The solar core as never seen before

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Abstract. One of the main drawbacks in the analysis of the dynamics of the solar core comes from the lack of consistent data sets that cover the low and intermediate degree range ($\ell = 1, 200$). It is usually necessary to merge data obtained from different instruments and/or fitting methodologies and hence one introduces undesired systematic errors. In contrast, we present the results of analyzing MDI rotational splittings derived by a single fitting methodology applied to 4608-, 2304-, etc..., down to 182-day long time series. The direct comparison of these data sets and the analysis of the numerical inversion results have allowed us to constrain the dynamics of the solar core and to establish the accuracy of these data as a function of the length of the time-series.

1. Introduction

Ground-based helioseismic observations, *e.g.*, GONG [5], and space-based ones, *e.g.*, MDI [10] or GOLF [4], have allowed us to derive a good description of the dynamics of the solar interior [12], [2], [6]. Such helioseismic inferences have confirmed that the differential rotation observed at the surface persists throughout the convection zone. The outer radiative zone ($0.3 < r/R_\odot < 0.7$) appears to rotate approximately as a solid body at an almost constant rate (≈ 430 nHz), whereas the innermost core ($0.19 < r/R_\odot < 0.3$) rotates slightly faster than the rest of the radiative region.

Most of these studies have used averaged MDI, GONG or GOLF frequencies to produce a high precision data set to infer time-averaged properties of the solar interior. The resulting mode set is reduced to the modes fitted for all, or at least most, epochs. The consequences of this restriction is particularly dramatic for the low degree and the low frequency modes - *i.e.* the modes that carry significant information about the rotation of the inner radiative zone [3]. This is why the time-averaging should be carried out by fitting the corresponding (long) time series instead. Fitting epochs of various lengths leads to averaging these epochs at the power spectrum level. This allows fitting spectra with higher signal to noise and thus extracting the most significant information, and leading to values consistent among the different sets.

We have used frequency sets resulting from fitting MDI time-series of various lengths in order to study the effect of the length of the time series on the estimation of the solar rotation in the inner radiative region. Specifically, rotational splitting sets were derived from fitting 4608-, 2304-, 1456-, 728-, 360- and 182-day long time series. An iterative inversion methodology [3] was applied to the data sets to infer the rotation rate in the solar interior.

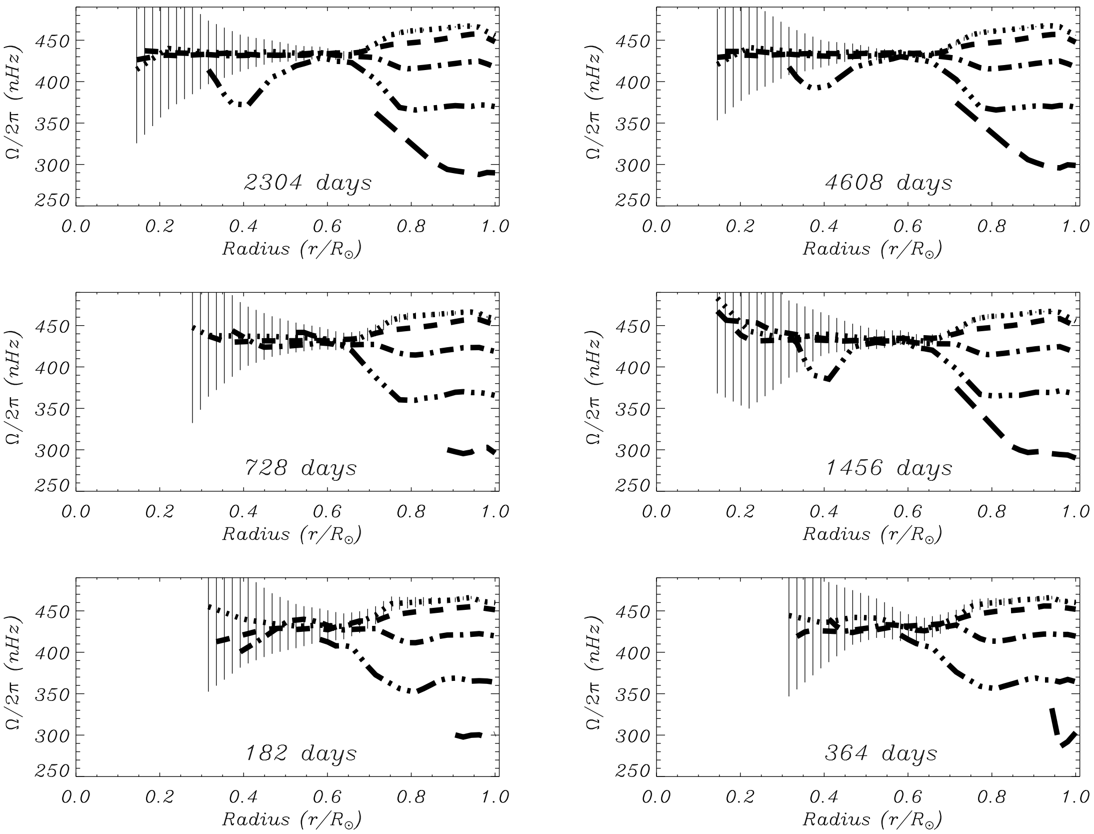

Figure 1. Inversions of the MDI data sets, plotted as a function of radius at several co-latitudes. The dotted, dashed, dotted-dashed, triple-dotted-dashed and long-dashed lines correspond to the rotation rate for the equator, and at latitudes of 20^o, 40^o, 60^o and 80^o, respectively.

