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Low-Degree High-Frequency p and g Modes in the Solar Core

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Summary. Solar gravity (g) modes propagate within the radiative part of the solar interior and are highly sensitive to the physical conditions of the solar core. They would represent the best tool to infer the structure and dynamics of the radiative interior, in particular the core, if they were properly detected and characterized. Although individual rotational splittings for g modes have not yet been calculated, we have to understand the effect of these modes, and also low-degree high-frequency p modes, on the inversion of the solar rotation rate between 0.1 and 0.2 R$_\odot$. In this work, we follow the methodology developed in Mathur et al. (2008) and García et al. (2008a), adding g modes and low-degree high-frequency p modes to artificial inversion data sets, in order to study how they convey information on the solar core rotation.

1 Introduction

Helioseismology has improved our understanding of the dynamical processes occurring within the solar interior (Thompson et al. 2003, and references therein), in particular the convective zone and the radiative zone down to 0.3 R$_\odot$ (Couvidat et al. 2003; García et al. 2004). However, the solar deep interior is still poorly constrained and the possible effect of the rotation rate in these regions on the solar structure distribution (e.g., sound speed and/or density) remains uncertain (Mathis & Zahn 2004, 2005; Turck-Chièze et al. 2008). These uncertainties should be added to the recently found discrepancies between helioseismic observations and theoretical modelling (Antia & Basu 2005; Turck-Chièze et al. 2004a; Mathur et al. 2007; Zaatri et al. 2007) when the new surface chemical abundances of Asplund et al. (2005) are used to calculate the structural model of the solar interior. In this context, gravity modes would add strong observational constraints about the structure and

dynamics of the solar core. A few individual candidates have been detected (Turck-Chièze et al. 2004b), but also global asymptotic properties (García et al. 2007, 2008a) that were used by García et al. (2008b) to infer the rotation rate of the solar core and to constrain various physical quantities.

Table 1. Artificial data sets, with ν (mHz) the mode frequency and ϵ its uncertainty.

Data set	g modes	p modes $\ell = 1, 3$	ϵ for $\ell = 1, 3$	p modes $\ell > 3$
Set 1	-	$1 \leq \nu \leq 2.3$	ϵ	$1 \leq \nu \leq 3.9$
Set 2	-	$1 \leq \nu \leq 3.9$	ϵ	$1 \leq \nu \leq 3.9$
Set 3	-	$1 \leq \nu \leq 3.9$	$\epsilon/3$	$1 \leq \nu \leq 3.9$
Set 4	-	$1 \leq \nu \leq 3.9$	$\epsilon/6$	$1 \leq \nu \leq 3.9$
Set 5	$\ell = 2,\ n = -3$	$1 \leq \nu \leq 3.9$	ϵ	$1 \leq \nu \leq 3.9$
Set 6	$\ell = 1 - 2,\ n = -1$ to -10	$1 \leq \nu \leq 3.9$	ϵ	$1 \leq \nu \leq 3.9$

An artificial rotation rate (blue curve in Fig. 1) was used to calculate the frequency splittings for p and g modes. The shape of this profile (note that between 0.15 and 0.2 $R_\odot$ the rate is 3 times that in the rest of the radiative zone) was choosen to study the effect of the different modes used in the inversion sets (Table 1). The inversions were carried out through the Regularised Least Squared methodology (Eff-Darwich & Pérez Hernández 1997), the mode sets came from the artificial rotational rate, and the data uncertainties and noise were calculated from observations (García et al. 2008c; Korzennik 2005). We know that the inner turning points of low-degree high-frequency p modes lay around 0.1-0.2 $R_\odot$ (García et al. 2008c), whereas those of g modes are confined in a small region below 0.2 $R_\odot$ (Mathur et al. 2008). A priori, these modes would significantly improve the inversion results in the solar core, but it is necessary to understand the effect of observational uncertainties and the number of modes to set the accuracy needed from peak fitting techniques to properly characterize the core.

