Chapter 1

Introduction

1.1 Motivation

The Sun is a fascinating star, which not only supports life on the Earth, but also exhibits some extraordinary scientific phenomena, such as solar flares, coronal mass ejections (CMEs), sun-quakes (Kosovichev & Zharkova, 1998), etc. It is solar magnetism that makes the Sun so fascinating, and it is solar eruptions caused by solar magnetism that makes the study of the Sun more and more important with the advent of the space age. The Sun exhibits an 11-year cycle of magnetic activities, and we just witnessed the passage of a solar activity peak in 2000 and 2001. Through magnetic reconnection which usually takes place in the corona above sunspots, solar flares are triggered, protons and electrons are immediately accelerated to high energies and escape into space. In addition, CMEs, which are often associated with flares, eject a great amount of plasma into space, sometimes towards the Earth. Powerful solar storms may knock out electricity supplies, interrupt electronic communications, and display wonderful auroral shows in high latitude areas on the Earth. These make the study of the Sun interesting and important.

Sunspots are dark areas on the solar surface where strong magnetic fields concentrate. They are a couple of thousand degrees cooler than quiet solar regions, and it is believed that this is caused by the convective collapse in the presence of strong magnetic fields of an order of 10^3 Gauss. Sunspots are relatively stable solar features, and they often remain on the solar surface without apparent shape changes for a few days or longer. The mass flows around sunspots have been under study ever since Evershed (1909) by analyzing various spectra (e.g., Schlichenmaier and Schmidt, 1999), and by tracking motions of small features such as umbral dots (e.g., Wang & Zirin, 1992). The dynamics of sunspots' umbra and penumbra on the surface has been quite clear, however, the interior structure and dynamics of sunspots remain largely unknown. Clearly, it is of great importance to study the subsurface dynamics of sunspots, because most of the magnetic flux that forms sunspots remains beneath the surface, and the growth and decay of sunspots depend heavily on the subsurface dynamics.

On the other hand, solar eruptions often occur in the solar chromosphere and corona above sunspots. Both the storage of magnetic energy that powers solar flares and the plasma motions that trigger solar flares may occur in the interior beneath the corresponding active regions. The study of sunspots' subsurface dynamics will certainly help us understand the connections between subsurface flows and solar eruptions above the solar surface.

The quiet solar regions are dominated by supergranules with a typical size scale of 30 Mm and a typical time scale of 20 hours. Supergranulation is characterized by its divergent flows with an order of 500 m/s. Small magnetic features often concentrate at the boundaries of supergranules, where supergranular divergent flows terminate and downward flows are observed(e.g., Wang, 1989). Supergranulation is generally believed to be a kind of solar convection cells on a scale larger than granulation and mesogranulation (existence of mesogranulation is often questioned), while many researchers dispute such an interpretation. Despite the convincing reports of downward flows along magnetic features at the boundaries of supergranules, no upward flows were observed convincingly inside supergranules, and the magnitude of vertical velocity inside supergranules is believed to be lower than 50 m/s. The magnetic field at the boundaries of supergranulation forms magnetic networks. Some researchers proposed that such magnetic field might be generated by the "local dynamo", a source different from that of active regions (Cattaneo, 1999).

The Sun exhibits an 11-year cycle of magnetic activity. During solar minimum years, sunspots are barely observed on the solar surface for a few months, although the magnetic network is still present. Occasionally, bipolar active regions emerge at high latitudes of approximately 35° in both hemispheres. With the evolution of the solar cycle from the minimum towards maximum, more and more bipolar active regions emerge on the solar surface with the preferred emergence latitudes migrating towards the solar equator by and by. During solar maximum years, dozens of sunspots may be observed on the solar disk in one single day. The magnetic polarities of bipolar active regions are not arbitrary: usually, in one hemisphere, the leading sunspots carry one polarity and the following sunspots carry the opposite polarity; on the other hand, the leading sunspots in one hemisphere carry a magnetic polarity opposite to that of the leading sunspots in the other hemisphere. This is known as "Hale's Law". Additionally, in both hemispheres, leading sunspots in bipolar active regions usually are located closer to the solar equator than the corresponding following sunspots. This is known as "Joy's Law". However, although these two laws are generally true, cases violating both laws are not rare. After the solar maximum passes, another solar cycle begins, and in this following solar cycle, the magnetic polarities in both hemispheres reverse compared to the preceding one.

