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Tracking Solar Gravity Modes: The Dynamics of the Solar Core

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The solar gravity modes have not been conclusively detected in the Sun as yet due to their small surface amplitudes. They have been actively searched for because they directly probe the solar burning core (below 0.2 solar radius). Using data from the Global Oscillation at Low Frequency instrument we detect a periodic structure, which is in agreement with the period separation predicted by the theory for gravity dipole modes. The detailed study of this structure, compared to simulations including the best physics of the Sun determined through the acoustic modes, would favor a faster core rotation rate than in the rest of the radiative zone.

Helioseismology reveals the solar interior through observations at the solar surface, of oscillation modes propagating inside the Sun (*1*, *2*). Pressure-driven modes (p modes) provide a very detailed picture of the solar interior (*3*). Indeed, the position of the base of the convective zone (*4*) and the Helium abundance (*5*) are some examples of the results achieved by the study of such modes. The structural inversions of the precise p-mode frequencies provide the stratification of crucial variables like the sound speed down to 0.05 solar radius ($R_{\odot}$) (*6*, *7*). However, p modes are less sensitive to other structural variables such as the density. There is less agreement between this parameter and the models in the deepest layers of the radiative zone. Moreover, the dynamical properties (*8*) of the solar interior are not well defined below 0.3 $R_{\odot}$—containing more than 60% of the total mass. For example, large uncertainties still remain in the solar rotation profile below 0.2 $R_{\odot}$ (see Fig. 1) due to the lack of sensitivity and the poor spatial resolution of the modes towards the deep interior (*9*). To progress at greater depths and down into the solar core, the study of another type of waves—the gravity-driven modes (g modes), for which the driving force is buoyancy—is needed. They would enable us to obtain a complete picture of the interior of our Sun. Indeed, these modes are trapped within the radiative region of the Sun and they become evanescent in the convective zone reaching the solar surface with amplitudes that could be very small (*10*). Even considering their low surface amplitudes, g modes remain the best probes to provide information from the solar burning core up to the top of the radiative region.

Solar g modes have been actively searched for since 1976 without success (*11*). Recently, an upper limit of ~1 cm s^{-1} has been obtained looking for relevant spikes in the Fourier spectrum of the observed signal above a given statistical threshold (typically 90% confidence level) and in the frequency region above 150 μHz (*12*–*14*). A more sophisticated search of multiplets (instead of individual spikes) reduces the detection level to a few mm/s yielding some g-mode candidates with a confidence level between 90% (*15*) and 98% (*16*). However, some ambiguity remains on their identification (attributed to quadrupole, $\ell = 2$, modes). Some scenarios have been studied explaining the visible peaks, which could constrain the physics and dynamics of the solar core. In this paper, we look instead for the almost constant predicted separation (ΔP_{ℓ}, see Fig. 2) between the periods of gravity modes with the same degree ℓ and consecutive radial order *n*. These separations are related to the structure and dynamics of the solar core (*17*). Indeed, this method is extremely sensitive to the rotation rate of the inner solar layers (*18*).

We have used almost 10 years of velocity observations, from April 11, 1996 to October 21, 2005 from the Global Oscillation at Low Frequency (GOLF) instrument aboard the ESA/NASA Solar and Heliospheric Observatory (SOHO) mission. SOHO is placed around the L_1 Lagrangian point, a region at 1.5 million kilometers from the Earth towards the Sun where the gravitational field between the Sun and the Earth-Moon system equilibrates the centrifugal force. This privileged position allows continuous and uninterrupted observations of the Sun, essential for helioseismology, and provides a very stable environment. The GOLF instrument is a resonant-scattering spectrophotometer (*19*) designed to measure the line-of-sight velocity displacements of the solar photosphere. The analysis of the temporal variation of the velocity (*20*) in Fourier space allows the determination of the solar oscillation parameters and the derivation of the properties of the solar interior (*21*).

