Study of Dynamics and Magnetic Field Structure of the Solar Convective Envelope using Sunspot Activity
Chapter 1

Introduction

1.1 Historical Introduction

The sun is closest star to earth that can be studied in detail with high spatial and temporal resolutions. It is a typical G2 type main sequence star which falls in the temperature range $5800^\circ K$ and generates energy from the nuclear fusion mainly of hydrogen atoms. The sun influences life on Earth, disrupts electrical power grids, satellite and telecommunication facilities, air-traffic, etc., due to solar cycle and activity phenomena like sunspots, flares and coronal mass ejections that consist of charged particles and magnetized plasma. However, solar cycle and activity phenomena were known long ago, even prehistoric people were familiar with them. Therefore by observing and studying these solar phenomena with modern technologies it is possible to understand the solar terrestrial relationship.

Sunspots are one of the interesting aspects of solar cycle and activity phenomena. Sunspots were observed during the initial period of 17th century, particularly in China by Chinese astronomers. However early observations were misinterpreted until Galileo gave a correct explanation. He also estimated the rotation period of sun to be nearly equal to a lunar month. Sunspots were also observed telescopically in 1610 by Thomas Harriot, Johannes Fabricus, and Christoph Scheiner. The early observers like S.A.Wilson, William Herschel, etc., in the late 18th and 19th centuries believed that spots are ‘holes’ through which the ‘cooler’ interior of the sun could be seen. Although sunspots were discovered in the sixteenth century, they were systematically studied only after the establishment of observatories all over the world.
A German amateur astronomer, Heinrich Schwabe, from his long years of investigation from 1851, concluded that the number of visible spots on the sun’s disk varied with time. Schwabe discovered the solar cycle period to be \( \sim 11 \) years. Later observations however established that the period is in fact 11.2 years. The cycle of activity of Sun is repeated nearly over this period, which is known as solar cycle. Within a solar cycle, the number of sunspots and the intensity of other transient phenomena change appreciably. This lead Rodolf Wolf to make systematic observations starting in 1848. He studied historical records from 1700 AD onwards and established the cyclic behavior of sunspot activity.

Solar activity is best measured by a quantitative index, the sunspot number, related to number of sunspot groups and individual sunspots present on the sun on a given day. Rudolf Wolf introduced in 1848, a simple and globally used Wolf number of sunspots or Relative sunspot number defined as \( R = k(10g + f) \), where ‘\( g \)’ is the number of spot groups, ‘\( f \)’ the number of all individual spots in these groups and ‘\( k \)’ is the reduction factor.

Solar rotation is variable with latitude, time and depth. The sun which is in the fourth state of matter i.e., plasma and behaves differently from normal gas. Sun rotates differentially, i.e., different latitude zones rotate at different rates. Each rotation of the sun is given a unique number called Carrington Rotation number starting from Nov 9, 1853. Richard Carrington’s observations of sunspots indicated that in the beginning of the solar cycle, sunspots appear around 40 degree north and south of heliographic latitude and drift towards the equator as the cycle progresses.

At the beginning of a solar cycle, sunspots tend to form at high latitudes, but as the cycle reaches a maximum the spots form at lower latitude. At the minimum of cycle, sunspots appear closer to the equator and as the new cycle starts sunspots again appear at high latitudes. This recurrent behavior of sunspots give rise to a butterfly diagram and was first discovered by English astronomer, Edward Walter Maunder in 1904. The period from 1645-1715 of greatly reduced level of solar activity is known as Maunder Minimum. This period of very low solar activity is closely associated with one of the coldest periods known as ‘Little Ice Age’ (1350-1850 AD) on the Earth. In this period most of the European countries experienced unusually
long and harsh cold winter leading to shortened growing seasons, failed crops and widespread famine. Eddy (1976) succeeded in convincing many researchers that there was real evidence for the absence of sunspot during the Maunder Minimum period. This has led scientists to study the possible influences of solar activity on terrestrial climate. In fact recent studies (Hiremath & Mandi 2004; Hiremath 2009b) confirm Eddy’s findings and one cannot neglect the solar influence on the Earth’s climate and environment.