Where does solar magnetism come from, and why does the Sun exhibit such a magnetic cycle? The generation of solar magnetism and the evolution of the solar cycle are believed to be caused by the solar dynamo, which operates at the "tachocline", located at the base of solar convection zone. It is believed that toroidal magnetic field is generated at the base of the convection zone. When the magnetic field rises up through the convection zone due to magnetic buoyancy, the magnetic field is amplified and poloidal magnetic field is then produced by the so-called α-effect. Finally, magnetic field emerges from the solar photosphere as bipolar active regions. Numerical simulations of the solar dynamo have shown that the generation and amplification of solar magnetism depend largely on the solar differential rotation and meridional flows (e.g., Dikpati & Charbonneau, 1999). Therefore, the solar interior rotational and meridional flows deduced from helioseismology play an important role in better simulation and understanding of the solar dynamo.

The Sun displays differential rotation, faster near the equator and slower near both poles. In the interior, the rotational rate displays a large radial gradient close to the base of the convection zone (e.g., Howe et al., 2000a), which is believed to be the location of the solar dynamo operation. For meridional flows, poleward flows with an order of 20 m/s were observed at the surface since the 1970s (e.g., Duvall, 1979). Inside the Sun, the poleward meridional flows were found extending nearly to the base of the convection zone (Giles, 1999). Although equatorward meridional flows are expected in order to keep the mass conservation, no evidence of such flows has been found directly from observations.

To summarize all the above, the subsurface flow fields of sunspots and supergranules are crucial to understand the origin and dynamics of these local solar features. The interior large-scale flows, including rotational and meridional flows, are the basis for understanding solar dynamo, the theory to explain the generation of solar magnetism and magnetic periodicity. However, the inference of these solar interior properties relies upon helioseismology, on both global and local scales.

On the other hand, the Sun is the only star we can observe and study in great details. As a typical main-sequence star in the H-R diagram, all the properties that we learn from the Sun, such as element abundances, temperature and pressure distributions, thickness of convection zone and radiation zone, the rotational and meridional flow profiles, the generation and evolution of magnetism, etc., are crucial for understanding other main-sequence stars and checking the stellar models.

Helioseismology is a unique tool to solve the challenges posed by the Sun. The last couple of decades witnessed a rapid progress in the field of helioseismology. By studying solar oscillation signals, helioseismologists have derived the interior structures of the Sun, including sound-speed variations and internal rotation speed as functions of both latitude and radius, as well as their variations with the solar cycle. On the other hand, local helioseismology emerged in the last decade as a new powerful tool to study interior structures and mass flows of local regions, such as supergranules and active regions. In the following, I will begin with an introduction of a brief history of both global and local helioseismology, and present some major results from this field.

1.2 Global Helioseismology

The five-minute solar oscillations were first observed by Leighton, Noyes, & Simon (1962), and later were interpreted as standing acoustic waves in the solar interior (Ulrich, 1970; Leibacher & Stein, 1971). This interpretation was later confirmed by further observations by Deubner (1975), Claverie et al. (1979) and Duvall & Harvey (1983). These observations established the solar oscillations range from low spherical harmonic degree to intermediate and high degrees, and opened a way for detailed inferences of solar interior properties, such as internal rotation rate (Duvall et al., 1984) and sound-speed variations (Christensen-Dalsgaard et al., 1985).