From the velocity measurements we compute the power spectral density (PSD) by means of a fast Fourier transform algorithm. To look for the periodical signature of the g modes in this PSD we compute a second power spectrum (PS) of the

PSD between 25 and 140 μHz (*22*). A significant broad structure in the region centered at ~24 minutes appears in this PS (Fig. 3). To characterize this feature we have first used two indicators: the maximum amplitude reached (6.5-σ) and the average power (2.95 times higher than the average power of the rest of the spectrum). Indeed, this feature has a high signal-to-noise ratio and, instead of seeing a single spike, it is a wide structure. Using a Monte Carlo simulation of N = $6 \cdot 10^5$ realizations (*22*) we estimate the probability (likelihood) of finding a similar structure (in terms of both indicators mentioned above) produced only by pure noise with the same statistical distribution as in the GOLF data between 22 and 26 minutes. As a result, the likelihood that this structure is not due to noise is 99.49%. Due to the finite number of realizations, there is an uncertainty of 0.13%.

The significant structure of the GOLF PS reveals the existence of quasi-periodic features somewhere in the PSD. Excluding an instrumental origin or a relation with convection (*22*) we have study the consequences of assuming that it is produced by the asymptotic properties of the dipole ($\ell = 1$) g modes. If this is the case, the position of the periodic structure in the PSD should follow the predicted positions of the gravity modes. To check this hypothesis, we reconstruct the fitted waves in the PSD that produces the significant ΔP_1 peak-structure found between 22 and 26 min in the PS (*22*).

The most striking result of this work is that the reconstructed waves issued from the real GOLF data show a pattern with their maxima at positions near those expected from solar models (Fig. 4 and fig. S7), supporting the conjecture that they are due to gravity modes. Using the previous Monte Carlo simulation, we can count the number of noise realizations that match the characteristics of the structure in the GOLF power spectrum, and show a reconstructed wave that behaves like the one expected from g modes. To do so, we correlate the reconstructed wave of a fixed solar model with, on the one hand, the reconstructed wave of the real data and, on the other hand, with the one from the Monte Carlo simulation. To be less dependent on the physics and dynamics of the model chosen, we use three different g-mode predictions from three different solar models: the seismic model (*23*), the standard model S (*24*) and the Nice standard solar model (*25*). We also use different scenarios for the dynamics inside the solar core. Thus, various solar core rotation rates placed at different depths in the solar core and with different rotation axes inclination are used (*22*). The correlation of the reconstructed waves of these sets of models with that of the real GOLF data—in the region between 2 and 8.5 hours— always gives a correlation above 20% with the highest values around 50%. The correlations with the Monte Carlo simulations are usually below 1%. Only 905 and 43 out of the N = $6 \cdot 10^5$ realizations reach 20 and 50% correlation respectively. Thus, the likelihood that this kind of periodic structure in the GOLF data is not produce by noise is at least of 99.85 and can reach 99.99% in the best case (up to 4-σ level of a normal distribution).

The set of parameters that characterizes the physics and dynamics inside the solar core is too large to be totally constrained by this first analysis. However, from all the sets of g-mode predictions used, we obtain better correlations with those having an inner rotation rate in the range three to five times higher than the rest of the radiative region and this being independent of the inclination axis and the radius of the core used (better results at $0.15R_{\odot}$). As seen in Fig. 4 the correlation is higher with the model with a higher rotation rate in the core. Unfortunately, the solar rotation profiles used in the simulations of the core are unrealistic (a constant rotation rate without differential rotation). On the other hand, the comparison with simulations including noise (fig. S10) tends to favor the hypothesis of a finite lifetime for the g modes as recently suggested (*26*). In both cases, further studies will be necessary.

The analysis presented here shows the robust detection of a spectral feature compatible with the presence of a periodic pattern in the PSD with a confidence level above 99.49% (corresponding to more than 3-σ of a normal distribution). The accurate study of this quasi-periodic pattern found in the GOLF data is compatible with the presence of gravity dipole modes with radial orders from $n = -4$ to -26, with a confidence level above 99.85%. A detailed comparison with solar models tends to favor a faster core rotation than in the rest of the radiative zone with more than 99.99% confidence level. The detection of g-mode asymptotic properties opens the opportunity for further studies of the rotation and the magnetic field inside the deepest layers of the Sun and can stimulate further observational studies with SOHO, ground based networks and next generation space missions such as Picard (*27*) and DynaMICCS (*28*).

