Session 1

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Large-scale flows in the Sun: Characteristics and time variations

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Abstract. The study of solar rotation has a 150-year history. Early studies were restricted to looking at the movement of sunspots; much later came studies using other tracers such as supergranules, and spectroscopic measurements using Doppler shifts of spectral lines. These studies also found evidence of other large-scale flows, such as the meridional flows in the north-south direction and the zonal flows, or torsional oscillations, parallel to the equator. However, until the 1980s, the study of solar rotation and large-scale flows was restricted to what could be observed on the solar surface. The advent of good helioseismic data changed that and gave us the means to study flows in the solar interior. Instruments like GONG, MDI and HMI have now collected helioseismic data for two solar cycles and these also allow us to study the large scale flows and their variations with time and solar activity. We review what the long data sets tell us about the these flows and discuss some of the differences between solar cycles 23 and 24.

Keywords. Sun:general, Sun:rotation, Sun:activity, Sun:oscillations, Sun:interior

1. Introduction

One of the most important uses of solar data sets that cover a long period is to determine changes that take place in the Sun. This is particularly true in the case of solar dynamics, i.e., flows in the solar interior.

Large-scale flows in the Sun can be divided into three major categories: (1) rotation, (2) zonal (i.e., east-west) flows, and (3) meridional (i.e., north-south) flows. Additionally there could be features near the poles that cannot be studied well because of limitations of the observations. The study of solar rotation in particular has a very long history, however, it was not till the availability of helioseismic data sets from projects such as GONG (Hill *et al.* 1996) and MDI (Scherrer *et al.* 1995) became available in the mid 1990s, that rotation in the interior could be studied in detail. GONG is still observing, and MDI has been replaced by HMI (Scherrer *et al.* 2012) and the data sets have continued to become longer. These data sets have also been critical in studying the depth dependence of zonal and meridional flows. Most results discussed in this review are those obtained from helioseismic analyses.

2. Solar rotation

The differential rotation of the solar surface has been known for a long time. Even from Christoph Scheiner's observations in the 17th century (Scheiner 1630), it was clear that sunspots near the equator rotate faster than those at higher latitudes. In this review we focus more in the internal rotation of the Sun; those interested in what tracers and spectroscopy show are referred to the review by Beck (2000).

Helioseismic data allowed the first estimates of the rotation rate of the solar interior. Duvall *et al.* (1984) estimated the rotation rate as a function of radius, but their data

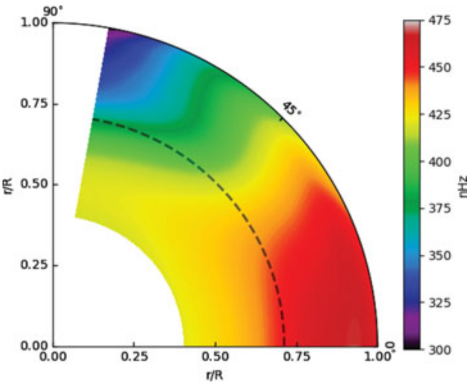

Figure 1. Solar rotation plotted as a function of radius and latitude. Results were obtained using GONG data. The data do not allow us to determine the rotation rate sufficiently well at very high latitudes or at radii less than about 0.4 $R_\odot$. The dashed line is the convection-zone base.

forced them to ignore latitudinal variations. Brown (1985) however, could gather enough data to determine the solar rotation rate both as a function of radius and latitude. More detailed results have been obtained since with GONG data (Thompson *et al.* 1996) and MDI data (Schou *et al.* 1998). These results changed what we thought we knew about the internal rotation of the Sun. Theoretical models of that time that reproduced the surface rotation rate indicated that rotation in the solar interior should be constant on cylinders (see Glatzmaier 1985), however, the picture that helioseismology revealed was quite different (see Fig. 1). The latitudinal differential rotation continues to about the base of the solar convection zone and below the convection zone, the Sun rotates almost like a solid body. There are two other notable features, the shear layer at the base of the convection zone where rotation changes from being differential to solid-body like, this is usually called the tachocline, and a near-surface shear layer where the rotation rate increases with depth.

