of our results we must have a look at the weighting function given by the so-called averaging kernels.

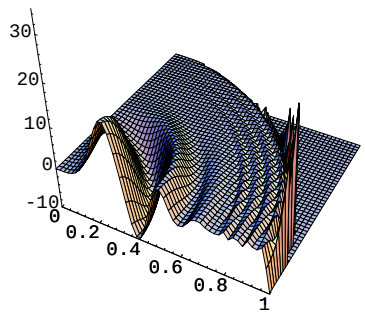

Figure 2: Averaging kernel at $r_0 = 0.2R_\odot, \theta_0 = 45^\circ$.

Figure 2 shows a 3D mid latitude averaging kernel obtained at $0.2R_\odot$ Contrary to the kernels at $0.4R_\odot$ which are well localized, (Corbard et al. 1996), the kernels at $0.2R_\odot$ for mid latitude and equator are not distinguishable and are both localized at the equator and $0.28R_\odot$. This result shows that our inversion is not able to detect a latitudinal dependency of the rotation rate even if it exists at $0.2R_\odot$ and that the solution obtained at all latitudes below $0.3R_\odot$ is an estimation of the rotation rate in the equatorial plane. Another problem arises from the fact that the averaging kernels calculated at $r_0 = 0.2R_\odot$ and below this depth are localized between 0.25 and $0.28R_\odot$. This indicates that the true rotation rate at a target location below $0.2R_\odot$ contributes only for a few part in the calculation of the inferred rotation rate at this location.

In conclusion our results lead to a solar core rotation of the order or smaller than the surface rotation at mid latitude and rule out core rotation significantly larger than surface rotation. The inversion is sensitive to the actual observational differences. Nevertheless the interpretation of the value of the rotation rate obtained below $0.2R_\odot$ depends strongly on the behavior of the rotation rate in the radiative interior. We note however that the integral of the averaging kernel between 0.25 and $0.6R_\odot$ is null. Thus, if we suppose that the rotation rate is constant in the radiative interior and down to $0.25R_\odot$, we can interpret the value obtained at $0.2R_\odot$ as a weighted averaged of the true rotation rate between 0.1 and $0.25R_\odot$ the weighting function being the corresponding part of the averaging kernel. Nevertheless although the solid rotation found between 0.4 and $0.6R_\odot$ is thought to be reliable, its extension down to $0.25R_\odot$ is more speculative and some little gradients in these zones can modify significantly the interpretation of the value of the rotation rate found at $0.2R_\odot$ and deeper. A better understanding of the rotation of the core should require a better agreement between the different analysis of the different observations. Some other global inversion techniques as SOLA (Pijpers & Thompson 1992) should be helpful by searching explicitly averaging kernels without any negative part. Such kernels, even larger than those obtained in this work should be useful to complete the interpretation of our results in the core.

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