Better frequency resolution requires a longer uninterrupted observation. Observation networks were thus constructed to meet such a requirement. Among them are the Taiwan Oscillation Network (TON; Chou et al., 1995), and the Global Oscillation Network Group (GONG; Harvey et al., 1996), which can also provide data for local helioseismology studies in addition to serving global helioseismology studies. Observations from space can provide uninterrupted observations from one single instrument with no seeing problems, and the instrument Michelson Doppler Imager (MDI) aboard spacecraft *Solar Heliospheric Observatory* (*SOHO*) (Scherrer et al., 1995) meets this purpose. *SOHO* was launched to Lagrange point $L1$ between the Earth and the Sun in December, 1995. Continuous data (except occasional interruptions) have been transmitted down to the Earth since then, and this greatly enriched helioseismological studies.

Observations by global networks and spacecraft have provided a great amount of valuable data, and thus have boosted scientific research significantly. The properties of solar structure, such as interior sound-speed and density distribution, were inferred. Based on solar models, e.g., the solar model S (Christensen-Dalsgaard et al., 1996), inferences of the sound-speed perturbation from observation were made to compare with the model. Basu et al. (1997) derived $\delta c^2/c^2$ from observation, and found that the derived values agreed with the model within 0.5% from around 0.1 $R_\odot$ to near the surface. Similar results were also obtained by, for example, Gough et al. (1996) and Kosovichev et al. (1997). This is exciting because it proved the success of both modeling efforts and helioseismic inferences.

In addition to the sound-speed distribution, the internal rotation rate can also be inferred from the observations of frequency splitting based on the equation:

$$\omega_{nlm} - \omega_{nl0} = \int_0^R \int_0^\pi K_{nlm}(r,\theta)\Omega(r,\theta) r \mathrm{d}r \mathrm{d}\theta, \tag{1.1}$$

where ω_{nlm} is angular oscillation frequency at the mode of radial order n, angular degree l and azimuthal order m, K_{nlm} is the sensitivity kernel that can be derived from eigenfunctions of the modes, and $\Omega(r,\theta)$ is the internal rotation rate to be inferred as a function of both solar radius and latitude. Equation (1.1) is a two-dimensional linear equation, and several inversion techniques have been developed to solve it, including the methods of optimally localized averages (OLA), regularized least squares (RLS), spectral expansion, etc. (see, e.g., Christensen-Dalsgaard, Schou, & Thompson, 1990). Inversion results showed that the internal rotation rate was basically consistent with the surface rate through the convection zone, and a sharp gradient of rotation rate existed at the bottom of the convection zone of around 0.7 $R_\odot$, denoted as tachocline, which is believed as the location of solar dynamo (Spiegel & Zahn, 1992; Thompson et al., 1996; Kosovichev et al., 1997; Schou et al., 1998).

It has been a few years since the start of MDI and GONG observations, and this makes possible the study of variations of solar interior properties with the evolution of solar cycle. Mixed faster and slower zonal flow bands at the solar surface, known as torsional oscillation, have been known for a couple of decades from analyses of solar Doppler data (Howard & LaBonte, 1980). Analysis of f-mode frequency splitting (Kosovichev & Schou, 1997; Schou, 1999) detected the existence of torsional oscillation extending to a depth of approximately 10 Mm. More recently, it was found that this phenomenon extended to the depth of 0.92 $R_\odot$ (Howe et al., 2000a), and later again, found that it might extend down to the tachocline through the entire convective zone at high latitudes (Vorontsov et al., 2002). The faster bands migrate towards the solar equator as the solar cycle evolves to the activity maximum, with the activity zones residing in the poleward side of the faster bands. Figure 1.1 shows the result obtained by Howe et al. (2000a).

