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Solar cycle variations of rotation and asphericity in the near-surface shear layer

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ABSTRACT

The precise shape of the Sun is sensitive to the influence of gravity, differential rotation, local turbulence and magnetic fields. So its precise measurement is a long-standing astrometric objective. It has been previously shown by different methods that the solar shape exhibits asphericity that evolves with the solar cycle. Thanks to the Michelson Doppler Imager (MDI) on Solar and Heliospheric Observatory (SoHO) and the Helioseismic and Magnetic Imager (HMI) aboard NASA's Solar Dynamics Observatory (SDO), and their capability to observe with an unprecedented accuracy the surface gravity oscillation (f) modes, it is possible to extract information concerning the coefficients of rotational frequency splitting, a_1, a_3 and a_5, that measure the latitudinal differential rotation, together with the a_2, a_4 and a_6 asphericity coefficients. Analysis of these helioseismology data with time for almost two solar cycles, from 1996 to 2017, reveals a close correlation of the a_1 and a_5 coefficients with the solar activity, whilst a_3 exhibits a long-term trend and a weak correlation with the solar activity in the current solar cycle indicating a substantial change of the global solar rotation, potentially associated with a long-term evolution of the solar cycles. Looking in more details, the asphericity coefficients, a_2, a_4 and a_6 are more strongly associated with the solar cycle when applying a time lag of respectively 0.1, 1.6 and −1.6 years. The magnitude of a_6-coefficient varies in phase with the sunspot number (SN), but its amplitude is ahead of the SN variation. The latest measurements made in mid 2017 indicate that the magnitude of the a_6-coefficient has probably reached its minimum; therefore, the next solar minimum can be expected by the end of 2018 or in the beginning of 2019. The so-called "seismic radius" in the range of f-mode angular degree: $\ell = 137 - 299$ exhibits a temporal variability in anti-phase with the solar activity; its relative value decreased by $\sim 2.3 \times 10^{-5}$ in Solar Cycle 23 and $\sim 1.7 \times 10^{-5}$ in Cycle 24. Such results will be useful for better understanding the physical mechanisms which act inside the Sun, and so, better constrain dynamo models for forecasting the solar cycles.

1. Introduction

Helioseismology is a powerful tool to study the structure and dynamics of the Sun's interior. Substantial progress has been made mainly due to the help of uninterrupted observations since 1995 by the GONG (Global Oscillations Network Group) and by the SoHO/MDI and SDO/HMI space instruments. Global helioseismology provides important information about the physics of localized structures beneath the surface of the Sun, which has led to major advances in our understanding of the solar dynamics such as detection of the sharp radial gradient of the differential rotation at the base of the convection zone (the tachocline) (Kosovichev, 1996), the near surface rotational shear layer (NSSL) (Schou et al., 1998) that occupies approximately the top 5% of the solar radius and presumably plays a fundamental role in the solar dynamo (Godier and Rozelot, 2001; Brandenburg, 2005; Pipin and Kosovichev, 2011), as well as to measurements of the seismic solar radius and its variations (Schou et al., 1997; Dziembowski et al., 1998, 2001; Lefebvre and Kosovichev, 2005; Lefebvre et al., 2007). Global helioseismology continues to produce new and challenging results along with local helioseismology, another means to access the internal dynamics and properties of the Sun (e.g. Kosovichev and Zhao, 2016). Of particular interest are the temporal variations of the surface gravity oscillation (f) modes that probe the dynamics and structure of the NSSL, as well as the solar seismic radius.

The surface gravity waves are excited by turbulent convection in the upper convective layer of the Sun. These fundamental modes, called f-

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modes, peak near frequency 3 mHz; and the envelope peak occurs near $\ell = 880$, covering the degree range of 100–1 200 in the observed power spectrum. Our analysis is focused on the low-frequency medium-degree f-modes in the range of $\ell = 137 - 299$, which were observed during the whole period of the MDI and HMI observations. In this range, the f-modes kinetic energy is concentrated within a layer of approximately 15 Mm deep, or about 2% of the solar radius (see Fig. 2 of Lefebvre and Kosovichev, 2005). The frequencies of these modes are affected by the surface magnetism and temperature/sound-speed changes not as significantly as the frequencies of acoustic (p) modes, are reflect large-scale variations in the near-surface shear layer. In addition, because these modes do not propagate to the surface they are characterized by narrow line widths in the oscillation power spectrum. This allows to measure the mode frequencies and splitting coefficients with high precision. Also, to reduce potential effects of strong surface variations caused by active regions we consider only the frequency splitting coefficient of low-degree, $a_1 - a_6$, corresponding to latitudinal variations described by Legendre polynomials of degree $j = 1 - 6$; the 'odd' coefficients describe the differential rotation, and the 'even' coefficients reflect the global asphericity (Reiter et al., 2015). The f-mode asphericity coefficients are mostly due to Lagrangian variations of the radius of the subsurface layers, although there still might be some direct effect of magnetic field and turbulent stresses. Up to now, the physics of the temporal dependence of the asphericity coefficients has not been fully analyzed and understood. Nevertheless, a correlation analysis presented in this paper shows interesting relationships and encourages further observational and theoretical studies using the great amount of available global helioseismology data.

2. Data and results

The time-series of solar oscillations used here have been provided by the two space missions SOHO (Solar and Heliospheric Observatory) (Scherrer et al., 1995) and SDO (Solar Dynamics Observatory) (Scherrer et al., 2012). The f-modes in the medium-degree range are not observed from the ground because of their low amplitude. The data from both instruments are available on-line from the SDO JSOC (Joint Science Operations Center) archive: http://jsoc.stanford.edu (Larson, 2016). The mode frequency analysis is performed using 72-day series of full-disk Dopplergrams. The HMI high-resolution data are specially prepared to match the spatial resolution of the MDI Medium-ℓ Structure Program (Kosovichev, 1996). We study here the whole time span ranging from April 30, 1996, to June 4, 2017. The total number of the frequency datasets combined from the two instruments for our analysis was 105.

