Chapter 7

Discussion and Conclusions

The time-distance measurements and inversion results presented in the previous two chapters give us new insight into the Sun's behaviour. First, these measurements will allow a more complete model of the Sun's angular momentum. Furthermore, the flows probably play an important role in the Sun's magnetic cycle. I will deal with both of these areas briefly, and finish with a few comments about future directions in this field.

7.1 Angular Momentum Transport

7.1.1 Maintaining differential rotation

The angular momentum density of the Sun is very high at the equator compared to the poles — even higher than it would be if the Sun rotated as a solid body. Since viscous forces should act to dissipate such an imbalance, there must be an active source of driving for the differential rotation. This driving force must act to accelerate the equatorial regions relative to the polar regions.

The interaction between the rotation, the meridional circulation, and large-scale convection is a complex one, best treated by numerical simulations. Research by Gilman and his collaborators (Gilman, 1972; Gilman and Miller, 1986) has shed considerable light on the role played by the meridional circulation. Their models predict exactly the type of meridional circulation which is described in chapter 6: a dominant single-cell pattern in each hemisphere, poleward at the surface and equatorward at the bottom of the convection zone. By considering the Coriolis forces which arise from such a circulation, Gilman has noted that the meridional circulation always acts to reduce the differential rotation. This effect is dominated, however, by the influence of large-scale convection. Correlations of longitudinal and latitudinal motions give rise to Reynolds stresses which transport angular momentum from the poles towards the equator, thus driving the differential rotation.

The observations presented here qualitatively support Gilman's convection models, and may serve as an additional constraint on the model parameters. Even though the role of the meridional circulation in maintaining the differential rotation is small, the magnitude of the flow itself is determined by the characteristics of the convection. It will be interesting to see if the convection simulations can also be brought into quantitative agreement with the observations.

Another interesting feature of these observations is the solar-cycle variation in the observed flows. At high latitudes, the meridional circulation (section 6.2.4) and the rotation (section 6.1.5) both show a significant change as solar activity increases. The polar regions show a slower rotation, so that the differential rotation is more pronounced. At the same time, the poleward meridional flow at the surface disappears and possibly reverses. This behaviour is consistent with the idea that the poleward meridional circulation acts to destroy the differential rotation. The underlying cause of this change, however, is unknown.

7.1.2 Asymmetry in flow patterns

The two-year observations indicate that the large-scale solar differential rotation is essentially symmetric about the equator[1]. On smaller scales, however, the observations do show significant differences between the northern and southern hemispheres.

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[1] Uncertainty in the direction of the solar rotation axis can lead to an *apparent* asymmetry in the angular velocity, as shown in appendix A.

One such feature was present throughout the entire two years of observation (section 6.1.3).

Very localized "jets" are not unheard of in dynamical models of the Sun, and indeed some similar features have been observed in inversions of global mode frequency splittings (Schou et al., 1998). However, this is the first time that an asymmetric feature of this type has been identified. It would perhaps be interesting to look at this region in more detail over a longer time period, and to optimize the resolution of the inversions in this area.

Finally, the observed north-south asymmetry in the solar meridional circulation is still unresolved. It is now my belief that the mean cross-equator flow is likely due to an instrumental effect as described in section 4.7.1. However, there is no *a priori* reason to believe that the meridional circulation must be always zero at the equator. The measurements have been presented as if the MDI camera was perfectly aligned with the spacecraft. Any subsequent information to the contrary can be used to correct the results.

7.2 The Solar Cycle

In addition to transporting mass and angular momentum, the measured meridional circulation must also transport magnetic fields from one latitude to another. It has long been believed that the solar differential rotation plays a critical role in the solar cycle; more recent models have also examined the possible role of the meridional circulation. In this section I will briefly describe and discuss these models in light of the measurements in this work.

7.2.1 Babcock-Leighton dynamo theories

During the 1960s, Babcock (1961) and Leighton (1964; 1969) described for the first time a coherent picture of the solar magnetic cycle using newly available measurements of the Sun's magnetic fields and surface motions. Although their models predated helioseismology, this work is still used as the foundation for much of our current understanding of the solar cycle. The model has come to be known as a *Babcock-Leighton* or $\alpha - \Omega$ dynamo model.

Conceptually, the Babcock-Leighton model begins with a subsurface poloidal (meridional) magnetic field. Since the Sun rotates differentially, a poloidal field line will become "wound up" by the rotating plasma until an amplified toroidal field has been produced. This is the so-called Ω-effect.

