Helioseismology over the Solar Cycle

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Abstract. Helioseismology has produced unprecedented measurements of the Sun’s internal structure and dynamics over the past 25 years. Much of this work has been based on global helioseismology. Now local helioseismology too is showing its great promise. This review summarizes very briefly the principal global results that may be relevant to an understanding of the origins of solar magnetism. Recent results regarding the variation of frequencies over the solar cycle and the temporal variations of subsurface flows are briefly summarized.

1. Introduction

Helioseismology is concerned with the study of the Sun’s internal structure and dynamics using the properties of acoustic waves that propagate through the interior and cause observable motion of the photosphere and lower solar atmosphere. The principal properties used for this study are the frequencies of resonant global modes of the Sun set up by these acoustic waves. Since the Sun is to a good approximation spherically symmetric, the horizontal spatial structure of the modes is described by spherical harmonics $Y_{lm}^m(\theta, \phi)$, where $\theta$ is co-latitude and $\phi$ is longitude. The modes are then labelled by three quantum numbers, the degree $l$ and order $m$ of the spherical harmonic and a radial order $n$ which is essentially the number of nodes in the mode’s structure in the radial direction. The frequencies $\nu_{nlm}$ depend on the conditions in the solar interior that affect wave propagation. In a non-rotating, perfectly spherically star the frequencies would have a degeneracy in that they would not depend on $m$ for given $n$ and $l$: this degeneracy is lifted by rotation, structural asphericities and magnetic fields, and measurements of the resulting frequency splitting can be used to make inferences about these properties. (The frequency splitting within a multiplet of given $n$ and $l$ can be decomposed into parts that are odd and even functions of $m$: the odd component arises from rotation, while the even component arises from magnetic and thermal asphericities and distortions of the shape of the star from spherical symmetry.) Application of inverse techniques provides maps such as of the adiabatic sound speed $c$, density $\rho$, rotation and wave-speed asphericities in the Sun’s otherwise impenetrable interior.

Spatially resolved measurements of the Sun’s oscillations by the Global Oscillation Network Group (GONG) and the Michelson Doppler Image (MDI) instrument on board the SOHO satellite began in the mid-1990s and thus now provide essentially continuous coverage of one solar cycle. The whole-disk Sun-as-a-star measurements of the Birmingham Solar Oscillation Network (BiSON) extend back even further. Thus helioseismology is able to comment on frequency
changes occurring over the solar cycle and possible changes in flows and acoustic asphericities over that time.

2. The mean solar structure and rotation

Many of the results from helioseismology have been well described in reviews such as that by Christensen-Dalsgaard (2002). Here we summarize briefly just a few of the mean properties revealed by helioseismology that are pertinent to an understanding of the Sun’s magnetic dynamo and the resulting activity cycle.

The Sun’s convective envelope is very nearly adiabatically stratified, whereas the radiative interior is subadiabatic. Thus the variation of the adiabatic sound speed with depth reveals where the transition between the two occurs. Such analysis locates the base of the convection zone at radius $r = 0.713 \pm 0.003 R_{\odot}$ from the centre of the Sun, where $R_{\odot}$ is the Sun’s radius (Christensen-Dalsgaard et al. 1991). Note that this measures the extent of the essentially adiabatically stratified region, which may include a region of convective overshoot if the motions are sufficient to make that region adiabatically stratified. Simple models incorporating such overshooting typically have a rather sharp transition from adiabatic stratification to subadiabatic stratification in the radiative interior; however, in the Sun the transition seems to be smoother than in the models (see Christensen-Dalsgaard et al. 2010).

Figure 1 shows the internal solar rotation over much of the convection zone and outer radiative interior inferred from MDI data. The Sun rotates differentially throughout the convection zone, with a transition to what appears to be near-solid body rotation in the radiative interior. Between the two regimes there is a rotational shear layer, the tachocline, which is now widely considered to play a role in the large-scale solar dynamo. There is also a near-surface shear layer which may also have a role. The tachocline is in fact narrower than the figure may suggest, because of the limited resolution of the inversion. Following first detailed quantification of the location and extent of the tachocline by Kosovichev (1996), subsequent investigators have mostly used a particular parametrization of the profile of the tachocline, giving its location and width (e.g. Charbonneau et al. 1999) as $0.693 \pm 0.002 R_{\odot}$ and $0.039 \pm 0.013 R_{\odot}$ at the equator: see these papers for the precise meaning of these parameters. The tachocline is prolate, with the location different by about $0.02 - 0.03 R_{\odot}$ at $60^\circ$ latitude. Thus the bulk of the tachocline is in a stable subadiabatic region at low latitudes, and straddles the base of the convection zone at higher latitudes.

3. Frequency variations over the cycle

Since sound waves traverse the interior of the Sun in a time of order one hour, the global frequencies are determined by essentially the instantaneous state of the solar interior. If the internal structure or dynamics change over the course of the solar cycle, these changes may be reflected in changes in the global frequencies. Indeed the frequencies and frequency splittings are observed to change over the cycle. Figure 2 shows the observed frequency shift in low-degree modes from BiSON observations, since 1985: the frequencies vary by about 1 part in $10^4$, the frequencies being highest at solar maximum. Also shown is the variation
over the same period in the 10.7 cm radio flux which is one widely used measure of solar activity. Clearly the frequency shifts and the solar activity levels are very well correlated.

Similarly tight correlations have been demonstrated between the shifts in intermediate-degree modes and the photospheric magnetic flux, with the latitudinal distribution of the magnetic flux also plausibly explaining the even component of the frequency splitting varies with time (Antia et al. 2001).

