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Sun's global property measurements: helioseismic probing of solar variability

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Abstract. Solar variability is controlled by dynamo processes in the Sun's interior. Global and local interior properties are measured by helioseismology. These measurements are based on observations of solar oscillations and waves which are excited by turbulent convection near the surface and propagate through the interior. Oscillation frequencies and travel times provide information about variations of the structure and large-scale dynamics inside the Sun. Recently developed methods of acoustic tomography provide 3D images of the solar interior. Variations of the global internal properties of the Sun have been measured for two solar cycles, and for the last 10 years the space mission SOHO and ground-based networks (GONG, BiSON, TON) provided continuous monitoring of the global properties. Recent helioseismic measurements of the structure and dynamics of the Sun provide new information about variations of the solar radius, asphericity, internal structure of sunspots and active regions, important for understanding mechanisms of the solar irradiance variations. The results provide support for a picture of a smaller and cooler, on average, Sun during the activity maxima, the higher irradiance of which is explained by a corrugated surface due to magnetic fields.

1. Introduction

Measurements with space-borne solar radiometers during the past 3 decades have revealed significant changes of the total solar irradiance (TSI) with solar activity (Fig. 1), most important of which are the long-term systematic increase of the TSI during the sunspot maxima and short-term decreases during the passage of sunspot groups on the disk (e.g. Fröhlich & Lean, 2004). These variations are of the order of 0.1%, and according to the Earth's climate models are too small to explain climate variations, such as the 'little ice age' during the Maunder minimum in 17th century. Therefore, it was suggested that in addition to the observed 11-year solar cycle variations, there are longer term TSI changes of higher amplitude (Lean, Beer & Bradley 1995). However, this suggestion remains speculative (Foukal, North & Wigley 2004).

In addition to global changes such as variations of the solar radius and effective temperature, theories of the TSI variations, reviewed by Spruit (2000) consider three 'local' mechanisms: 1) 'thermal shadows' at the surface, caused by deeply buried magnetic structures; 2) sunspot blocking of the heat flux; 3) excess emission by small-scale magnetic magnetic fields (facular emission). The last two mechanisms are considered as the most significant for the observed TSI variations on the scale of the 11-year cycle and for short-term variations, and are widely employed in empirical irradiance model (e.g. Solanki, Krivova & Wenzler 2005). However, the physics of the irradiance mechanisms, which is related to subphotospheric dynamics and the interaction with magnetic fields, is still poorly understood. The sunspot blocking is, perhaps, the most interesting because of the mystery of where the blocked heat flux goes. Simple arguments (Spruit 2000) suggest that the inner parts of sunspots are cooled by downdrafts, and because of these there is no 'pile up of the heat below the spot, and because of the long thermal scale of the convection zone the heat does not appear on the surface, perhaps, except of very narrow and weak ring around the spots. The facular emission is caused by the extra radiation from deeper and hotter 'walls' of magnetic elements. The extra cooling may cause dark rings around the elements and downflows of cooler and heavier plasma along the walls of the elements. The thermal shadow expected from magnetic structures below the surface (Spruit 1977) has probably much smaller effects on the surface temperature than the surface magnetic fields (Spruit 2000).

Helioseismology provides tools for testing the irradiance mechanisms, allowing us to measure both the global properties of the Sun and the local subsurface structures and dynamics associated with magnetic fields. Helioseismic diagnostics of the solar plasma are based on observations of acoustic waves stochastically excited by turbulent convection in the granulation layer near the visible surface of the Sun and propagating through the solar interior. The acoustic waves are reflected in the deeper layers of the Sun (because the sound speed increases with the depth) and travel back to the surface. The waves with frequencies higher than the acoustic cut-off frequency escape into the atmosphere. The waves with frequencies below the acoustic cut-off frequency of the solar photosphere are reflected at the surface and become trapped in the interior, forming resonant modes (Fig.2). These waves are used as a diagnostic tool in helioseismology. A general review of helioseismology is given by Christensen-Dalsgaard (2002). In this article, I discuss briefly some recent results of helioseismic measurements of variations of the solar radius, large-scale asphericity, and also subsurface structure and dynamics of sunspots and large-scale fields, and, in addition, present an attempt to detect a thermal shadow.

