Chapter 1

Introduction

Helioseismology has been a powerful tool for measuring the structure and rotation of the solar interior. However, there are still many aspects of the Sun's dynamics which are not well understood. This thesis uses the recently developed method of time-distance helioseismology, closely analogous to seismic exploration in geophysics, to search for large-scale flows in the interior of the Sun. With this technique, data from the Michelson Doppler Imager (MDI) have been used to measure the meridional circulation deep in the solar convection zone for the first time. The results show that the measurements are consistent with a meridional circulation which is 20 m/s poleward at the solar surface, and roughly 3 m/s equatorward at the base of the convection zone. The turnover point is just below $r = 0.80\mathrm{R}_{\odot}$. The meridional circulation is also observed to be varying with time, with the possible appearance of an equatorward surface flow at high latitudes during the rising phase of the solar magnetic cycle. In addition to these important results, the measurements have yielded interesting results for the solar differential rotation, including the possible detection of a highly localized asymmetric feature with an amplitude of 200 m/s.

All of these measurements illustrate the unique capabilities of the time-distance technique for looking at the solar interior in a new way. Furthermore, these results will have a bearing on our understanding of solar dynamics, particularly the solar cycle and the maintenance of the rotation profile.

In the remainder of this chapter, I will discuss large-scale flows, emphasizing those aspects which I believe to be important for understanding the research described in the rest of this dissertation. In section 1.1, I will explain why these measurements are important to our understanding of the Sun and stellar physics in general. Section 1.2 will define some of the terms which are used to describe these flows, and describe the previous observations which are relevant to this work. Finally, in section 1.3 I will briefly summarize the important results contained in this dissertation.

1.1 Large-Scale Flows and Solar Dynamics

The Sun is by far the most studied and well-understood of all the stars in our sky. Scientific observations of the Sun date back to the invention of the astronomical telescope in the first decade of the seventeenth century, when Galileo and other early observers turned their crude early instruments toward the brightest object they could see. With these first observations came the "discovery" and systematic study of sunspots. Almost two hundred years later, it was discovered (Schwabe, 1843) that the number of sunspots visible on the disk of the Sun varied with an eleven-year cycle. Shortly thereafter, Carrington (1858) described what is now known as the *butterfly diagram*, which indicates that sunspots gradually move toward the equator during the progression of the solar cycle.

Despite this long history of observation, the basic puzzle of the eleven-year sunspot cycle is still basically unsolved. Since the work of Hale (1908), it has been known that sunspots are regions of strong magnetic field. In the last few decades it has been shown that all aspects of the solar magnetic field undergo a similar eleven-year cycle. It has also been shown that the cycle is only quasi-periodic, with occasional extended minima. This behaviour has important implications for our technologically advanced civilization, and may even impact on Earth's climate.

Clearly, if we want to understand the solar magnetic cycle we cannot ignore the Sun's dynamics. Flows on the Sun transport mass, energy, momentum and magnetic field from one location to another, and must play an integral role in the solar cycle. Any explanation of the regeneration of the surface magnetic field must also be consistent with the observed flows. Recent models suggest that the main role in this regeneration is played by the Sun's differential rotation, where the angular velocity varies with latitude. However, other flows may also be important for explaining certain aspects of the cycle behaviour.

On a more subtle level, the solar differential rotation is itself a puzzle. How does the Sun maintain a rotation where the angular velocity at the equator is higher than that at the poles? The balance of angular momentum must be acheived through the interplay of meridional and convective motions. Again, models of the Sun's convection and dynamics must be reconciled with the observed velocities.

In this work, my main objective is to measure an aspect of the solar velocity field which has never been measured before: the meridional circulation in the solar interior. The meridional circulation probably has an important role in both the solar dynamo and the angular momentum balance. I will also present some new measurements of the interior rotation. These measurements serve to justify the method, but also contain some hints of interesting new phenomena.

1.2 Previous Observations

1.2.1 Differential rotation

Magnetic feature studies

Recorded observations of sunspots on the solar disk stretch back at least 500 years from the present time. The motion of these features across the solar disk was the first indication that the Sun is a rotating body. A number of observers in the seventeenth and eighteenth centuries observed the rotation of the Sun from the motions of sunspots (see for example Eddy *et al.* (1976)). In 1863 R.C. Carrington published his landmark work *Observations of the Spots on the Sun* from observations made over a period of nine years. In it, he established the orientation of the Sun's rotation axis and defined a heliographic coordinate system that is still in use today, almost 150 years later. Carrington also made the first quantitative measurements of the differential rotation, finding that sunspots at high latitudes have longer rotation periods than those at low latitudes. It is common practice in the literature to desribe the rotation profile with three coefficients,

$$\Omega(\lambda) = A + B\sin^2\lambda + C\sin^4\lambda \tag{1.1}$$

where Ω is the angular velocity and λ is used in this work to refer to the solar latitude.