We recall the basic definition of f-mode frequency $\nu_{n,\ell,m}$, where ℓ and m are the spherical harmonic degree and the azimuthal order respectively, and n is the radial order which is zero for f-modes. The a-coefficients for each l obtained from the SOHO-MDI and SDO-HMI data, are defined by

$$\nu_{n,\ell,m} = \nu_{n,\ell} + \sum_{j=1}^{6} a_j(n,\ell)\mathscr{P}_j^{\ell}(m), \tag{1}$$

where $\nu_{n,\ell}$ is the mean ('central') multiplet frequency, and $P_j^{\ell}(m)$ are orthogonal polynomials of degree j defined by $\mathscr{P}_j^{\ell}(\ell) = \ell$, and $\sum_{m=-\ell}^{l} \mathscr{P}_i^{\ell}(m)\mathscr{P}_j^{\ell}(m) = 0$ for $i \neq j$ (Ritzwoller and Lavely, 1991).

The odd coefficients (a_1, a_3, a_5) reflect the rotational part of the fine structure in the spectrum of solar oscillations, whilst the even coefficients (a_2, a_4, a_6) reflect the solar asphericity (e.g Dziembowski and Goode, 2004). The higher degree coefficients calculated up to degree 36 are used to study migrating zonal flows ('torsional oscillations') (Kosovichev and Schou, 1997). In this work we use only the low-order splitting coefficients ($a_1 - a_6$) and also the central mode frequencies $\nu_{n,\ell}$ that are calculated with higher precision and provided as a separate dataset.

To study the variations with the solar cycle we averaged the coefficients over a common subset of modes which were observed in all 72-day periods. The total number of f-modes in the common subset which covers the range of ℓ from 137 to 299 is 152. The averaged odd coefficients are plotted in Fig. 1, and the averaged even coefficients are plotted in Fig. 2. The error bars are calculated using the formal error estimates provided for the measurements of individual modes (Larson and Schou, 2015). The solid curves show eighth-degree polynomials fitted to the averaged coefficients. For comparison with solar activity, we used the daily sunspot number data from the WDC-SILSO, Royal Observatory of Belgium, Brussels, to calculate the 72-day averages which correspond exactly to the helioseismology intervals. These averages are shown in Fig. 3*a*.

All the coefficients show strong changes over the 21-year period that spans two solar activity cycles, but not all of them show corresponding cyclic variations. In particular, it is striking that while a_1 and a_5 show two peaks corresponding to the sunspot maxima, the a_3-coefficient shows a negative peak corresponding to maximum of Solar Cycle 23, but there is no such peak for the current Cycle 24. From the helioseismology theory it follows the a-coefficients correspond to the differential rotation law expressed in terms of the associate Legendre functions, $P_n^m(\theta)$, (Kosovichev, 1988):

$$\Omega(\theta)/2\pi = \langle a_1 \rangle - \left[\frac{2}{3}\langle a_3 \rangle P_3^1(\theta) + \frac{8}{15}\langle a_5 \rangle P_5^1(\theta)\right] \Big/ \sin\theta, \tag{2}$$

The helioseismic odd a-coefficients can be compared with the corresponding coefficients of the surface rotation law, which were determined by Snodgrass (1984): $a_1^s = 435$ nHz, $a_3^s = -21$ nHz, and $a_5^s = -4$ nHz.

The observed variations of the coefficients (Fig. 1) show that the magnitude of a_1 increased during the solar maximum, but the magnitude of a_3 and a_5 decreased, meaning that they change in anti-phase with the solar activity cycle. This also means that the angular variation of the subsurface differential rotation was reduced (it became more solid-like). However, it is intriguing that during the Cycle 23 the a_3 coefficient significantly decreased but remains almost constant during the Cycle 24. Although the behavior of the last term (a_5 coefficient) in both cycles was qualitatively similar. This shows that there is a substantial change in the global dynamics of the Sun during the current relatively weak cycle. An unusual behavior of the migrating zonal flows, so-called "torsional oscillations" has been noticed in this solar cycle from global and local helioseismology measurements (Howe et al., 2013; Kosovichev and Zhao, 2016).

The even a-coefficients shown in Fig. 2 correspond to the solar asphericity in terms of the Legendre polynomials $P_2(\cos\theta)$, $P_4(\cos\theta)$, and $P_6(\cos\theta)$ (Kuhn, 1988). All of them show a two-peak structure corresponding to the two solar maxima of 2000–2002 and 2012–2015. However, it appears that the asphericity of the Sun dramatically changes from the solar minimum to maximum. During the solar minima the asphericity was dominated by the P_2 and P_4 terms, and P_6 contribution was negligible. But, during the activity maxima P_2 became small, but the values of P_4, and, in particular, P_6 substantially increased. This means that the P_2 asphericity changes in anti-phase with the solar cycle, while the P_4 and P_6 change in phase. At this point, we cannot make a physical interpretation of these variations, but, it is interesting that the primary terms describing the solar oblateness is reduced practically to zero, meaning that the asphericity associated with the solar activity during the maxima almost compensates the rotational distortion expressed in terms of the second-order Legendre polynomial.

To quantify the temporal behavior of the f-mode coefficients we calculated their cross-correlations with the sunspot number. The cross correlations with variable time lag were calculated for the whole 21-year period. Table 1 shows the maximum cross-correlation values, r, and the time lags. The positive values mean the corresponding a-coefficients predominantly vary in phase with the solar cycle, while the negative values mean that the coefficients vary in anti-phase. The uncertainties are