References and Notes

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31. The GOLF experiment is based upon a consortium of institutes (IAS, CEA/Saclay, Nice and Bordeaux Observatories from France, and IAC from Spain) involving a large number of scientists and engineers, as enumerated in (*19*). SOHO is a mission of international cooperation between ESA and NASA. The authors thank T. Appourchaux, W. J. Chaplin and all the PHOEBUS group (*12*) for useful discussions and comments.

Supporting Online Material
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Materials and Methods
Figs. S1 to S10
References

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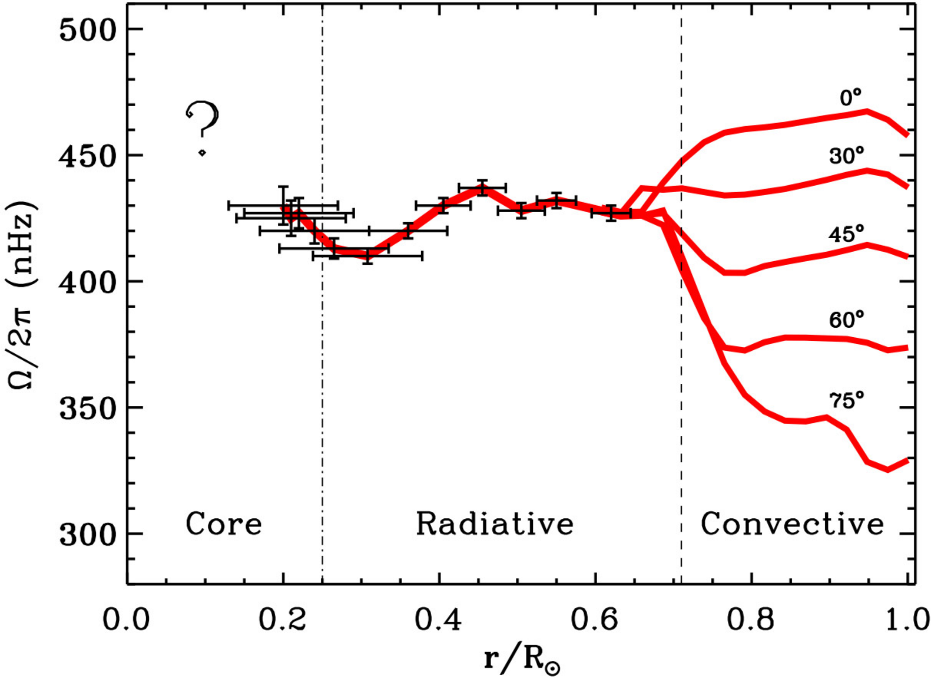
Fig. 1. Inversion of the solar rotation rate (Ω) using modes $\ell \leq 25$ from long time series (2088 days) of GOLF (*29*) and Michelson Doppler Imager (MDI) (*30*). In the Convective zone the differential rotation rate at different colatitudes is plotted. In the radiative region, the rotation becomes rigid down to ~0.3 $R_\odot$. The horizontal and vertical 1-σ error bars progressively increase towards the core because the p modes are less and less sensitive and because fewer and fewer modes are available for the inversion at these depths. Below 0.2 $R_\odot$ the rotation profile is unknown.

