Detection of Zonal Shear Flows Beneath the Sun's Surface from F-Mode Frequency Splitting

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ABSTRACT

We report on the first successful measure of the zonal variations of the Sun's differential rotation (so-called torsional oscillations) by helioseismology. Using new helioseismic data from the Michelson Doppler Imager (MDI) on board SOHO, we have detected zonal flow bands with velocity variation of 5 m/s at a depth of 2-9 Mm beneath the surface. The subsurface flow is inferred from rotational splitting of frequencies of the fundamental (f) mode of solar oscillations in the range of angular degree l from 120 to 250, using a 144-day uninterrupted time series of the Sun's Doppler velocities. The structure of the subsurface shear flow resembles the pattern of the torsional oscillations observed on the surface. Comparing with previous surface measurements we found evidence for migration of the flow bands towards the equator.

Subject headings: methods: data analysis — convection — Sun: rotation — Sun: interior — Sun: activity — Sun: oscillations

1. Introduction

Differential rotation of the solar convection zone plays a very important role in the mechanism of solar activity (e.g. Gilman, 1992; Snodgrass, 1992). It has been noticed from the observations of the solar surface and interior that the differential rotation profile exhibits variations with the solar cycle (Howard and LaBonte, 1980; Goode and Dziembowski, 1991). The surface observations have also shown the existence of zonal bands of slow and fast rotation. These bands migrate slowly from high to low latitudes during the 11-year cycle of solar activity, resulting in a specific pattern originally called 'torsional oscillations' (Howard and LaBonte, 1980). The migrating flow bands seem to correlate with the migrating magnetic activity bands well-known from the 'butterfly diagram' (Snodgrass, 1991). However, the relation between the zonal shear flow and activity bands is not understood. Some theories suggest that the zonal variations of the differential rotation result from the back reaction of the large-scale dynamo-generated magnetic field, so-called magnetic quenching (Schussler, 1981; Küker *et al.*, 1996). Other theories convey the idea that the shear is produced by the Coriolis force due to downflows at the boundaries of azimuthal convective rolls (Wilson, 1987; Jones and Galloway, 1987). Helioseismology provides a means to distinguish between the theories by studying the variation of the shear flow with depth.

We have determined the velocity of the solar rotation beneath the surface from rotational splitting of frequencies of the fundamental (f) mode of solar oscillations of intermediate spherical harmonic degree $l = 120 - 250$. This mode represents horizontally propagating surface waves similar to short water waves. The f-mode frequencies are essentially insensitive to the stratification and thermodynamics of the surface layers. However, due to advection and the Coriolis force the frequencies of prograde and retrograde waves are different and depend on the azimuthal flow velocity in the subsurface layer where the waves propagate.

2. Measurement of F-Mode Rotational Splitting

The measurements of the rotational splitting of f-mode frequencies were carried out using 144-day series of solar Doppler images obtained from the Medium-l Program of the Michelson Doppler Imager (MDI) on board SOHO (Scherrer *et al.*, 1996). The data represented 1-min averages of the line-of-sight Doppler velocity. Because of a telemetry bandwidth restriction, the original 1024×1024-pixel images were binned down on-board to 200×200 resolution using a Gaussian weighting scheme optimized to reduce spatial aliasing and noise (Kosovichev *et al.*, 1997). These, so-called, Medium-l data provide spectra of f and p modes up to $l = 300$. In this analysis, we used only f-mode frequency data in the angular degree range from 120 to 250, which were obtained for the first time. The amplitude of this mode is approximately 10 times lower then the p-mode amplitudes at similar degree. Therefore, this mode is not easily detectable in the ground-based data due to atmospheric noise.

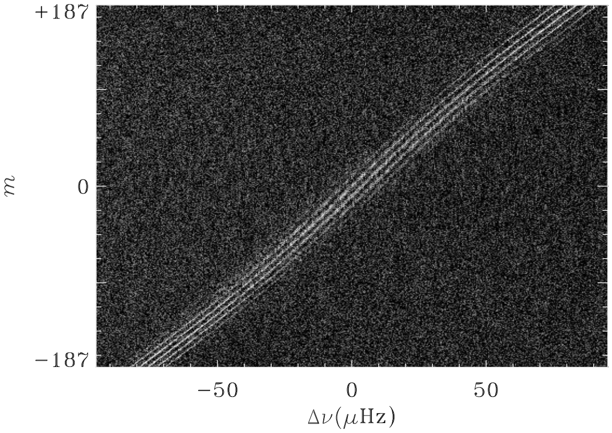

Fig. 1.— An example of the power spectrum of the f mode at l=187 and different azimuthal order m as a function of $\Delta\nu \equiv \nu_{lm} - \nu_{l0}$, obtained from the SOHO/MDI data. The slope results from the frequency splitting due to rotation. The curvature of the slope depends on the variation of the rotational velocity with latitude. Different spectral lines correspond to spatial sidelobes - f modes of adjacent l. The central frequency, ν_{l0}, of $l = 187$ multiplet is $1379.932 \pm 0.004\mu$Hz.