2. Results and conclusions

The average rotational profiles obtained from the inversions of the 4608-, 2304-, 1456-, 728-, 360- and 182-day long sets are shown in Fig. 1. The longer the time-series associated with the data, the deeper is the significance of the inversions. Moreover the latitudinal extent of the inversions also increase with the length of the time-series, resulting in better estimations of the rotational rate at high latitudes.

The rotational rates obtained from 4608- and 2304-day long time series might presently represent the best estimates of the dynamical conditions of the solar inner radiative region, including the core. The sun seems to rotate as a rigid solid in the entire radiative region from the equator up to approximately a co-latitude of 50 degrees. A striking feature shows up at approximately $0.4R_\odot$ and 60 degrees in latitude, namely a "dip" that is clearly visible not only in the inversions of 4608-, 2304-day long sets, but also in those associated to the 1456-day long time series. The rotational rate down to approximately $0.18R_\odot$ is nearly constant within error bars, not exceeding in any case 600 nHz. The poor estimations of the solar rotational rate in the inner radiative region using shorter time-series (360- and 182-day long) also happens using the GONG pipeline data [2], that still uses 108-day long time series and a methodology developed back in 1990 [1]. The same applies to MDI observations, since it is using 72-day long time series and an algorithm devised in 1992 [11]. Moreover both GONG and MDI pipelines contain systematic errors [8], [9].

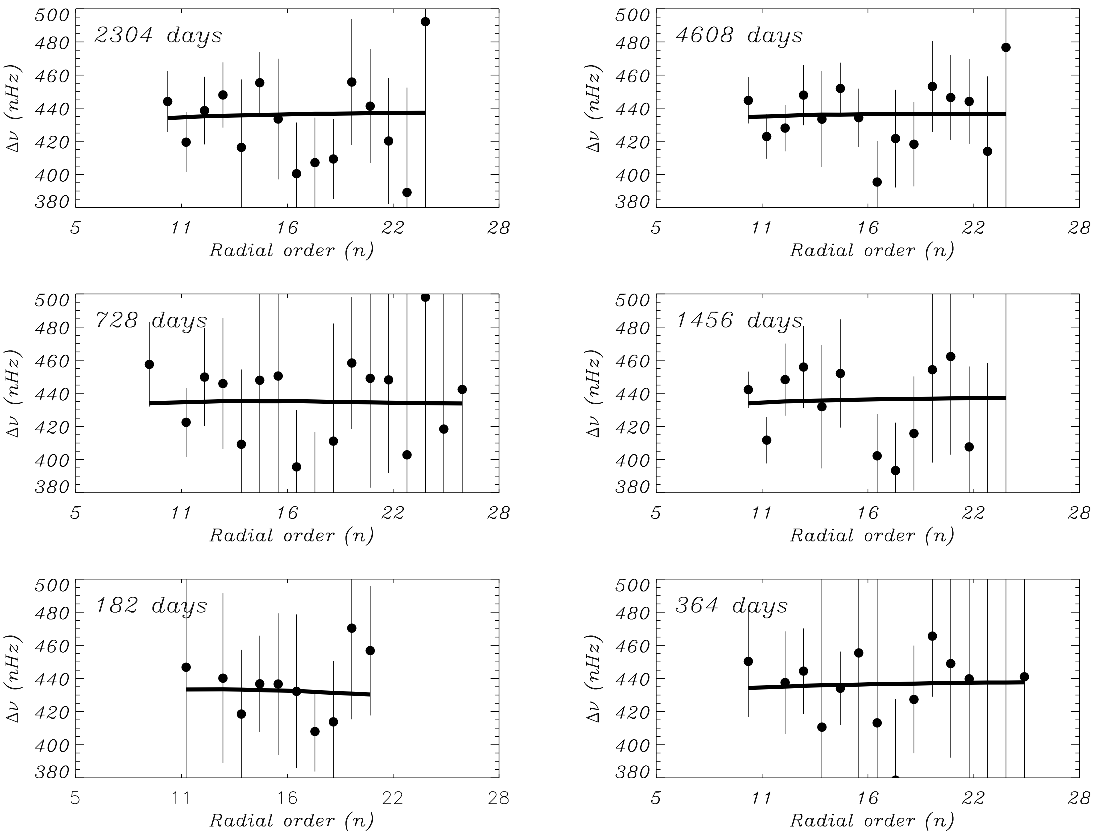

Figure 2. Observational sectoral frequency splittings as a function of radial order for $\ell = 1$ modes. The different panels correspond to the average splittings obtained from the time-series defined in this work (see text for details). The solid lines correspond to the theoretical splittings obtained from the rotational profiles of Fig. 1, under the supposition the radiative region rotates rigidly at 433 nHz.