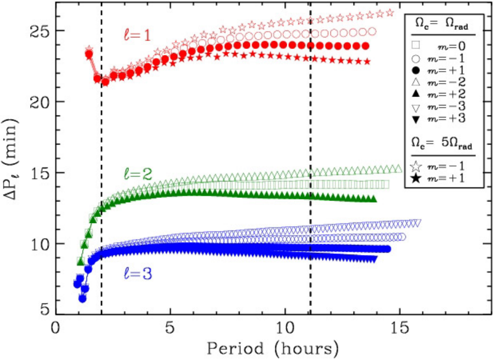
Fig. 2. Separations in period, ΔP_ℓ, between consecutive radial orders (n, n+1) gravity modes for ℓ = 1, 2 and 3 (red, green and blue colors respectively) and using the theoretical frequencies from the seismic model. The constant periodicity is achieved at 6, 4 and 2 hours for the modes ℓ = 1, 2 and 3 respectively. Ω_c is the angular velocity of the solar core and $\Omega_{rad} \cong 433$ nHz is the angular velocity of the remaining radiative zone. The star symbols show the effect, on the dipole (ℓ = 1) modes, of an increased solar core rotation rate—up to five times faster than the remaining radiative zone ($\Omega_c = 5\ \Omega_{rad}$)—below $R_c = 0.15\ R_\odot$. For the sake of clarity we have not drawn the effect for higher degree modes. We can notice that inside the zone limited by the two vertical dashed lines (from ~2 to ~14 hours corresponding to 25 to 140 μHz), we expect periodicities between 22-26 min, 9-15 min and 5-11 min for the ℓ = 1, 2, 3 modes respectively.

Fig. 3. PS of the PSD, normalized to the standard deviation, for the real GOLF data (top) and a numerical simulation (bottom) of ℓ = 1, 2 and 3 gravity modes computed using the seismic model, a core rotating at 433 nHz and without noise. The shaded region corresponds to the zone where the ΔP_1 peak is expected. This pattern changes slightly (with maxima at ~7.3- σ or 6-σ) when shorter frequency ranges in the PSD are used (fig. S2). The horizontal dashed line at 5.81-σ corresponds to 99.7% confidence level for individual peaks (equivalent to 3-σ level of a normal distribution). A full interpretation of the other highest peaks at low period is given in (*22*).

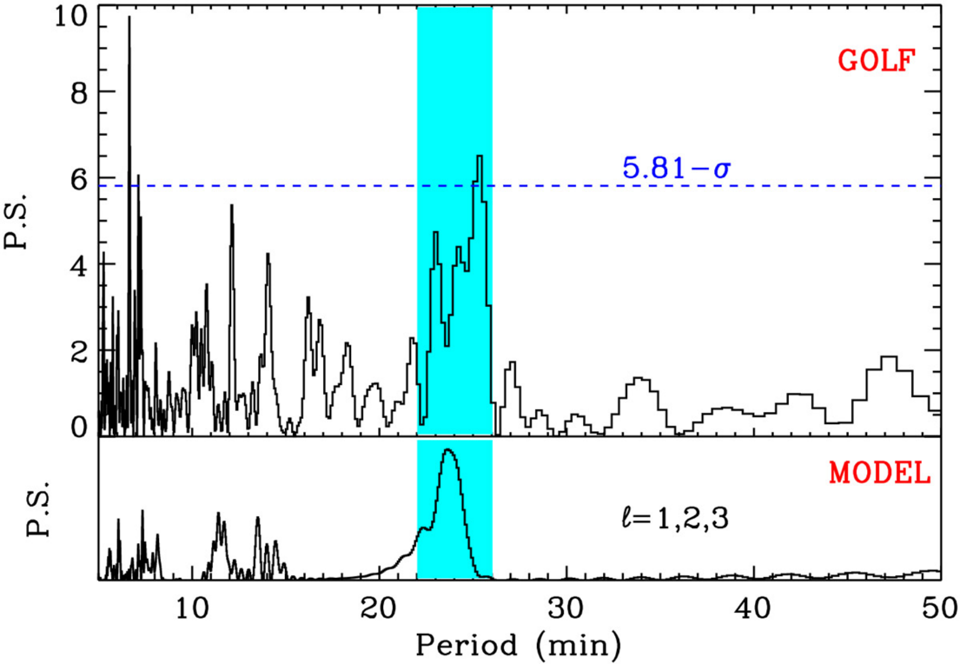
Fig. 4. Reconstructed waves in the PSD (arbitrary units) corresponding to the peak-structure between 22 and 26 minutes in the PS for the GOLF data. Top: Comparing the theoretical reconstructed waves (red curve) with the one issued from GOLF (green curves), we first observe that the maxima match rather well the expected positions of the g modes at low periods. Moreover, we also remark that the latter is wider and for periods greater than four hours it is divided in two waves suggesting the presence of both *m* components of the ℓ = 1 modes (higher splitting). The correlation between both reconstructed waves is 36.2%. Bottom: The higher correlation, 43.5%, between the second model (a core rotating five times faster than the radiative zone below $R_c = 0.15\ R_\odot$) and GOLF tends to favor a faster rotation rate in the core than in the rest of the radiative zone. As a comparison the correlation with randomized data is below 1% (fig. S8).