2. Helioseismic Measurements of Solar Properties

Methods of helioseismology can be described in two broad categories, global and local (e.g. Kosovichev 1999). Global helioseismology describes the solar oscillations in the Fourier domain and deals with eigenfrequencies and eigenfunctions of global normal modes, while new local helioseismology techniques, investigate local dispersion properties of solar waves (ring-diagram analysis (e.g. Haber et al. 2004) phase shifts (acoustic holography of Braun & Lindsey (2000) or travel times (time-distance helioseismology of Duvall et al. (1993). In particular, time-distance helioseismology investigates the oscillation properties of the Sun in the real space: travel times and distances.

In global helioseismology, the oscillation frequencies of the trapped oscillations (normal modes) are measured and used for inferring the global structure and rotation of the Sun. The hydrostatic structure properties (such as the sound-speed, density and adiabatic exponent) and the rotation rate are usually considered as a 2D function of radius and colatitude or represented in terms of a series of Legendre polynomials of sine latitude with coefficients depending on radius. In general, the oscillation frequencies of normal modes are grouped into multiplets for various angular degree l and radial order n of the mode eigenfunctions. Frequency splitting of the multiplet components corresponding to modes of various angular degree m depend on the rotation rate of the solar plasma and non-spherical components of the solar structure. The radial (spherically symmetric) component of the structure properties is determined from the mean frequencies of the mode multiplets. The internal differential rotation and asphericity are inferred from parameters of frequency splitting. Only symmetrical North-South components of the structure and rotation can be obtained by the methods of global helioseismology. Typically, 2-month

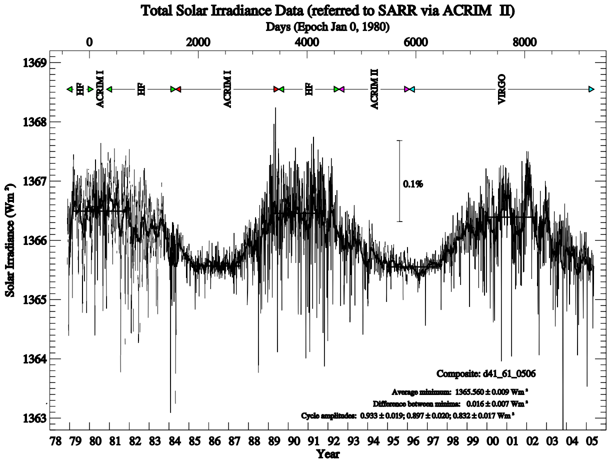


Fig. 1. Composite of total solar irradiance (TSI) (Fröhlich & Lean 2004) measured by different space-based radiometeres. The thick curve is a three-month running mean.

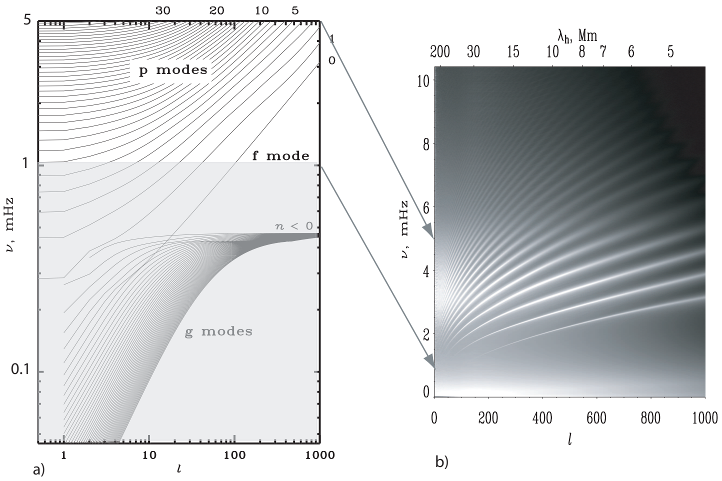


Fig. 2. a) Theoretical spectrum of solar oscillations (Christensen-Dalsgaard 2002); the shaded lower part of the spectrum that includes g-modes has not been observed. b) Observed power spectrum of solar oscillations from the MDI instrument on SOHO (Scherrer et al. 1995)). The arrows indicate the correspondence between the theoretical and observed spectra.

long time series of solar oscillations are used for measuring the mode frequencies from oscillation power spectra with the relative accuracy $10^{-5} - 10^{-6}$.