Most of the early measurements of the Sun's surface flows relied on the same techniques used by Carrington, namely careful observation of sunspots in white-light images. The results have been varied and in some cases confusing. For example, the rotation rates measured by tracking individual sunspots are significantly different from those measured by tracking sunspot *groups* (for examples, see Howard (1984)). Furhermore, large sunspots rotate more slowly than small ones (Howard, 1984), and young sunspots rotate faster than old ones (Zappala and Zuccarello, 1991).

One of the drawbacks of using sunspots as tracers is that the features can exhibit significant evolution during a disk transit, changing in size and shape as time passes. Furthermore, sunspots rarely appear above 30° latitude, and are rare at cycle minina, which makes their spatial and temporal coverage less than ideal.

This last difficulty can be overcome by using magnetic features other than sunspots, such as faculae. Studies of chromospheric and coronal features associated with photospheric magnetic fields stretch back to the early part of this century. Near the equator, such features generally rotate like sunspots (see Howard (1984)); their differential rotation, on the other hand, can be quite different. There is also evidence that the velocity is correlated with feature lifetime and, in some cases, size (Belvedere et al., 1977).

To add to the confusion, the rotation of the large-scale photospheric magnetic field pattern exhibits quite different behaviour. Wilcox and Howard (1970) found that although the field follows a sunspot-like rotation pattern at low latitudes, the velocity is significantly higher than the sunspot rate at higher latitudes. Later investigation (Wilcox et al., 1970) showed that the longest-lived part of the pattern approached a solid-body rotation profile ($B = C = 0$ in equation 1.1).

All of these discrepancies may be related to the extent of the different magnetic features in depth. Since the rotation rate changes with radius, features which are

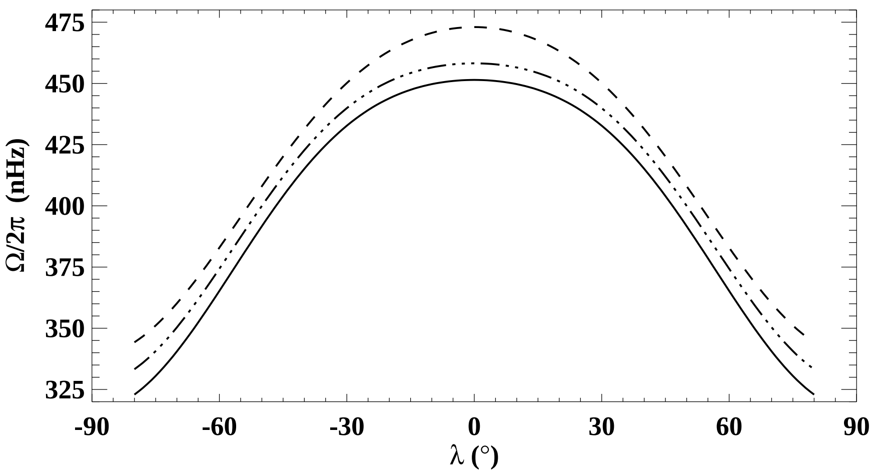

Figure 1.1: Some well-known measurements of the solar surface rotation. The angular frequency $\Omega/2\pi$ is plotted as a function of latitude λ. The solid curve shows a result from Ulrich *et al.* (1988) using direct Doppler measurements from Mount Wilson. The dashed curve is from Snodgrass and Ulrich (1990), using motions of Doppler features; the dash-dot curve is from the same paper, using motions of magnetic features.

rooted at different depths may have different angular velocities[1]. Indeed, measurements using magnetic features all suffer from this ambiguity, since the subsurface structure of the magnetic field is unknown. In order to find the velocity of the photospheric plasma, a spectroscopic approach must be employed.

Surface Doppler measurements

Using the Doppler shift of solar spectral lines, it is possible to measure the line-of-sight velocity of the solar photosphere directly. Because the height of formation of each spectral line is thought to be well-understood, this procedure provides an unambiguous measurement of the velocity of the solar plasma at a particular height. Furthermore, the velocity can be measured at very high latitudes and at any time of the solar cycle, which is an advantage over the use of magnetic tracers.