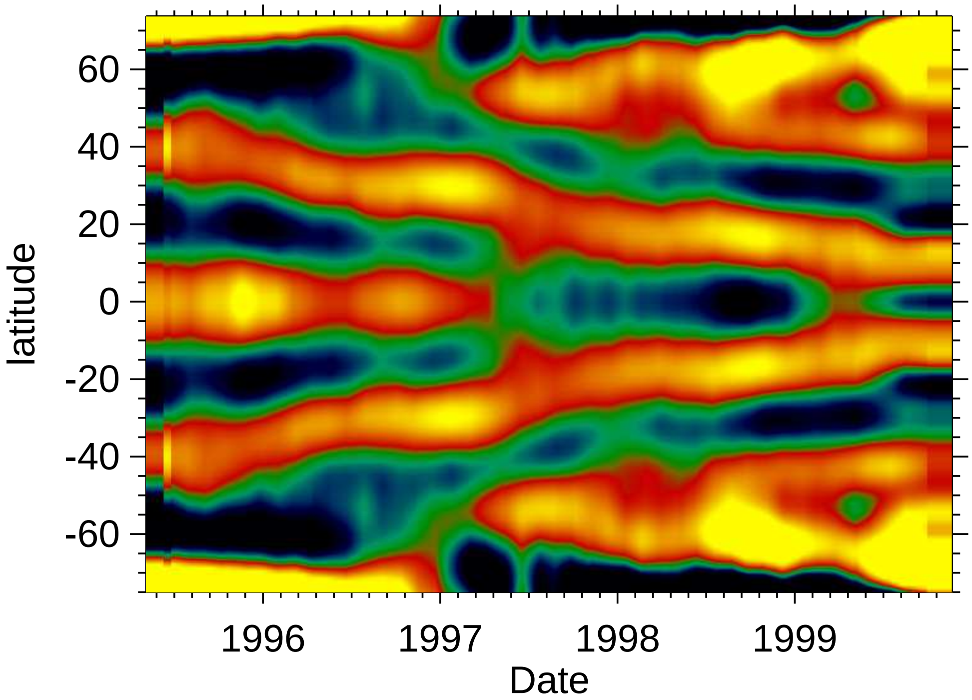

Figure 1.1: The migration of the faster zonal bands towards the solar equator with the evolution of solar cycle. The fastest(*red and yellow*) and slowest (*blue and dark*) rotation rate in the plot are 1.5 and -1.5 nHz. The results were obtained at a depth of $0.99R_{\odot}$. The plot is adopted from Howe et al. (2000a).

Another solar cycle dependent variation found by helioseismology is an oscillation of the internal rotation rate, with a period of 1.3 years near the base of the convection zone (Howe et al., 2000b), which may have some interesting implications in understanding the solar dynamo.

1.3 Local Helioseismology

Global helioseismology has successfully presented us with results on internal sound-speed structures and rotation rates of the Sun, but it still leaves many questions unresolved. For instance, it cannot detect the rotational asymmetry between solar northern and southern hemispheres; it cannot determine the meridional flows, which are perhaps as important as the differential rotation in understanding the solar dynamo; it cannot disclose the structure and dynamics of local features, such as supergranules and sunspots. In order to answer these questions, three major local helioseismic techniques have been proposed since the late 1980s and early 1990s, and currently they are still under development. These three techniques are ring-diagram helioseismology, acoustic holography, and time-distance helioseismology.

1.3.1 Ring-Diagram Helioseismology

The idea of ring-diagram helioseismic analysis was first proposed by Gough & Toomre (1983) and Hill (1988). It was suggested that in the Fourier domain (ω, k_x, k_y), mode frequencies would be changed by the local velocity field through advection of the wave pattern. Figure 1.2 shows examples of cross sectional cuts at different frequencies obtained by the dense-pack approach (Haber et al., 2002). The power spectra can then be fitted by the following profile

$$P = \frac{A}{(\omega - \omega_0 + k_x U_x + k_y U_y)^2 + \Gamma^2} + \frac{b_0}{k^3} \tag{1.2}$$

where two Doppler shifts ($k_x U_x$ and $k_y U_y$), background power b_0 and central frequency ω_0, width Γ and amplitude A are parameters to be fitted (Haber et al., 2002). The fitting parameters are then passed on to infer the depth dependent flows by solving a one-dimensional regularized least squares inversion problem.