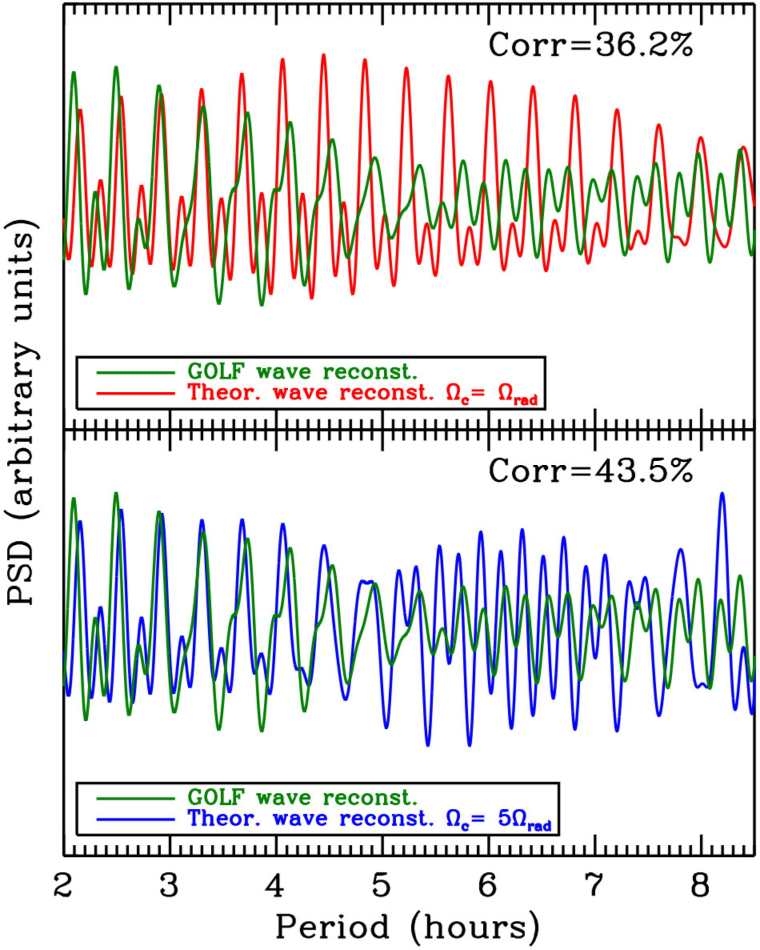


500
450
400
350
300
Ω/2π (nHz)
?
0°
30°
45°
60°
75°
Core
Radiative
Convective
0.0
0.2
0.4
0.6
0.8
1.0
r/R⊙



$\ell=1$
$\ell=2$
$\ell=3$
$\Omega_c = \Omega_{rad}$
$m=0$
$m=-1$
$m=+1$
$m=-2$
$m=+2$
$m=-3$
$m=+3$
$\Omega_c = 5\Omega_{rad}$
$m=-1$
$m=+1$
ΔP_ℓ (min)
Period (hours)
5
10
15
20
25
0
5
10
15


GOLF
5.81−σ
P.S.
MODEL
ℓ=1,2,3
P.S.
Period (min)
0
2
4
6
8
10
10
20
30
40
50



Corr=36.2%
GOLF wave reconst.
Theor. wave reconst. $\Omega_c = \Omega_{rad}$
Corr=43.5%
GOLF wave reconst.
Theor. wave reconst. $\Omega_c = 5\Omega_{rad}$
PSD (arbitrary units)
Period (hours)
2
3
4
5
6
7
8