On the other hand, the determination of the rotation profile from spatially resolved

[1]See Beck (2000) for a detailed discussion of this topic.

Doppler observations is a fairly complicated process which is made more difficult by effects such as observer motions, scattered light, and correlations of brightness with velocity. In addition, it is not always possible to unambiguously separate the rotation from the other background velocity fields.

The first attempts to measure the surface motions of the Sun directly from the Doppler effect were made late in the nineteenth century, but the modern era in Doppler measurements began with the invention of the photoelectric spectrograph (Howard and Harvey, 1970). Some of the most precise determinations of the surface rotation profile have been made from very careful analyses of daily observations at Mount Wilson (Snodgrass, 1984; Ulrich et al., 1988). Currently, there are also high-quality data available from the GONG network of instruments (Hathaway et al., 1996). Although the measurements are very precise, there is still significant discrepancy between the different observations. Some of this variation may be solar in origin; in particular, the rotation rate may vary with the solar cycle.

Another way to measure the rotation from Doppler measurements is to observe the motions of "features" in Doppler images. The most common approach is to observe the motions of supergranules. Supergranules are convection cells with a typical size scale of 30 Mm at the solar surface and a typical lifetime of a day. In many ways the measurement of flows using supergranules is much easier than the direct measurement of the surface Doppler velocity (Snodgrass and Ulrich, 1990). Interestingly, the rotation rate as measured using supergranules is significantly faster than that measured from magnetic features or from the direct Doppler observations. This is sometimes interpreted as an indication that the supergranules are "rooted" in layers below the surface which rotate more rapidly than the surface itself.

Figure 1.1 shows some of the most widely quoted measurements of the surface angular velocity, and clearly depicts the differential rotation.

Helioseismic observations

With the advent of helioseismology it became possible to determine the solar rotation profile as a function of radius and latitude[2]. The first such determinations were made in the mid-1980s (Duvall et al., 1984; Brown and Morrow, 1987; Brown et al., 1989). Recent improvements in the accuracy of the observations and in the sophistication of the analysis techniques mean that we can measure the rotation of the convection zone with a precision on the order of 1 nHz (Schou et al., 1998). These results indicate that the angular velocity of the convection zone is roughly a function of latitude alone, with the radiative interior exhibiting a solid-body rotation of about 435 nHz. Betweeen these two regions is a thin layer of strong shear which has been dubbed the *tachocline* (Spiegel and Zahn, 1992). A second region of relatively large radial gradient in the rotation rate is found near the solar surface.

1.2.2 Torsional oscillations

Closely related to the differential rotation is the so-called "torsional oscillation" of the Sun, first observed in 1980 (Howard and LaBonte, 1980) and since confirmed by longer series of measurements (Snodgrass and Howard, 1985b; Snodgrass and Howard, 1985a; Ulrich et al., 1988). The torsional oscillation is a pattern of bands of faster-than-average and slower-than-average rotation. When a constant smooth function of latitude (equation 1.1, for example) is subtracted from the rotation profile, these bands have a residual amplitude of a few metres per second. The peaks in this residual are observed to propagate towards the equator, and the pattern repeats itself on a timescale of $10 - 20$ years. This behaviour is strikingly similar to the well-known butterfly diagram for solar magnetic activity.

Another interesting discrepancy between the expansion in equation 1.1 and the Sun's rotation can be found in the polar regions. With observations at higher spatial resolution and with longer time coverage it has become possible to more accurately determine the rotation rate near the solar poles (Kosovichev and Schou, 1997; Ye and Livingston, 1998). These measurements indicate that the rotation near the poles

[2]A brief discussion of the theoretical background will be given in chapter 2.

is in fact significantly slower, compared to the equatorial rate, than would be implied by equation 1.1. There are also indications that this *polar vortex* varies quite substantially during the solar cycle.

Until recently, helioseismology has had relatively little to say about the depth dependence of the torsional oscillation, mainly due to limited latitude resolution (see section 2.2.2). Now, however, instruments like MDI and the GONG network offer the possibility of observing the torsional oscillation below the surface. Kosovichev and Schou (1997) used frequency splittings of the f-mode to show that the bands did have some extent in depth. They also showed that the observed slow rotation near the poles probably persists to some depth also. More recently, Howe *et al.* (2000) and others (Toomre et al., 2000) have been able to observe the torsional oscillation pattern down to a depth of $0.92\,\mathrm{R}_\odot$ using p-modes.