2 The effect of low-degree high-frequency p modes

When low-degree high-frequency p modes are added to the inversion data sets (1 to 4), the increase in the rotation rate below 0.2 $R_\odot$ is detected in all cases but the maximum rate is not recovered (Fig. 1). Only for data sets 3 and 4, with the error bars significantly lowered, is the decrease of the rotation rate in the solar coredetected, although the actual values are not recovered. The resolution kernels show that the deepest point sensed by the inversion shifts from 0.15 down to 0.12 $R_\odot$, explaining the peak sensitivity of these sets to the region between 0.1 and 0.15 $R_\odot$.
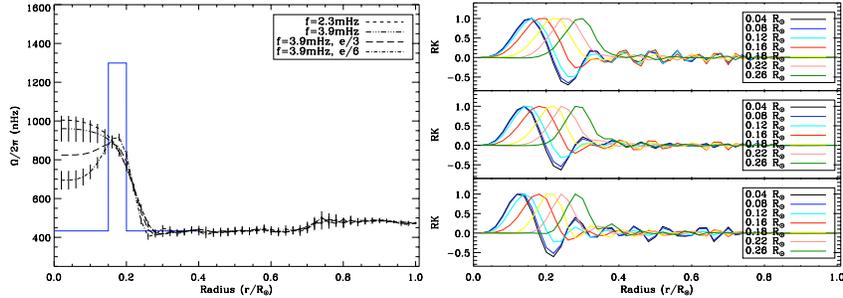
Fig. 1. Left: Rotation profiles (equatorial) reconstructed from different sets of p modes. Right: Resolution kernels of sets 1 (top), 3 (middle), and 4 (bottom).

3 The effect of g modes in the inversions

The effect of adding g modes on the inversions was analyzed adding 1 mode (set 5) and 20 modes (set 6) g to set 2 (Fig. 2). In both cases, the uncertainties in the g modes were 75 nHz, although two more sets (set 5+ and 6+) with the uncertainties reduced to 10 nHz were also computed. The inversion of set 5 is comparable to that of set 3 where no g modes were used. This result reflects the fact that individual g modes should be detected with accuracies significantly lower than 75 nHz. For sets 6, 5+ and 6+, the rotation rate recovered in the core is similar to the actual artificial rate. Hence, the detection of a few very accurate g modes will give similar information as a larger set of less accurate data. The resolution kernels show that the deepest point at which the inversion is sensitive shifts from 0.15 down to 0.03 $R_\odot$. However, the sensitivity is still quite low between 0.05 and 0.15 $R_\odot$ (set 6 in Fig. 2) when only g modes are used in the inversion. With a lower error bar, we probe several points between 0.03 and 0.15 $R_\odot$. Moreover, the resolution kernels are quite broad, explaining that we do not retrieve the rotation rate between 0.15 and 0.2 $R_\odot$ (average on the width of these kernels). To study this region it would be necessary to significantly reduce the observational uncertainties for low degree and high frequency p modes. Finally, resolution kernels for sets 6, 5+ and 6+, exhibit less wiggles above $\approx$0.3 $R_\odot$: they are less polluted by the rotation of the outer layers.

4 Conclusion

Gravity modes are necessary to improve our inferences on the rotational rate at the solar core. However, these modes should reach a certain level of accuracy, namely uncertainties for the frequency splittings significantly lower than 75 nHz, to assure that at least one g mode will be sufficient to greatly improve our sensitivity to the dynamics of the core. Although gravity modes
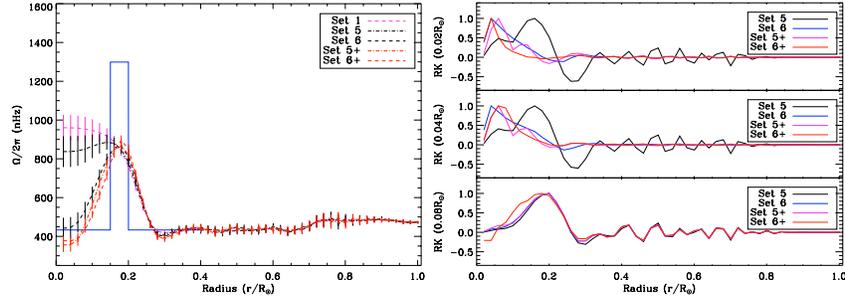
Fig. 2. Left: Same as Fig. 1 with 1 and 20 g modes (ϵ=75 and 10 nHz). Right: Resolution kernels for sets 5, 6, 5+ and 6+ at 0.02, 0.04, and 0.08 $R_\odot$.

will certainly improve inversion results below 0.1 $R_\odot$, it would be necessary to properly characterize low-degree and high-frequency p modes to resolve the region between 0.1 - 0.2 $R_\odot$.

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