This technique has been carried out by many researchers to infer the rotational speed and meridional flows in the upper solar convection zone (e.g., Schou & Bogart, 1998; González Hernández et al., 1998; Basu, Antia, & Tripathy, 1999; Haber et al., 2000, 2002). The rotational rates inferred from the ring-diagram analyses were compared with those inferred from global frequency splittings, and reasonable agreement was reached (Haber et al., 2000). Poleward meridional flows were also derived in both hemispheres, and a hemispheric asymmetry was found. More recently, Haber et al. (2002) and Basu & Antia (2003) investigated variations of solar rotational and meridional flows with the solar cycle. Haber et al. (2002) reported an extra flow cell, equatorward flows in the northern hemisphere a few megameters below the solar

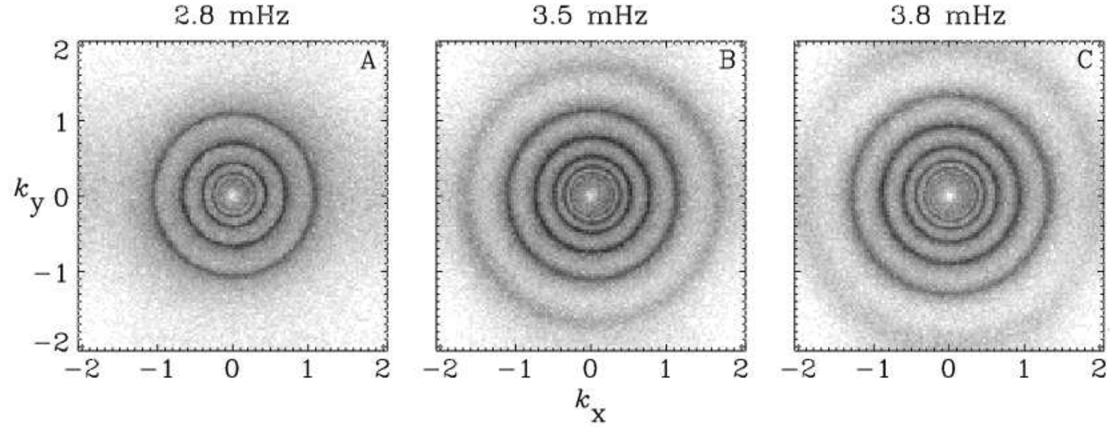

Figure 1.2: Cross sectional cuts of a three-dimensional ring-diagram power spectrum at three different frequencies. The plot is adopted from Haber et al. (2002).

surface, but this was not confirmed by Basu & Antia (2003) and Zhao & Kosovichev (2004). By use of MDI dynamics campaign data, Haber et al. (2002) made synoptic flow maps, coined as "solar subsurface weather", to study local dynamics, in particular, around large active regions.

Ring-diagram analysis was also used to study local variations of acoustic frequencies, but with poor spatial resolution. Hindman et al. (2000) derived the local frequencies from the dense-pack ring-diagram data, and found that large frequency shifts were often associated with active regions. They believed that the physical phenomenon that induces the frequency shifts might be confined within the near-surface layers rather than deep in the Sun. Similar results were also found by Rajaguru, Basu, & Anita (2001).

1.3.2 Acoustic Holography

Analogous to the optical holography, acoustic holography is a tool to image acoustic power of the solar interior, especially beneath solar active regions. This technique was developed by Lindsey & Braun (1997) (for more, see the review by Lindsey & Braun, 2000a) and in parallel, by Chang et al. (1997), who coined this technique as "acoustic imaging" (see the review by Chou, 2000).

Acoustic holography is based on the computation of

$$H_{\pm}(\mathbf{r}, z, \nu) = \int_P \mathrm{d}^2\mathbf{r}' G_{\pm}(\mathbf{r}, \mathbf{r}', z, \nu)\psi(\mathbf{r}', \nu), \tag{1.3}$$

where H_+ and H_- are the monochromatic egression and ingression, and ψ is the local acoustic disturbance at surface location $\mathbf{r}'$ and frequency ν. G_+ and G_- are Green's functions that express how a monochromatic point disturbance at a position $\mathbf{r}'$ on the surface propagates backward and forward in time to the focus at $\mathbf{r}$ and depth z. By computing the egression and ingression powers, "acoustic moats" and "acoustic glories" were found associated with solar active regions (Lindsey & Braun, 2000a).