The spectrum of solar oscillation modes is very rich and includes acoustic (p) modes, surface-gravity (f) modes, and internal gravity (g) modes (Fig. 2a). However, only the upper part of this spectrum that includes p- and f-modes has been observed (Fig. 2b). The g-modes have not been detected. Local time-distance helioseismology measures travel times of acoustic and surface gravity waves between various points on the surface, and uses these measurements to infer properties, sound speed and flow velocities in the local area of the wave propagation. It allows us to obtain 3D images of the sound-speed perturbations and maps of plasma flows. Since the solar oscillation are stochastic, the travel times are measured from a cross-covariance function averaged over localized surface areas and over some periods of time. Typically, 8-hour series of Doppler velocity oscillation data are used to measure the travel times. This method is currently being intensively developed (Birch & Kosovichev 2000; Gizon & Birch 2002; Birch et al. 2004; Couvidat et al. 2004). The most important tasks are to develop methods for travel-time sensitivity functions, taking into account the finite wavelength effects and influence of magnetic fields, and also robust inversion methods for noisy data. Most of the current inferences are made in the theoretical ray approximation ignoring the magnetic effects. While these assumptions certainly are not sufficiently accurate for small-scale structures and areas of strong magnetic field, it is remarkable that the azimuthally and North-South averaged time-distance maps of subsurface flows reproduce very well the inversion results for differential rotation from global helioseismology (e.g. Hindman et al. 2004; Zhao & Kosovichev 2004).

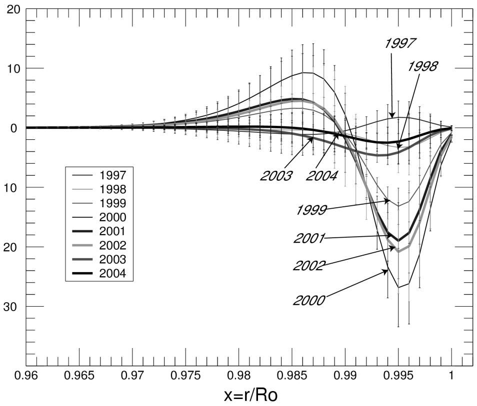


Fig. 3. $\langle \delta r \rangle$ as a function of the fractional radius $x = r/R_\odot$, obtained as a solution of the inverse problem for Eq. 1. Notice the behavior of the curve near $x = 0.99$. The errors are the standard deviation after average over a set of random noise added to the relative frequencies.

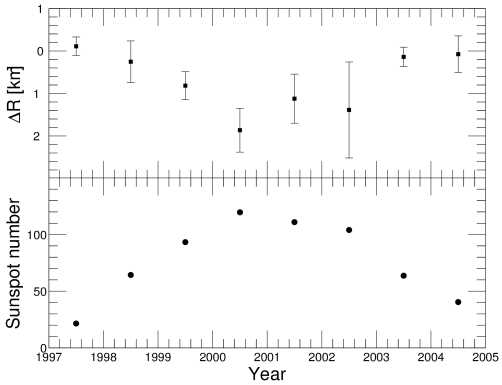


Fig. 4. Top: temporal variation of ΔR near the solar surface at $r = R_\odot$ from the solution shown in Fig.3. Bottom: Variation of the sunspot number for the same period. The variation of the seismic radius at the surface is found in antiphase with the solar cycle with an amplitude of about 2 km.

3. Variations of the Solar Radius and Subsurface Stratification

Using SOHO/MDI (SOlar and Heliospheric Observatory/Michelson Doppler Imager) data for the last 9 years and, more precisely, the temporal variation of f-mode frequencies, Lefebvre & Kosovichev (2005) have computed the variation of the radius of subsurface layers of the Sun by applying helioseismic inversions. As a starting point for the f-mode frequency inversion, they used the equation derived by Dziembowski & Goode (2004) who established a relation between the relative frequency variations $\delta\nu/\nu$ for f-mode frequencies and the associated Lagrangian perturbation of the radius $\delta r/r$ of subsurface layers:

$$\left(\frac{\delta\nu}{\nu}\right)_l = -\frac{3l}{2\omega^2 I}\int dI \frac{g}{r}\frac{\delta r}{r} \qquad (1)$$

where l is the degree of the f modes, I is the moment of inertia, ω the eigenfrequency and g the gravity acceleration.