Motion of material within a sunspot can be derived from analysis of spectroscopy of spot. Within a spot group, velocity of the flow appears to be very complex. From an analysis of H-alpha spectroheliograms of spot, Hale observed the inflow of gas into the spot. The most correct picture of gas flow in the spot was proposed soon after by J. Evershed, who found that at the photospheric level, the gas flows outward from umbra into penumbra. Measurements of intensity and Doppler shifts in the spot spectra reveal that Evershed motion vary with distance from the center of the spot. At the upper levels of solar atmosphere a reverse flow is observed. This is known as Evershed effect.

Using Zeeman splitting of spectral lines, Hale measured magnetic field structure of sunspots and showed that it is in the range of 100 G for small spots to about 3000 G or more for larger ones. Remnant magnetic field persisted in the spot region even when the spot disappeared. The sunspot groups are classified into three classes according to the nature of magnetic polarity in the following way.

1. The unipolar groups consist of individual spots or groups of spots with similar magnetic polarity.

2. The bipolar groups that have two main spots with opposite polarity. One of these is called a leader spot while the other is called a follower spot.

3. The complex groups of spots contain spots with opposite polarity mixed together. Statistics shows that about 90% spot groups are bipolar, about 10% are unipolar, while complex spot groups are rare.

The unipolar spots are generally identified as the last visible preceding spots in
bipolar groups when the following spots have already completely decayed on the photosphere.

The most remarkable feature observed in a bipolar spot group is the reversal of magnetic polarities in either hemisphere with the beginning of a new cycle. Thus when magnetic polarities are taken into account, a complete cycle has a period of about 22 years. This is known as 22 year magnetic cycle.

1.2 Sunspot

Magnetic flux emerges as bipolar regions with a wide range of sizes through the sun’s photosphere. Sunspots are identified as active regions, a localized region on solar surface, which develops from larger magnetic dipoles. Sunspots are sites of intense magnetic field structures which are visible on solar surface but appear dark because they are cooler than the photosphere owing to the partial suppression of convective energy transport by magnetic field. A typical sunspot picture taken by solar optical telescope (SOT) on board Hinode, a Japanese space satellite is shown in Fig 1.1.

The Sun is typically very active when sunspot counts are high. Sunspots can generate solar events like solar flares and coronal mass ejections. Well developed sunspots consist of two distinct regions, viz., umbra and penumbra. Outer section of the sunspot is called the penumbra, and a darker central region is named the umbra. Some sunspots contain light bridges which are bright bands crossing the umbra. The umbra contains small bright structures called umbral dots. On the closer look, penumbra is found to be containing several filaments. The fibrils of the filament extend up to the umbra. Matter flows outwards along these filaments. This outflow is known as Evershed effect. Near the solar limb the penumbral distribution is asymmetric and this effect is known as Wilson effect. Sunspots exhibit considerable range of sizes, and the size is well approximated by a log-normal size distribution (Bogdan et al. 1988; Baumann & Solanki 2005). Large sunspots can reach diameters of 60,000 km, but are relatively rare. Sunspots smaller than 3000 km in diameter are also rare. Small sunspots live for hours, the largest ones for months.

Sunspots’ lifetime $\tau$, increases linearly with their maximum area, then decay
Figure 1.1: Sunspot picture taken by SOT on board Hinode space satellite.

slowly until they vanish from the surface. The decay is thought to be driven by turbulent diffusion of the magnetic field (Meyer et al. 1974; Petrovay & van Driel-Gesztelyi 1997) structure.

Sunspots usually show up as small forms that are irregularly shaped, and grow within days or weeks to their full size. While they can last weeks or months, they do eventually disappear, often by breaking into smaller and smaller sunspots. The number of sunspots observed on the surface of the sun varies from year to year.

The sunspot cycle maximum is the term for the maximum solar activity and solar minimum is the lowest point of solar activity that takes place approximately every eleven years. Along with the number of sunspots, the location of sunspots varies throughout the sunspot cycle. At solar minimum, sunspots tend to form around latitudes of 30 degree to 45 degree north and south of the sun’s equator. As the solar cycle progresses from solar maximum to minimum, sunspots tend to appear closer to the equator, around a latitude region of 15 degree. Towards the end of a cycle, with solar minimum once again approaching, sunspots form quite close to solar equator, around 7 degree north and south latitude zones. There is often an overlap in this latitudinal migration trend around solar minimum, when sunspots
of the outgoing cycle are forming at low latitudes and sunspots of the upcoming cycle begin to form at high latitudes once again. This gradual equatorward drift of sunspots throughout the sunspot cycle, which was first noticed in the early 1860’s by the German astronomer Gustav Sporer and the Englishman Richard Christopher Carrington, is often called Sporer’s Law.