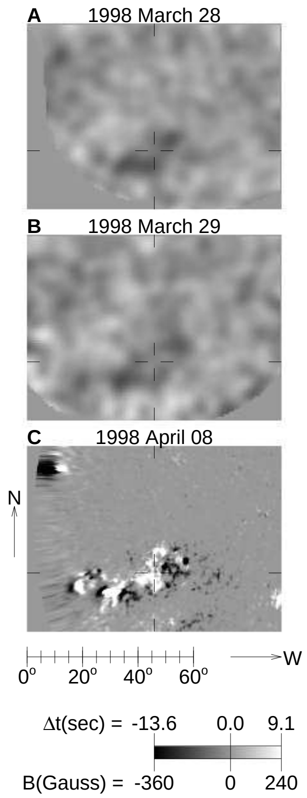

Figure 1.3: The far side acoustic images constructed by use of Dopplergrams of March 28 and 29, 1998, and the magnetogram of April 8, 1998. The acoustic anomalies seen on March 28 and 29 have the same Carrington longitude as the active regions seen in the magnetogram of April 8. This plot is adopted from Lindsey & Braun (2000b).

This technique was eventually used to successfully detect large active regions on the far side of the Sun (Lindsey & Braun, 2000b), as shown in Figure 1.3.

Phase-sensitive acoustic holography was later developed to derive the phase differences by correlating the egression and ingression signals (Braun & Lindsey, 2000).

$$C(\mathbf{r}, z, t) = \int \mathrm{d}t' H_{-}(z, \mathbf{r}, t') H_{+}(z, \mathbf{r}, t' + \tau) \tag{1.4}$$

The phase differences may yield information about dynamics, which then can be used to derive subsurface flow fields. The supergranular flow fields and outflows from sunspots were inferred by such an analysis (Braun & Lindsey, 2003). Numerical modeling for better understanding and better interpretation of acoustic holography is still ongoing.

1.3.3 Time-Distance Helioseismology

Time-distance helioseismology was first developed by Duvall et al. (1993, 1996), and then widely used as a tool to study interior properties of the Sun. Giles et al. (1997) confirmed that the solar meridional flows are poleward, and also extended the poleward flow into the deeper convection zone, although the existence of equatorward return flows is still uncertain. Rotational velocity was also derived from time-distance helioseismology (Giles, 1999), and compared to results from global frequency splittings. Reasonable agreement was found.

Time-distance helioseismology was also used to detect local properties. By deriving the travel times of acoustic waves through the underneath of supergranules, Duvall & Gizon (2000) tried to infer $\nabla \times \mathbf{v}_{\mathrm{h}}$ ($\mathbf{v}_{\mathrm{h}}$ stands for the two-dimensional horizontal velocity) and $(\nabla \times \mathbf{v}_{\mathrm{h}})/(\nabla \cdot \mathbf{v}_{\mathrm{h}})$, which may imply the vorticity and kinetic helicity inside and outside the supergranular regions. More recently, Gizon, Duvall, & Schou (2003) detected the wavelike nature of supergranules that may explain the previously observed faster rotation rate of supergranules.

Inversion of time-distance helioseismology was performed to infer the interior sound-speed variations and flow fields of sunspots (Kosovichev, 1996; Kosovichev, Duvall, & Scherrer, 2000; Jensen et al., 2001). It was found that the sound speed beneath sunspots is faster compared to the quiet Sun except in the region immediately below the sunspot's surface. Downdrafts and inward flow patterns were found below sunspots, which may provide an explanation for why sunspots can remain stable for a few days.

Forward modeling of time-distance helioseismology was carried out as well. Continuous efforts to model time-distance data by the Born-approximation were made (Birch & Kosovichev, 2000; Birch et al., 2001; Birch, 2002), and a general framework of computing forward problems and an example of distributed-source sensitivity kernels were described by Gizon & Birch (2002).