In conclusion, most if not all measured temporal variations in the mean frequencies and in the even component of the frequency splittings are likely caused by surface changes in the magnetic field, or by something that is highly correlated with them. There is little evidence for any contribution to the frequency changes over the solar cycle from structural or magnetic variations in the deeper interior. However, the results in Fig. 2 hint that there may be something else going on: as reported by Broomhall et al. (2009), there is some indication of a biennial oscillatory signal in the frequencies at all times that is however only apparent in the 10.7 cm flux signal at high activity levels; compared with previous minima, the frequencies are even lower at the present time relative to the 10.7 cm flux activity, and the correlation between frequencies and activity is less good in the declining phase of the most recent cycle than at other times. All these aspects may indicate some contribution from the subsurface layers. There
Figure 2. Variation of mean low-degree frequencies over two solar cycles (from Broomhall et al. 2009). Symbols with error bars show frequency shifts; the continuous curve (and the right-hand scale) show corresponding levels of the 10.7 cm radio flux over the same epoch.

is also evidence of a change in the wave speed at the base of the convection zone of about one part in $10^4$ between solar minimum and solar maximum according to the analysis by Baldner & Basu (2008).

4. Flow variations over the cycle

The observed changes in the odd component of the frequency splittings provide strong evidence for temporal variations in the subsurface rotation of the Sun. The so-called torsional oscillations – weak but coherent banded zonal flows superimposed on the overall rotation profile – were discovered in surface Doppler measurements about three decades ago and have been shown by helioseismology to persist through a substantial fraction of the convection zone (Howe et al. 2000a). Indeed, much of the convection zone seems to exhibit angular velocity variations (Vorontsov et al. 2002). In spite of the present extended solar minimum, the equatorward migration of new prograde banded flows from mid-latitude is already well underway, though its rate of migration is slower than it was during the previous minimum (Howe et al. 2009). Based on an analysis of these flows, Howe et al. estimate a length of approximately 12 years for Cycle 23.

A similar analysis to that of Howe et al. (2009) but extended to high latitudes reveals further interesting behaviour of the rotation rate over time (Howe et al. 2010, in preparation). For example, at 75° latitude the rotation rate has varied by almost 25 nHz over the cycle, reaching a minimum at around the start of 1999 and a maximum in 2003/4: for the past two years it pretty well repeated its behaviour of 11.5 years ago. At even higher latitudes the behaviour is rather similar, though there is a curious double peak to the maximum, with one maximum in 2003 and the second one around the start of 2006: bearing in mind that
these global results do not separate out the northern and southern hemisphere, it is unclear at present whether the double-peak represents episodic behaviour or a difference in timing between the two hemispheres in reaching their maximum rotational speed.

There is also evidence of a change in rotation rate near and possibly also beneath the base of the convection zone in the rising phase of the last cycle, with a period of about 1.3 years, according to the analysis by [Howe et al. (2000b)](#).

5. Local helioseismology – potential and issues

Inversions based solely upon global mode frequencies have no longitudinal resolution, nor can they distinguish the northern and southern hemispheres. Various local helioseismic techniques offer the capability to study local features and different structures and flows in the two hemispheres. One such technique is ring-diagram analysis (or simply ring analysis). Another is time-distance helioseismology. With these techniques it has proved possible to study the subsurface meridional flow and its variation over the solar cycle, but thus far only in the outer few per cent by radius of the solar interior. Down to about 15 Mm the meridional flow is fairly uniform, of order 20 m/s, and poleward in direction, though with evidence of subsurface counter-cells being present in the northern hemisphere around the time of solar maximum and in the southern hemisphere during the declining phase of Cycle 23 ([Haber et al. 2006](#)). A measurement of the meridional circulation much deeper in the convection zone would be a valuable constraint on flux-transport dynamo models (e.g. [Dikpati & Gilman 2009](#)). However, such a measurement is challenging: an estimate indicates that the meridional flow at the base of the convection zone may not be detectable with measurements spanning an interval less than a solar cycle ([Braun & Birch 2008](#)).

There is also strong evidence from local helioseismology of signatures of evolving structures (thermal and/or magnetic) under active regions (e.g. [Kosovichev et al. 2000](#)). However, there do appear to be significant discrepancies between the inferences obtained using different methods ([Gizon et al. 2009](#)) which indicates that a better understanding of the forward modelling of the interaction of waves with magnetic structures and the resulting observables is required.

6. Conclusions

Helioseismology has produced unprecedented measurements of the Sun’s internal structure and dynamics over the past 25 years. These include having mapped the solar rotation over most of the interior, and discovering the solar tachocline.

The frequencies of the Sun’s global oscillations change over the solar cycle. Observed changes the odd component of the frequency splittings reflect changes in the solar internal rotation in possibly below the convection zone. The behaviour of the banded zonal flows (torsional oscillations) give a length of approximately 12 years for Cycle 23.

Most of the changes in mean multiplet frequencies and in the even component of the frequency splittings comes from changes at or very close to the surface, caused by changes in the surface magnetic field (or something that is
highly correlated with the surface field). The frequencies of low-degree modes
are lower this minimum than during the previous minimum: there may be some
subsurface differences in the two minima that account for this. There may also
be some small variation in wave speed at the base of the convection zone corre-
lated with surface activity.

Local helioseismology clearly detects temporal and spatial variations, and is
the fastest developing area of helioseismology. But there is a need for improved
forward models in order to make robust inferences about the physical causes of
those variations.

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