Solar rotation rate changes with time. The latitudinally averaged rotation rate increases with solar activity in the near-surface layers (Antia & Basu 2013). This component tracks solar activity so well that the differences in activity in the solar minimum before cycle 23 and that before cycle 24 can be seen quite clearly.

There have been questions of whether there are time variations in the tachocline. The tachocline is believed to be the seat of the solar dynamo and hence any observed changes will be critical inputs to the study of solar dynamo. Howe *et al.* (2000a) had claimed to detect a 1.3 year period in the rotation rate at the base of the convection zone, however, other independent analyses (Antia & Basu 2000; Basu & Antia 2001; Corbard *et al.* 2001) did not find any such variation. Howe *et al.* repeated their analysis to find that the periodicity was not present after 2001 (Howe *et al.* 2007). Antia & Basu (2011) did a comprehensive forward modelling of the tachocline to look for possible time dependent changes. The only significant change that they found was in the jump of the rotation rate across the tachocline. However, the change was small. They did not see any evidence for a 1.3 year period.

The changes in the near surface shear layer are more difficult to quantify. Antia & Basu (2010) obtained differing results with GONG and MDI data sets which made them doubt the results. Barekat *et al.* (2016) looked at the gradient of the rotation rate in the near-surface shear layer and found two cyclic patterns, one at low latitudes and one at

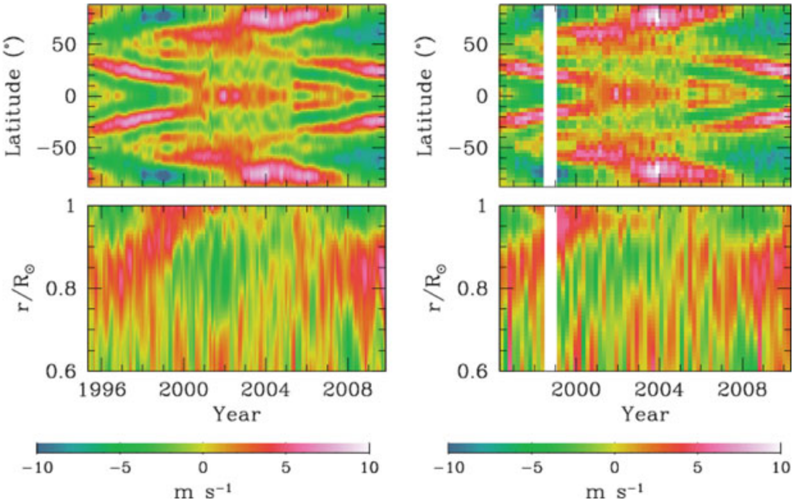

Figure 2. Zonal flow speeds obtained using GONG (left panels) and MDI (right panels) data. The top panels show the latitude vs. time plot at 0.98 $R_\odot$, while the lower panels show the depth vs. time plot for 15° latitude. (Figure from Antia & Basu 2010).

high. They used data from MDI and HMI and did not check what GONG data would show.

3. Zonal and meridional flows

First discovered by Howard & Labonte (1980), zonal flows, or torsional oscillations as they used to be called, are bands of retrograde and prograde flows parallel to the equator. The flows are seen in the entire convection zone (see e.g., Howe *et al.* 2000b; Antia & Basu 2000, 2001; Vorontsov *et al.* 2002). Perhaps the most interesting feature of the flows is that they change with time — the amplitudes and phases of the flows vary as a function of latitude, depth and the phase of the solar cycle (Antia & Basu 2010; Howe *et al.* 2005).

In Fig. 2 we show the time dependence of the zonal flows as a function of latitude at a radius of 0.98 $R_\odot$ and as a function of depth at a latitude of 15°. At the active latitudes, the bands move towards the equator as the solar cycle progresses, and at higher latitudes, the bands move towards the poles. The former is pattern is reminiscent of the butterfly diagram, and the latter follows the same pattern as the high latitude magnetic flux during each cycle. Further analysis by Antia *et al.* (2008) have shown that the butterfly diagram correlates better with the gradients of the zonal flows, and that sunspot positions coincide with region of highest zonal-flow gradients (Fig. 3).