This toroidal field erupts at the surface in the form of bipolar magnetic regions (meant to represent sunspots). These magnetic regions are assumed to erupt with their "leading" (*i.e.* in the direction of rotation) poles located equatorward of their "trailing" poles; in this way, the poloidal component of the bipolar region is opposite that of the original poloidal field in that hemisphere. The α-effect is the name given to the mechanism which converts the toroidal field to poloidal field; different models account for this effect through slightly different mechanisms.

Once the bipolar regions have reached the surface, supergranular convection gives rise to an effective diffusion, which results in a net transport of trailing-polarity flux towards the poles. As more trailing-polarity flux moves to the poles, the polar fields are eventually reversed. This is in agreement with the butterfly diagram of the solar cycle, where the polar fields change sign each half-cycle.

The butterfly diagram gets its name from another obvious pattern in the field structure: as each half-cycle progresses, the sunspots appear at lower and lower latitudes. Numerically, Leighton found that in order to create stable oscillations of this type, his model required a radial gradient in the angular velocity. Furthermore, the observed equatorward migration of the magnetic eruptions could only be explained by a rotation rate which increases inward. As noted above, this work predated the birth of helioseismology as a diagnostic tool; it is now well known that the radial gradient in the angular velocity is rather small in the convection zone, except perhaps near the solar surface. There *are* strong gradients in the rotation rate at the base of the convection zone, but at low latitudes the rate is decreasing inward.

In addition, the original work by Babcock and Leighton did not include any meridional circulation. More recently, new models have been created which include meridional circulation, particularly Wang *et al.*(1991), Choudhuri *et al.*(1995), and Dikpati

& Charbonneau (1999). I will focus on the model by Wang *et al.* as representative of this class of models, in order to discuss some of the implications of the measurements I have made in this work.

7.2.2 Implications for the Wang *et al.* model

The meridional circulation plays two important roles in the dynamo model of Wang *et al.* First, the poleward meridional circulation at the surface helps to carry the flux from decaying trailing-polarity sunspots towards the poles. In earlier models, this poleward migration (and thus, ultimately, the polar field reversal) was accomplished by diffusion alone. Adding a meridional circulation therefore allows for smaller values of the supergranular diffusion. Second, the model postulates an equatorward return flow at the base of the convection zone. This flow is responsible for the "butterfly" migration of sunspots during the solar cycle, eliminating the need for an angular velocity profile which increases inward.

The stability and period of the dynamo created with this model depend quite sensitively on the magnitude of the equatorward return flow. Wang *et al.* observed that a change in this velocity of as little as 25% could make the dynamo oscillations unstable[2]. The authors present a "best" model with a return velocity of 1.3 m/s. The observations presented in chapter 6 indicate that the velocity is somewhat higher; however, it is obvious that the current measurements cannot constrain the velocity enough to distinguish between competing dynamo models.

The poleward surface velocity, on the other hand, is now quite strongly constrained by these measurements and others from helioseismology. Many dynamos use a peak value of $\simeq 10\,\mathrm{m/s}$, which is significantly lower than has been observed. In addition, there is preliminary evidence that the circulation profile changes significantly during the solar cycle. The results presented in section 6.2.4 about the possible appearance of a second, equatorward, circulation cell during the rising phase of the cycle are

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[2] Charbonneau and Dikpati also found that the dynamo characteristics depended very sensitively on the value of the return velocity.

especially intriguing. In the dynamo models mentioned above, the meridional circulation is not allowed to vary with time; further observations will be important for establishing the pattern for an entire cycle.

7.2.3 Suppression of magnetic buoyancy

Another aspect of the solar magnetic dynamo which can be affected by the size and shape of the meridional circulation is the physical location of the strong toroidal field. Parker (1975) pointed out that magnetic buoyancy acting on flux tubes in the convection zone would cause them to rise to the surface very quickly. A flux tube with a field strength of 100 gauss would rise too quickly to be significantly amplified, and thus Parker concluded that the amplification process must take place at the very bottom of or just below the convection zone.

Another possible solution to the problem was suggested by van Ballegooijen (1982) and later expanded upon by van Ballegooijen and Choudhuri (1988). The basic premise is that an equatorward meridional circulation in the lower part of the convection zone can act to counteract the effects of magnetic buoyancy through drag on the flux tube. For a toroidal loop, the magnetic tension and the Coriolis force act to pull the tube toward the rotation axis; the magnetic buoyancy acts to pull the loop radially toward the surface, and the meridional circulation can cause a drag force which acts to pull the loop toward the equatorial plane in the horizontal direction.