1.2.3 North-south asymmetry in rotation

Some of the surface measurements of the rotation have shown small differences between the rotation rates of the two hemispheres (Howard and Harvey, 1970; Schroter and Vazquez, 1978; Godoli and Mazzucconi, 1979; Arevalo et al., 1982; Howard et al., 1983; Snodgrass, 1983; Komm et al., 1993a). In most cases, the northern hemisphere was found to be rotating slightly more slowly than the southern hemisphere. It is interesting to note that there are also magnetic asymmetries between the two hemispheres, where during the time in question the northern hemisphere has been more magnetically active. The connection between these two observations is not clear, but this asymmetry may be important for both solar-cycle models and for the angular momentum balance of the Sun.

It should be noted that some of the measurement techniques mentioned above cannot be used to measure the difference in rotation between the northern and southern hemispheres. In particular, in the case of global helioseismology, the very accurate frequency-splitting techniques can unambiguously extract only the symmetric component of the angular velocity. This has prevented any measurements of the asymmetry of the internal rotation.

1.2.4 Meridional circulation

The meridional circulation is defined as the flow in meridian planes, which are planes of constant heliographic longitude. To be more precise, I will use the term meridional *flow* to describe any velocity along meridian planes, and meridional *circulation* to describe the axisymmetric (*i.e.* global) component of the flow pattern.

Magnetic feature studies

Like the solar rotation, the meridional circulation was first measured by tracking the motions of sunspots in visible-light images. In the case of the meridional circulation, the small flow velocity makes the measurement even more problematic. If the flow is on the order of 10 m/s, the meridional motion of a sunspot is roughly 10^7m during a disk transit. This corresponds to less than 1% of the solar diameter, an effect which can be swamped by random and systematic motions of the sunspots. As a result, measurements from sunspots have produced widely scattered results: Ribes *et al.* (1985) found alternating poleward and equatorward meridional flows of up to 100 m/s; Howard and Gilman (1986) found a poleward flow of 10 m/s; and Kambry *et al.* (1991) found an equatorward flow of 10 m/s.

Studies using smaller magnetic features are generally more reliable, since the large number of features present reduces the effect of random motions and feature evolution. Most measurements of the meridional flow using these techniques have yielded a poleward flow of about 10 m/s (Komm et al., 1993b; Latushko, 1994; Meunier, 1999)).

As with the tracer measurements of rotation, these observations suffer from an ambiguity of depth. Measurements of Doppler shifts can be used to get a true surface determination.

Surface Doppler measurements

Direct Doppler observations can also reveal the meridional flow of the solar plasma, but again the measurement is much less reliable than measurements of the rotation. The surface motions of the plasma are dominated by the rotation ($\sim$ 2000 m/s) and by small-scale convection ($\sim$ 500 m/s), and acoustic oscillations ($\sim$ 1000 m/s); they are further confused by observational effects like the convective blue shift. The first successful observation of the solar meridional circulation was made by Duvall (1979) using measurements from the Wilcox Solar Observatory. More recently, careful observations from Mount Wilson (LaBonte and Howard, 1982; Ulrich et al., 1988) and from the GONG network (Hathaway et al., 1996) have been successful in measuring the meridional flow more precisely. These observations indicate a poleward flow in both hemispheres, with magnitudes ranging from 10 to 25 m/s. Part of the variation between measurements might be explained by a real time variation of the flow; there have been indications of variation in the meridional circulation with phase of the solar cycle (Komm et al., 1993b; Hathaway, 1996).

It also should be mentioned that in many instances these measurements of the meridional circulation make certain assumptions about the north-south symmetry of the flow, in order to separate it from other, larger flow components with different symmetries. Under this procedure, the velocity determined is the component of the meridional circulation which is antisymetric about the equator (poleward or equatorward), under the assumption that the symmetric (equator-crossing) part is relatively small.

Local helioseismology

Although helioseismology has been extremely successful in measuring the Sun's internal rotation it has only recently been used to measure other velocities. These recent measurements follow the rapid development of *local helioseismology*, techniques which use the local propagation of waves to measure the properties of a relatively small area of the solar interior. Time-distance helioseismology, used for this work, is one of these techniques.