However, the inversion results are still far from representing the actual variations of frequency splittings at low degrees (Figures 2 and 3). Longer time series mean lower uncertainties, revealing that the observational splittings (specially at larger frequencies) do not match the theoretical splittings obtained from the inverted rotational rates. This is an intriguing result that could be just an artifact of the fitting methodology or the observational time-series; although it could be an unknown solar dynamical feature that ought to be explored.

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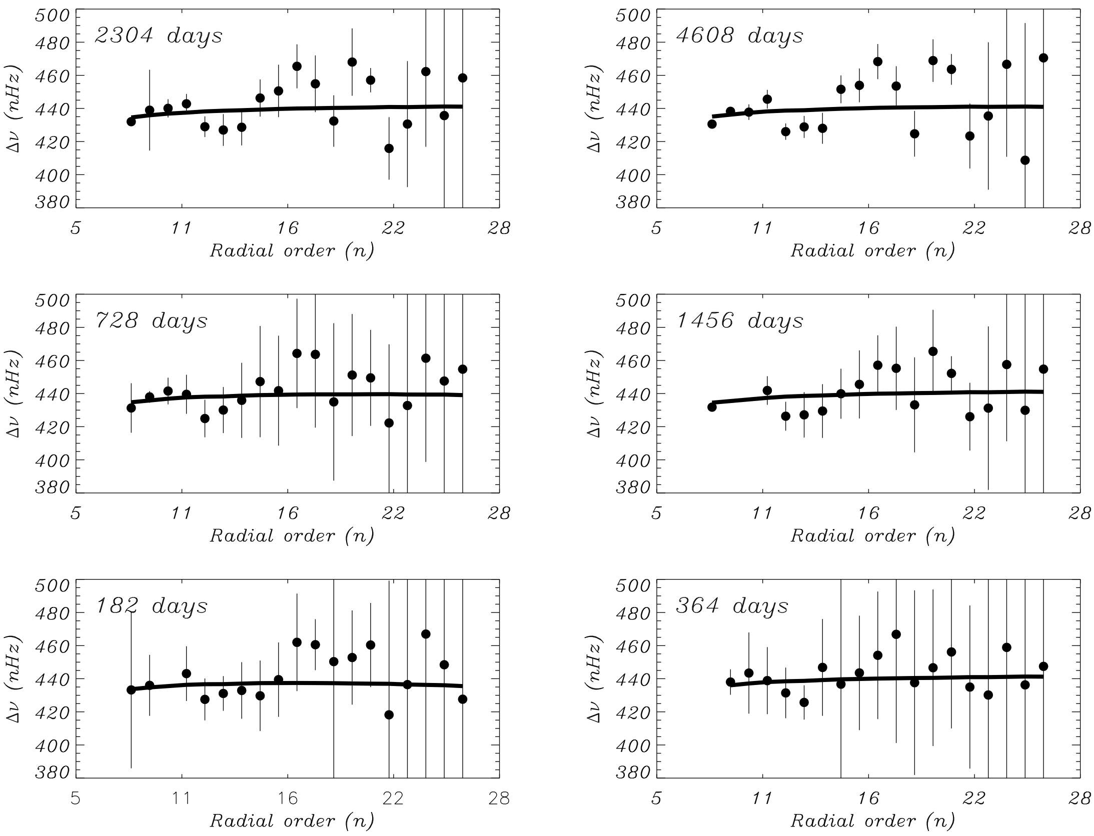

Figure 3. As in Fig. 2, but for $\ell = 2$ sectoral modes.

References

[1] Anderson, E. R., Duvall, T. L.,Jr., & Jefferies, S. M. 1990, *ApJ*, **364**, 699

[2] Eff-Darwich, A., Korzennik, S. G., Jiménez-Reyes, S. J., & García, R. A. 2008, *ApJ*, **679**, 1636

[3] Eff-Darwich, A., Korzennik, S. G., & García, R. A. 2009, *AN*, in press

[4] Gabriel, A. H., et al. 1995, Sol. Phys, **162**, 61

[5] Harvey, J. W., et al. 1996, Science, **272**, 1284

[6] Howe, R. 2009, Living Reviews in Solar Physics, **6**, 1

[7] Korzennik, S. G., Rabello-Soares, M. C., & Schou, J. 2004, *ApJ*, **602**, 481

[8] Korzennik, S. G. 2005, *ApJ*, **626**, 585

[9] Korzennik, S. G. 2008, Astronomische Nachrichten, **329**, 453

[10] Scherrer, P. H., et al. 1995,Sol. Phys. , **162**, 129

[11] Schou, J. 1992, Ph.D. Thesis,

[12] Thompson, M. J., Christensen-Dalsgaard, J., Miesch, M. S., & Toomre, J. 2003, Ann. Rev. Astron. Astrophys., **41**, 599