The authors found that, under certain conditions, flux tubes of considerable strength can be stable to small perturbations in position in the lower part of the convection zone. Specifically, the tube can be stable in regions where the meridional flow is equatorward and increasing outward. The measurements of chapter 6 do not indicate any such regions, but of course this is not ruled out by the observations.

7.3 Conclusions

7.3.1 Summary of results

The measurements presented in the previous chapters show that the technique of time-distance helioseismology can be used to measure solar flows on global scales. In addition to the development of this method, this dissertation contains several important new results.

First, the meridional flow has been measured below the solar surface. The results presented here are an expansion of previous work (Giles et al., 1997; Giles and Duvall, 1998; Giles et al., 1998) which measured the subsurface circulation for the first time. In this work, the measurements have been extended to the base of the convection zone. In chapter 6 it was shown that the measurements are consistent with the presence of a single circulation cell in each hemisphere, with a poleward flow at the surface of 20 m/s and an equatorward velocity of 3 m/s at the base of the convection zone. The turning point for the circulation is at $0.80 R_\odot$. These last two quantities are not very tightly constrained by the measurements; however, their combination is constrained by considerations of conservation of mass.

Second, the solar rotation has been measured for each hemisphere independently. In addition to demonstrating the success of the time-distance method, these measurements indicate evidence of a localized, strongly asymmetric feature in the rotation. The feature is a region near 40° latitude and $0.92\,R_\odot$ which exhibits a faster rotation rate in the southern hemisphere than in the northern. The difference in zonal velocity may be as much as 200 m/s, which corresponds to 14% of the symmetric component of the velocity. The spatial extent of the asymmetry is uncertain, since it may be smaller than the wavelength of the acoustic waves used in the measurements.

Third, the near-surface rotation and meridional circulation appear to show significant time variation during the rising phase of the solar cycle. The measurements span somewhat more than two years of observations, beginning at solar minimum in the early summer of 1996. The solar rotation appears to decrease in the polar regions as activity increases; the meridional circulation also decreases and perhaps even reverses to become an equatorward flow. It will be interesting to see if these patterns continue in the MDI data from 1999 and beyond.

Fourth, the time variations of the measurements show some effects which are probably related to our uncertainty in the Carrington elements which describe the Sun's rotation axis. The measurements presented in Appendix A show that the inclination of this axis with respect to the ecliptic plane (denoted by i) is less then Carrington (1863) proposed; in this work I suggest a new value of $i = 7.15°$.

7.3.2 Future work[3]

The study of solar flows has been an area of active study for as long as there have been solar astronomers. No doubt this will continue into the foreseeable future. The tools of helioseismology have proven to be extremely valuable in this search, and the time-distance technique developed by Duvall and others has already proven to be a worthy addition.

A precise determination of the meridional circulation at the base of the convection would be a significant observational constraint on solar dynamo theories. The measurements presented here show that the time-distance technique can be used to determine the large-scale meridional velocities. The current precision is not yet enough to discriminate between competing theories, but already at least two important facts have been established. First, the observations clearly show that the meridional circulation is a global phenomenon, and not just confined to the surface. Since a velocity of 1 m/s has been shown in some models to have important effects on the dynamo oscillations, models which ignore the meridional circulation are probably incomplete. Second, the magnitude of the poleward flow near the surface is now very well constrained by several methods in helioseismology. This surface flow may play an important role in the polar field reversal of the magnetic cycle.

In terms of improvement to this work, I believe that the interpretation of time-distance measurements will be an area of increased focus over the next few years.

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[3] If any researchers are interested in the measurements used in this work, Appendix B contains a table of the datasets which have been created during this research project, along with a brief explanation of how they can be retrieved from the archives at Stanford. These might be especially interesting to those who would offer an improved interpretation of the measurements.

Thus far most workers in the field have concentrated — as I have, in this dissertation — on making new and interesting measurements. Most of these measurements have been interpreted within the framework of the ray approximation. Although I believe this method to be quite adequate for the scope of the current work, I also expect that more general techniques will be developed in the near future.

Furthermore, the MDI instrument is, as of this writing, still in good working order. In fact, more than eight months' worth of Dopplergrams have been taken since the last image used for this work. This is especially intriguing given the changes seen in the 1998 Dynamics period.

Finally, some day it will be possible to make similar obervations from other spacecraft. Perhaps some will travel out of the ecliptic plane and allow a view over one of the solar poles. Some may allow measurements for very long travel distances by coordinating multiple platforms. Over the course of this research project, much has been learned about efficient and effective processing of MDI images for time-distance helioseismology, and these lessons should be put to good use in the future.