Since this dissertation mainly focuses on the studies of time-distance helioseismology, more detailed descriptions of measurements, sensitivity kernels, and inversions are presented in the following chapters.

1.4 Results Contained in this Dissertation

Chapter 2 introduces the observational techniques and inversion methods that are used in this dissertation. Some key details of time-distance measurements are given, following which one should be able to repeat such measurements. The derivation of the ray-approximation based sensitivity kernels is also presented in this chapter, and all inversion results throughout this dissertation are based on such kernels. Based on the work of Kosovichev (1996) and Jacobsen et al. (1999), I have developed two different inversion codes: one using LSQR algorithm and one based on Multi-Channel Deconvolution (MCD). The details of these two inversion techniques and the comparison of inversion results are also presented in this chapter.

A well-observed sunspot with high resolution was studied to infer its subsurface flow fields in Chapter 3. A converging and downward directed flow was found from just beneath the solar surface to a depth of approximately 5 Mm, and below this, an outward and upward flow was derived. This result may support the cluster sunspot model proposed by Parker (1979), and also agrees with result of numerical simulations for magnetoconvection (Hurlburt & Rucklidge, 2000).

The same analysis technique was then used to study a fast-rotating sunspot in order to understand the surface dynamics of this special phenomenon. A vortex, in which plasma rotated in the same direction as observed in white light images at the surface, was found near the surface, but an opposite vortex was found in deeper layers at a depth of about 12 Mm. A structural twist of the sunspot was also found by inferring subsurface sound-speed variation structures. These results are presented in Chapter 4.

It has been an interesting topic to study the magnetic helicity (or current helicity) of solar active regions, which may provide a useful tool to understand the solar subsurface dynamics, and to investigate the relationship between solar eruptions and the helicity in the corresponding active region. Our time-distance helioseismology inversions provide us three-dimensional velocities below the solar surface and thus enable us to compute the subsurface kinetic helicity of active regions. We have studied 88 active regions, and found that the kinetic helicity tends to carry a negative sign in the southern hemisphere, and a positive sign in the northern hemisphere. This statistical study is presented in Chapter 5.

Some attempts were made to derive the flow structures of supergranules. But due to the strong cross-talk effects between the divergent (convergent) flows and downward (upward) flows at the center (boundary) of supergranules, it is difficult to derive reliable vertical velocities by inverting time-distance measurements. Nevertheless, horizontal return flows were found for some large supergranules at the depth of approximately as 12 Mm, which might suggest that supergranules have a convective structure. The depth of supergranules was derived based on the correlation of horizontal flow divergences at the surface with different depths, and it was approximated 14 Mm. These results are presented in Chapter 6.

MDI had a $\sim$2 months dynamics campaign each year following its launch in December of 1995. These observations provide valuable data to study the "solar subsurface weather", and also to study the variation of various solar properties with the solar cycle, since these data cover the years from 1996 to 2002, from the solar minimum to past the solar maximum. One Carrington rotation was selected from each year for study, and synoptic flow maps were then constructed from the surface to a depth of 12 Mm for all these selected Carrington rotations. Interior rotational speed, meridional flow speed and vorticity distribution were deduced from such synoptic flow maps. Migrating zonal flows, migrating converging residual meridional flows, and some properties of vorticity distributions were found from these computations. Large-scale flows were then obtained by averaging these high resolution results, which could be used to compare with results obtained by ring-diagram analyses. This work is presented in Chapter 7.

Once we have synoptic flow maps, we can overlap the magnetic synoptic map with the synoptic flow map to study the relationship between the magnetic field strength and rotational speed of magnetic features on the solar surface. After masking the major active regions, we found that the residual rotational speed of weak magnetic features (mainly pores and network structures) is nearly linearly proportional to its magnetic field strength. This linear relationship varies with the phase of solar cycle, and the linear ratio is largest during solar maximum years. In addition, it was found that the plasma of the following polarity has a faster speed than the plasma of leading polarity but with the same magnetic field strength. These results are included in Chapter 8.

A summary is given in the last chapter, Chapter 9, with some perspective on the future studies in time-distance helioseismology.