The main result is that the radius of the subsurface layers of the Sun changes non-uniformly, that is the near-surface layers are contracting while the deeper layers are expanding with the increase of the solar activity level (Fig.3). They found a variability of the "helioseismic" radius in antiphase with the solar activity, with the strongest variations of the stratification being just below the surface around $0.995R_{\odot}$. Besides, the radius of the deeper layers of the Sun, between $0.975R_{\odot}$ and $0.99R_{\odot}$ changes in phase with the 11-year cycle.

The helioseismic estimates show that the near-surface variations are in antiphase with the solar cycle with an amplitude of the order of 2 km (Fig. 4). However, the sensitivity of these inversions which are robust below $0.995R_{\odot}$, is quite low at the surface, and localized variations of the surface radius may not have been detected. High-degree f-mode data are required to improved the surface estimates.

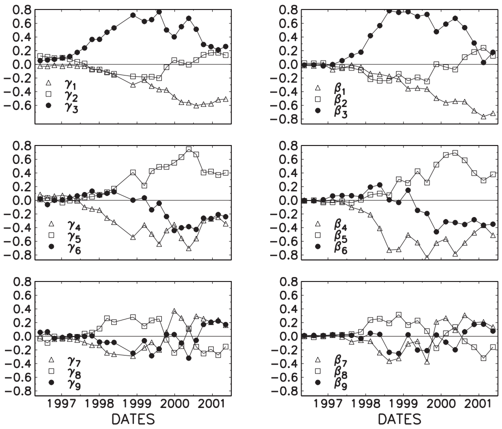


Fig. 5. In the left panels, the behavior of γ_k ($k > 0$) is shown as a function of time from the SOHO/MDI data. The right panels show the corresponding β's. It is clear that there is detailed agreement to P_{18} (or γ_9), which bears out the close relation of what happens just beneath the surface to what happens in the atmosphere.

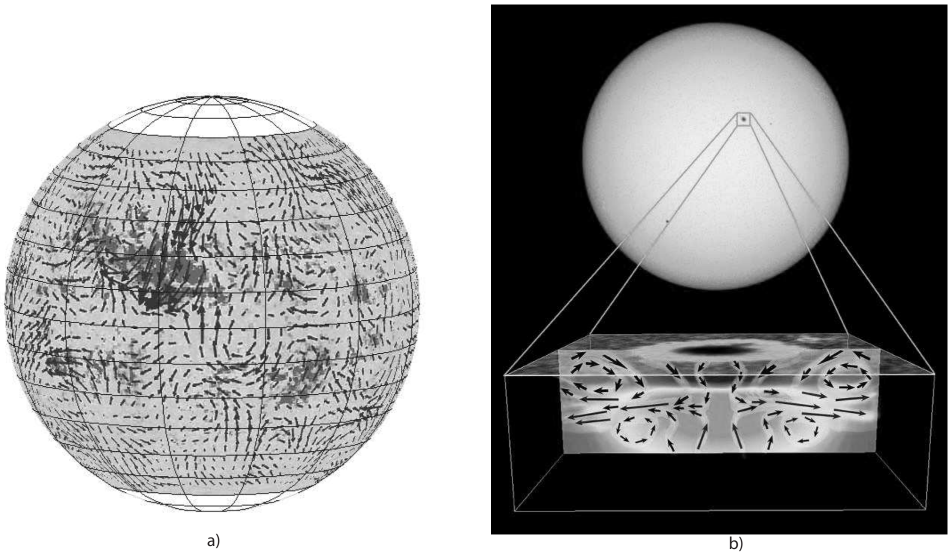
4. Solar Asphericity and Helioseismology Limit on TSI Variations

Helioseismology also measures the aspherical components of the solar structures from the even components of the p-mode frequency splitting. The subsurface asphericity can be represented in terms of Legendre polynomials of sine latitude, P_{2k} (e.g. Dziembowski & Goode 2004). The coefficients of this expansion, γ_k, are shown in Fig. 5 (Dziembowski & Goode 2003). These coefficients show that during the solar minimum of 1996-97 the asphericity was negligible, but it rapidly increased with the solar activity, much faster than the changes in the spherical structure of the Sun. These authors also used the Ca II K data (which are a chromospheric measure of solar activity) from Big Bear Observatory to determine how the subsurface perturbations are related to solar atmospheric conditions. The results are also shown in Figure 5 in the form of coefficients β_k, obtained by projecting the Ca-line data into Legendre polynomials of even degree.