The time-dependence of the zonal flows at any latitude can be fitted to a series of sinusoids: $\delta v(r,\theta,t) = \sum_{k=1}^{k=3} A_k \sin(k\omega_0 t+\phi_k)$. For $\omega_0 \simeq 11.7$ years, the nominal duration of cycle 23 as was done by Antia & Basu (2013), then it turns out that the form fits the zonal flows in cycle 23 very well, however, cycle 24 was different. The same value of ω_0 could fit the low- and high-latitude flows of both cycles, but could not fit the cycle 24 zonal flows in the intermediate latitudes, revealing cycle-to-cycle differences in the flows.

Meridional flows (i.e. north-south flows) play an important role in flux-transport dynamos. In the near-surface layers, the flows are believed to transport flux from the equator to the poles, and in the interior the flux is transported back into the lower latitudes to

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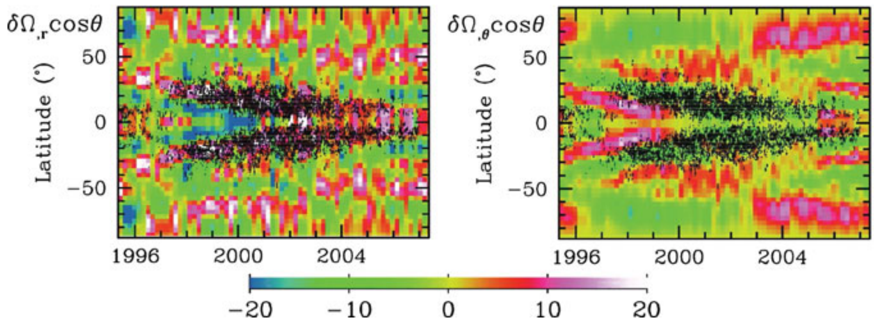

Figure 3. Radial and latitudinal gradients of zonal flows at 0.95 $R_\odot$ superposed on the butterfly diagram showing the distribution of sunspots as obtained from the Greenwich sunspot data. The scale is marked in units of nHz $R_\odot^{-1}$. The abscissa in in units of years. (Figure from Antia, Basu, & Chitre 2008).

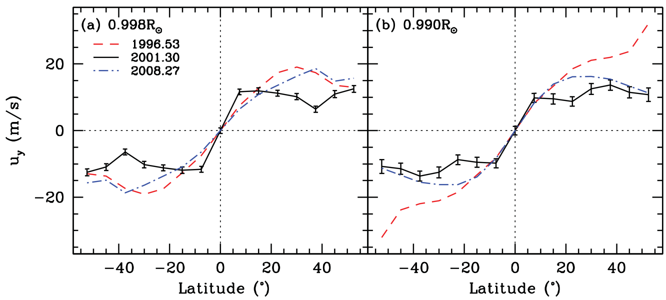

Figure 4. Helioseismic inferences on the north-south component of solar meridional flows as obtained with MDI data. Results are shown at two depths for epochs close to the minima of cycles 23 and 24, and the cycle 23 maximum. Results are from Basu & Antia (2010).

begin the next cycle. Thus one of the aims of determining the characteristics of meridional flows has been to determine the depth of the so-called "return flow"; most dynamo models assume that it is at the tachocline. The surface values of the flows can be obtained by magnetic feature tracking (e.g., Hathaway & Rightmire 2010), but as usual, helioseismic techniques are needed to determine the depth dependence. However, the signature of flows in global mode data are subtle and hard to detect, and hence local helioseismology methods (see Gizon & Birch 2005 for a review of these methods) need to be used to determine the flow velocities as a function of radius. The first estimates of sub-surface meridional circulation were made using time-distance measurements (Giles *et al.* 1997). Subsequent measurements were made using the ring diagrams method (Basu *et al.* 1999; Haber *et al.* 2002; Basu & Antia 2010)

Ring diagram analyses have shown that in the near surface layers, the flows are from the equator to the poles in both hemispheres. Unfortunately, these analyses are sensitive only to depths of 15-20 Mm. In these layers one finds a substantial solar-cycle related variation of the flows (see Fig. 4). Meridional flows appear to be faster during solar minimum than at solar maximum (see e.g., Komm *et al.* 1993; Basu & Antia 2003, 2010).