Figure 1 shows the power spectrum of the f mode at $l = 187$, obtained by performing a spherical harmonic transform in space and a Fourier transform in time. The spectrum includes several adjacent modes which could not be separated by the harmonic analysis because only half of the solar surface is observed. The

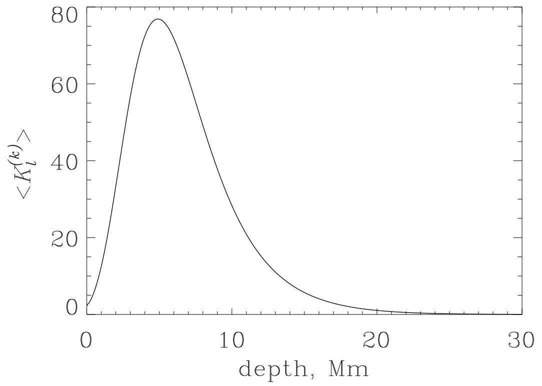

Fig. 2.— The f-mode averaging kernel function which weight averages of the azimuthal velocity determined from the frequency splitting.

modes of the positive azimuthal orders, m, correspond to prograde modes and have frequencies higher than the modes with negative values of m, which correspond to retrograde modes. The slope and the shape of the frequency splitting depend on the solar flows (Duvall *et al.*, 1986).

The f-mode frequencies ν_{lm} were determined from the power spectra in terms of a series of orthogonal polynomials in m, $\mathcal{P}_k^{(l)}(m)$ (Schou, 1992):

$$\nu_{lm} = \sum_{k=0}^{N} a_l^{(k)} \mathcal{P}_k^{(l)}(m). \tag{1}$$

Polynomials $\mathcal{P}_k^{(l)}(m)$ are normalized using the relation $\mathcal{P}_k^{(l)}(l) = l$. With this normalization, they asymptotically correspond to Legendre polynomials of ratio m/l at high l: $\mathcal{P}_k^{(l)}(m) \to lP_k(m/l)$, which were used in early helioseismic measurements (Duvall *et al.*, 1986). We have used $N = 36$ terms in Eq.(1) for each split multiplet. Presentation of the data in the form of Eq.(1) allows us to separate effects of rotation and asphericity: the odd terms depend only on rotation, while the even terms depend on the perturbations to the Sun's hydrostatic structure and the second-order effects of rotation.

3. Estimate of Subsurface Zonal Velocity

The odd terms in Eq.(1) are associated with the rotation velocity, $v(r, \theta)$, as a function of the radius, r, and colatitude, θ, expressed in terms of the associate Legendre functions, $P_k^1(\theta)$, often used for the representation of the solar velocity field (Snodgrass, 1992; Kosovichev, 1988),

$$v(r, \theta) = \sum_{k=1,3,\ldots}^{N} A_k(r) P_k^1(\theta) \tag{2}$$

where the weighted averages of radial functions $A_k(r)$ are proportional to the observed coefficients $a_l^{(k)}$:

$$\int_0^R A_k(r) K_l^{(k)}(r) dr = a_l^{(k)} \beta_{kl}, \tag{3}$$

where the numerical factor β_{kl} is generally calculated through the Clebsch-Gordan coefficients (Ritzwoller and Lavely, 1991). However, for the medium-l modes considered in the Letter, we have found that the asymptotic relation $\beta_{kl} \approx [P_k^1(0)]^{-1}$ is sufficiently accurate. The measured splitting coefficients, $a_l^{(k)}$, depend very weakly on l. The integral kernels $K_l^{(k)}(r)$ are localized in the subsurface layers and are also very similar for different values of l. Thus, taking an average over l and applying the mean-value theorem to Eq.(3), we obtain

$$\overline{A_k(r)} = \langle a_l^{(k)} \beta_{kl} \gamma_{kl}^{-1} \rangle, \tag{4}$$

where $\gamma_{kl} = \int_0^R K_l^{(k)}(r) dr$. The overbar indicates the radial average, and the angular brackets denote the l-average. Therefore, the solar flow velocity averaged across the layer where $\langle K_l^{(k)}(r) \rangle$ peaks (Fig. 2) is

$$\overline{v(\theta)} = \sum_{k=1,3,\ldots}^{N} \overline{A_k(r)} P_k^1(\theta). \tag{5}$$

We have used 18 terms in Eq.(5) to estimate $\overline{v(\theta)}$ in the subsurface layer. The results are shown in Figure 3. The upper panel shows the rotation rate $\overline{v(\theta)}/(2\pi R \sin\theta)$, where R is the radius of the surface layer, and the lower panel shows the deviation from a smooth rotation law represented by the first three terms in Eq.(5). The variations of the zonal velocity are typically 5 m/s and occur on the characteristic scale of 10-15°. The latitudinal resolution of the measurements estimated from the width of the local averaging kernels (Backus and Gilbert, 1968) is approximately 6-7°, and is shown by horizontal bars in Fig.3. The results reveal two zones moving faster and