Several such methods have been successfully used to measure meridional flows in the Sun (Patrón et al., 1995; González Hernández et al., 1998; Schou and Bogart, 1998; Basu et al., 1998; Braun and Fan, 1998). Since the measurement of the internal meridional circulation is one of the key results of the work presented here, these other helioseismic measurements are crucial for establishing the validity of the various methods and determining their limitations. Although it is not within the scope of this document to describe these techniques in detail, the above references can be consulted for independent confirmation of some of the results presented here.

1.3 Observations In This Work

This dissertation adds to previous measurements of large-scale flows in the Sun with four key results: the depth and latitude dependence of the meridional circulation in the deep convection zone; the north-south asymmetry of the differential rotation; the time variation of the near-surface meridional circulation during the ascending phase of the solar sycle; and the depth dependence of the torsional oscillation. In addition, appendix A offers a new measurement of the direction of the solar rotation axis.

1.3.1 The deep meridional circulation

The first helioseismic measurement of meridional flow below the solar surface was made using ring diagrams (Patrón et al., 1995); the first measurement of the global component was published by Giles *et al.* (1997). Subsequent measurements of the flow in the near-surface layers (Giles and Duvall, 1998; Braun and Fan, 1998) have confirmed that the poleward flow observed at the surface persists to the limit of observation, with a relatively weak dependence on radius. This thesis contains the extension of these measurements all the way to the base of the solar convection zone. Although the sensitivity to flows at this depth is very small, the measurements are consistent with a single-cell meridional circulation with a surface amplitude of 20 m/s, an equatorward flow at the base of the convection zone with amplitude 3 m/s, and a turnover radius of $r \sim 0.80\mathrm{R}_\odot$.

1.3.2 North-south asymmetry in rotation

Early time-distance measurements (Kosovichev, 1996; Giles and Duvall, 1998; Giles et al., 1998) indicated that the near-surface solar rotation was slightly asymmetric. Such measurements are probably complicated somewhat by observational effects, including the uncertainty in the Carrington elements (see appendix A) and the MDI plate scale uncertainty (section 4.7.2). In this work, however, an interesting and highly localized asymmetry is observed in the rotation profile at a latitude of about 40° and a radius of $0.92\,R_{\odot}$. The asymmetry seems to be persistent during two years of observation.

1.3.3 Time variation of meridional circulation

Since the meridional circulation plays an important role in some dynamo models of the solar cycle, the variation of the flow during the cycle is of interest. The observations in this thesis show that there was a significant change in the velocity profile between 1997 and 1998. During this time there was also a significant increase in magnetic activity. Although the measurements at highest latitudes are rather uncertain, it appears that the single-cell pattern observed in 1996 (Giles et al., 1997; Schou and Bogart, 1998) and 1997 changes dramatically, with a possible equatorward surface flow for latitudes above 60°.

1.3.4 Depth variation of torsional oscillation

Although the torsional oscillation is clearly visible at the solar surface, the observations presented here show no indication of a torsional oscillation pattern below $0.95\,R_{\odot}$. This contradicts recent results from global analysis which show the pattern down to $0.92\,R_{\odot}$. It is possible that the measurements in this work are too noisy to resolve the small velocity signal at that depth.

1.3.5 New Carrington elements

During a search for longitudinal variation of the meridional and zonal flows, it was discovered that the velocities showed strong periodic signals with periods equal to the orbital period of the SOHO spacecraft. Appendix A shows that this variation can be largely explained by a small error in the Carrington elements i_c and Ω_c which describe the direction of the Sun's axis of rotation; the data suggest corrections $\Delta i = -0.091°$, $\Delta\Omega = -0.18°$.

These central results, along with a more complete explanation of their scope and limitations, will be described in the remainder of this dissertation. In chapter 2, I will discuss the technique of time-distance helioseismology as it applies to the measurement of solar flows. In chapter 3, I will briefly describe the Michelson Doppler Imager and the images that are produced by that instrument. The fourth chapter outlines the methods that I have used to analyze those images, including the various interpolation, filtering and fitting procedures. Chapter 4 also includes a discussion of some of the instrumental uncertainties which influence the measurements, and how they have been accounted for. In chapter 5, I will discuss the interpretation of the measurements, in particular the solution of an ill-posed inverse problem to reconstruct the velocity in the solar interior. Chapter 6 will present in more detail the main results outlined in section 1.3; chapter 7 briefly outlines the impact that these results might have on our understanding of the Sun's evolution and dynamics, in particular theories of the solar dynamo and angular momentum balance. The final chapter concludes by summarizing the key results and discusses how this work might be improved and extended in the future.