The results revealed an extremely close agreement between the subsurface and chromospheric structures, perhaps, explaining why the solar activity data provide good proxies for the irradiance variations. The mean p-mode frequencies represented by the P_0 term, increase with the activity level, which is consistent with the radius variations but would require the near-surface temperature increase about 1% at the photosphere, which is of an order of magnitude larger than allowed by observations. Thus, Dziembowski & Goode (2003) concluded that the main factor that causes the mean frequency increase is a growth of the turbulent pressure. This remains to be proved. Perhaps, the most significant conclusion of these helioseismology measurements is that there are no shape asymmetries at activity minimum or radial changes from minimum to minimum. Therefore, it is difficult to imagine how the Sun could be less irradiant than at activity minimum. This puts a hard limit on the hypothetical long-term component suggested by Lean et al. (1995) for the solar forcing of the Earth's climate.

5. Structure and Dynamics of Active Regions and Sunspots

Time-distance helioseismology (Zhao & Kosovichev 2004) and also local measurements of the p-mode frequency shifts by the



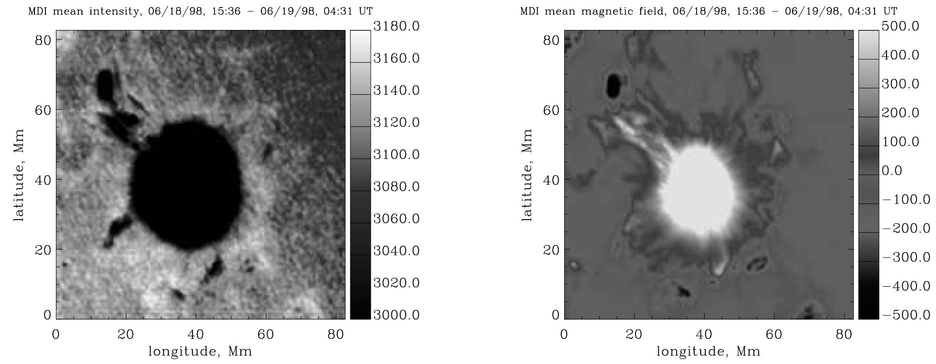
a) b)

Fig. 6. a) Synoptic large-scale subsurface flows obtained by time-distance helioseismology. The longest arrows correspond to 50 m/s. The grayscale background map shows magnetic regions. b) The sound-speed structure and the axisymmetrical component of plasma flows below a sunspot. The lighter color shows where the sound speed is higher than averaged and dark color shows where the sound speed is lower. The depth of the box is about 12 Mm. The transion from lower to higher sound speed occurs at the depth of 4-5 Mm. The characteristic flow speed is about 1-2 km/s.

'ring-diagram' analysis (Haber et al. 2004), have provided synoptic maps of subsurface flows, which revealed large-scale converging plasma flow with a characteristic speed of about 50 m/s around the active regions where magnetic field is concentrated (Fig. 6a). These stable long-living flow patterns affect the global circulation in the Sun. It is particularly important that these flows change the mean meridional flow from the equator to the poles, slowing it down during the solar maximum years. This may have important consequences for the solar dynamo theories which invoke the meridional flow to explain the magnetic flux transport into the polar regions and the polar magnetic field polarity reversals usually happening during the period of maximum of solar activity.

On the scale of sunspots, measurements of travel times of acoustic waves also reveal converging downward flow patterns with speed of 1-2 km/s, extending beneath sunspots to depth of 4-5 Mm. In the deeper layer, the flows are mostly diverging and directed upward (Zhao et al. 2001, Fig.6b). At first sight, the converging subsurface flows contradict to the well-known diverging Evershed and moat flows observed at the surface. However, such diverging flows are detected in travel time variations of surface gravity (f-mode) waves (Gizon 2003). Since the acoustic waves propagate mostly vertically at the surface, this leads to the conclusion that the surface Evershed and moat flows are probably quite shallow, and, perhaps, not deeper than 0.5 Mm.