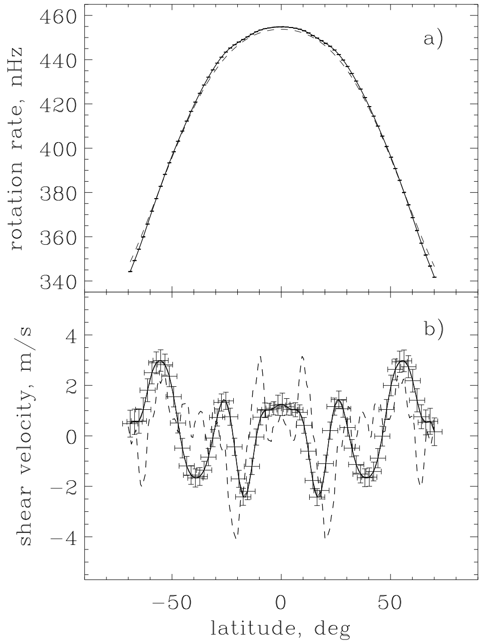

Fig. 3.— (a) The rotation rate, $\overline{v(\theta)}/2\pi R\sin\theta$, in the subsurface layer 2-9 Mm deep as a function of latitude as determined from the f-mode frequencies (solid curve). The dashed curve shows the surface rotation rate obtained from Doppler measurements (Snodgrass, 1992). (b) The variations of the azimuthal velocity from a smooth rotation law represented by the first three terms of Eq.(5). The error bars show 3σ random error estimates from the data. The horizontal bars show the latitudinal resolution. The dashed curve shows the symmetric component of the surface flows (Hathaway *et al.*, 1996).

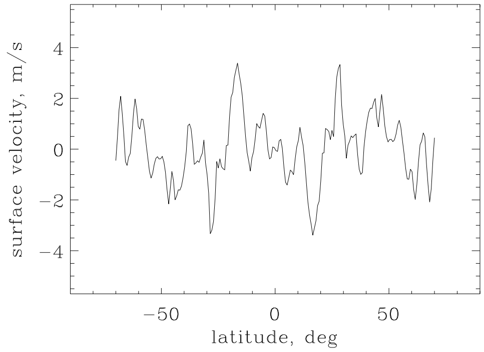

Fig. 4.— Antisymmetric component of the surface zonal flow from the measurements by Hathaway *et al.* (1996).

two zones moving slower relative to the smooth differential rotation. We note that the spatial resolution of the data is much higher than the characteristic scale of the velocity variations. The velocity of the zonal flows, 5 m/s, is substantially smaller than the mean velocity of rotation, which is about 2,000 m/s. However, the zonal variations are very significant. We have detected similar variation in the frequency splitting of low-order p modes. A two-dimensional inversion analysis of the whole data set is currently underway. It will provide information about the extension of the zonal shear flow into the deep interior.

4. Comparison with Surface Measurements

In Figure 3, we compare the subsurface rotation rate and the zonal variations with the surface measurements. The agreement appears to be quite good. The rotation rate is somewhat higher than the surface rotation rate in the equatorial region, obtained from Doppler measurements (Snodgrass, 1992) (dashed curve), indicating an increase of the angular velocity in the subsurface layer. At latitudes higher than 50 degree, the subsurface layer rotates slower than the surface. The zonal variations of the subsurface velocity are compared with the symmetrical component of the surface flows inferred from 6 months of the GONG data by Hathaway *et al.* (1996). The measurements show good correspondence with each other. However, in our measurement, the low-latitude peaks are shifted towards the equator by approximately 5° compared to the GONG result. This shift can be explained by migration of the torsional shear pattern because our observations were carried out almost one year after the GONG observations. The drift speed of 5°/year is not inconsistent with the surface observations (Snodgrass, 1992).

The surface measurements have also revealed a significant difference between the flows in the northern and southern hemispheres. In Figure 4, we show the antisymmetric component of the surface flow extracted from Hathaway *et al.*'s data. This component looks somewhat noisier than the symmetrical one shown in Fig.3b. Nevertheless, the zonal shear flows seem to be different in Northern and Southern hemispheres. The present helioseismic data allow us to determine only the component of the flow which is symmetrical relative to the equator. The non-symmetrical component of the internal flow can be determined, in principle, from frequency splitting of high-l modes, or from local helioseismic analyses (Duvall *et al.*, 1997). This is a very important direction of analysis of the SOHO data.

5. Discussion

The results show two zones of faster and two zones of slower rotation in each hemisphere of the Sun. This is generally consistent with the pattern of the 'torsional oscillations' (Howard and LaBonte, 1980) and migrating activity belts which are thought to be associated with the zones of the maximum shear. The physical mechanism of the torsional oscillations is not understood, and the problem needs theoretical development (e.g. Gilman and Fox, 1997). Our measurements indicate that the torsional oscillations are extended to, at least, 9 Mm beneath the Sun's surface providing new constraints on the theories.

New helioseismic data from the SOHO space mission will also give us information on the structure of the shear flows in the deep interior and about the stability and evolution of the flows with time, information crucial for understanding solar dynamics and activity.

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