There have been many time-distance studies too (e.g., Rajaguru & Antia 2015; Jackiewicz *et al.* 2015; Chen & Zhao 2017), but the results do not agree with each other. All results however, appear to show that there are multiple cells within the convection zone. There is no consensus as yet about a return flow in the tachocline.

As was discussed in Section 2, we do not have good estimates of the rotation rate at the polar regions. The global helioseismic data used to determine rotation rates do not have

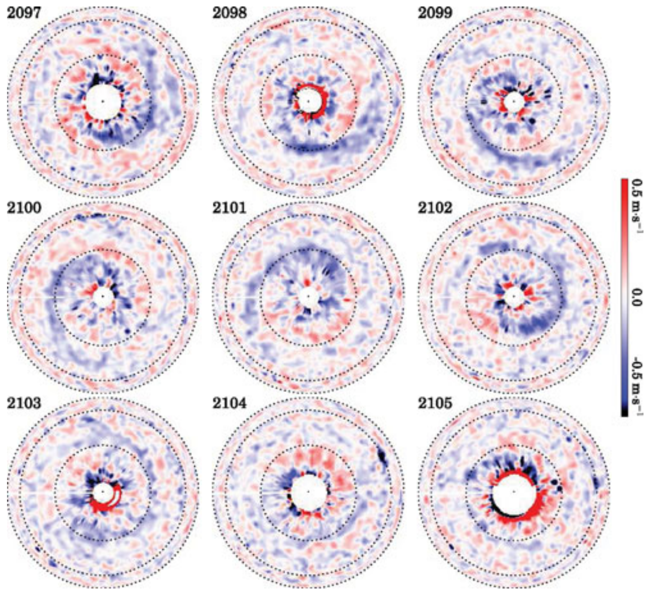

Figure 5. Synoptic maps of the zonal flow anomalies in the northern hemisphere for nine successive Carrington rotations, plotted in an orthographic projection centered on the north pole. Carrington longitude 0° is at left, with longitude increasing counter-clockwise, in the direction of solar rotation. The dashed circles are latitude lines at intervals of 30°. Results are from Bogart, Baldner, & Basu (2015).

much sensitivity there. Local helioseismic techniques are more promising in this regard. With GONG and MDI data, one cannot get reliable local-helioseismic results about the flows, whether zonal or meridional, at very high latitudes, however, the higher resolution of HMI data allows us to go higher in latitude.

Bogart *et al.* (2015) showed that there are "anomalies" in the zonal flows at high latitudes. The "anomalies" are defined as the residuals obtained after subtracting the average zonal flow obtained with the first four years of HMI data. These anomalies vary in space and time and reveal some long-lived, distinct bands (see Fig. 5). These bands stretch from southwest to northeast in the northern hemisphere, and have the opposite orientation in the southern hemisphere indicating that the features are being dragged by the shear caused by differential rotation The features can last a few months.

Unfortunately, even with HMI data we cannot sample the poles and determine what happens to the flows there. Observations made from the ecliptic plane are not going to help there. The Solar Orbiter Mission (Müller *et al.* 2013) should be able to help there.

4. Concluding thoughts

Helioseismology has allowed us to determine characteristics of solar internal dynamics and their time variations reasonable well. Most of the time variations appear to be connected to the solar cycle. However, we do not yet know the nature of the rotation of the solar core and the the poles. Also not known reliably are the details of the meridional flows as a function of depth, and in particular, whether or not there is a return flow in the tachocline. Many dynamo models assume a return flow there to reproduce some of the observed features (e.g., Chakraborty *et al.* 2009; Hazra *et al.* 2014).

Of course we do not understand some of the physics behind what we observe. For instant, why there is a cycle-to-cycle variation in the dynamics? Clearly this has to do

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with the difference between different solar cycles, thus ultimately we need to understand why the solar cycles differ. We also do not know why the zonal flows (particularly their gradients) are correlated with sunspot positions, raising the question which is the cause and which is the effect, or whether the two locked in a feedback mechanism.

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