Estimates of the sound-speed variations show that in the upper layer, 4-5 Mm deep, the sound speed is lower than this in the surrounding plasma, but it becomes higher than the average in the deeper layers (Kosovichev et al. 2000). This probably means that the region of the cool plasma of sunspots where the convective heat transport is inhibited by strong magnetic field is only 4-5 Mm deep, and, thus, sunspots as cool plasma objects are relatively shallow compared to their typical horizontal



a) b)

Fig. 7. a) MDI continuum intensity image of a sunspot averaged for 13 hours; b) MDI magnetogram of the same sunspot for the same period of time.

size of 10-20 Mm. The higher sound speed in the deeper regions is probably due to a higher plasma temperature caused by accumulation of heat. In principle, strong magnetic field could also explain the inferred sound-speed variations. However, this requires very high field strength which seems to be unlikely because of the presumed conservation of magnetic flux in the sunspot structure with depth. Thus, it seems that the heat flux blocked by sunspots is accumulated in deep layers, 4-5 Mm below the surface, and is hold by downflows surrounding sunspots. The MDI intensity images reveal very weak bright rings at the outer boundary of the moat flow as illustrated in Fig.7 (Kosovichev et al. 2002). However, relationships between local irradiance variations and sunspot dynamics have not been established.

Emerging from local helioseismology picture of the sunspot structure and dynamics seems to correspond very well to the cluster model of sunspots (Parker 1979). However, this picture is still very schematic and have to be improved by future observations and data analysis.

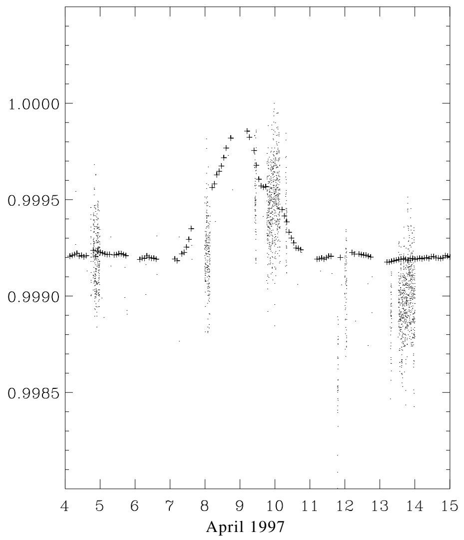


Fig. 8. The relative MDI continuum intensity averaged in a box of 400”x400” at the central meridian just above the equator during the passage of a complex of activity in April 1997 (points), and the corresponding relative variations of the unsigned magnetic flux averaged in the same box (crosses).

6. Search for Thermal Shadows

Kosovichev et al. (2002) have also looked at the irradiance variations associated with a complex of activity. Figure 8 shows the MDI continuum intensity averaged in a box of 400”x400” at the central meridian just above the equator. It does not include the active regions. The dots show the relative intensity measurements which are available only for 5 short intervals, and the crosses show the corresponding averaged absolute values of magnetic field (appropriately scaled). There is a maximum related to the passage of the active longitude through this box. It is interesting that the intensity seems to be systematically lower after the passage. This is probably related to deep magnetic structures connected to the active longitudes and affecting the energy transport in the interior. However, further detailed investigation is required to confirm this result.

7. Conclusions and outlook

Helioseismology has uncovered intriguing dynamics of plasma in the Sun's interior. Many of the initial results are unexpected and counterintuitive and are not explained by the current theoretical models. The current results provide support for a picture of a smaller and cooler, on average, Sun during the activity maxima, the higher irradiance of which is explained by a corrugated surface due to magnetic fields.

For understanding the basic mechanisms of solar activity, magnetic energy generation, storage and release, it is important to investigate in detail the processes of emergence and evolution of active regions, and also relatively small-scale subsurface plasma motions in these regions. Future space experiments, Helioseismic and Magnetic Imager (HMI) instrument on Solar Dynamics Observatory, and PICARD mission scheduled for launch in 2008 will measure Doppler velocity, vector magnetic field and irradiance almost uninterruptedly, providing high-resolution data for these investigations.

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