Using Zeeman effect Hale discovered sunspots’ magnetic field structure and Zeeman effect is the amount of splitting of spectral lines in the presence of strong a magnetic field structure that depends upon strength of magnetic field and Lande g factor. Observations show that magnetic field structure is strongest at the center of the sunspot, i.e. at the umbra and decreases gradually outwards. Magnetogram is a pictorial representation of the variation in strength of magnetic field. It shows mainly “line-of-sight” component of magnetic field structure. MDI is an instrument that is used to take magnetograms of the sun in order to measure velocity and magnetic field structure in sun’s photosphere, to learn about the convection zone and about the magnetic field structure that controls the structure of solar corona. Typical SOHO/MDI magnetograms (Fig 1.3) show that the darkest areas in a magnetogram are regions of south magnetic polarity and white areas are regions of north polarity. Grey areas indicate that there is no magnetic polarity. From the magnetograms it is observed that sunspots usually occur in bipolar pairs, with negative and positive polarities. In case of bipolar spots, the magnetic field lines emerge from one polarity towards the outer solar atmosphere and enter into other opposite polarity.

Sunspots can be used for determination of sun’s rotation as tracers. Hence, from the movement of sunspots on the surface, it was discovered that the sun rotates on its axis and differentially. That is sun rotates differently at various latitude zones. The speed being greatest in the equatorial region where the period is almost 25 days and least at poles where the period of rotation is almost 35 days. Rotation for all latitudes can be expressed as

\[ \omega = A + B\sin^2\theta + C\sin^4\theta, \]  

(1.1)

where \( \omega \) is the rotation, A, B, C are coefficients and \( \theta \) is the latitude.
Present consensus is that the sunspots originate below the solar surface. In the convective envelope, owing to differential rotation and cyclonic turbulence, so called “dynamo mechanism” is supposed to wind the poloidal magnetic field structure into toroidal magnetic field structure leading to formation of the sunspots. It is believed that solar cycle and activity phenomena are produced and maintained by such a dynamo mechanism although such mechanisms have fundamental difficulties and inconsistent with physics of convective envelope (Hiremath 2009a). Once sunspots are formed, they have lower density structure and due to buoyancy raise towards the surface. Yet there are no satisfactory theories for explanation of the formation and evolution of the sunspots and, the solar cycle and activity phenomena.

1.3 Flares

One of the most frequently observed events are solar flares which are sudden, localized transient events with increase in brightness that occur in active regions near sunspot. Solar flares are the most energetic explosions in the solar system that have a direct effect on the earth’s atmosphere. Energetic particles that escape into interplanetary space are dangerous to astronauts and cause damage to electronic components of satellites. The intense radiations from a solar flare travels to earth in eight minutes which directly affect the ionosphere and radio communications at the Earth.

Typical energy probably due to annihilation of oppositely directed magnetic field structures, released in a large flare is of the order of $10^{27}-10^{32}$ erg/second. When magnetic energy is released energetic particles including electrons, protons and heavy nuclei, are heated and accelerated in the solar atmosphere. Here flares can be defined as powerful, sudden, rapid eruptions that have intense variations in the brightness of solar radiations and occur in the atmosphere of sun in magnetically active regions.

Two scientists R. C. Carrington and R. Hodgson independently observed a large flare in white light picture of the sun. The first solar flare was recorded in an astronomical literature was on September 1, 1859. During the occurrence of flares, the sun emits radiations across the entire electromagnetic spectrum. Typically there
are three stages of solar flare occurrence. They are precursor stage, impulsive stage
and decay stage. In precursor stage, the release of magnetic energy is triggered.
Emission of soft x-ray is detected in this stage. In the second or impulsive stage,
protons and electrons are accelerated to energies exceeding 1 MeV and radiations
such as radio waves, hard x-rays, and gamma rays are emitted. In the last stage,
i.e., decay stage, a gradual build up and decay of soft x-rays can be detected. Solar
flares extend to the outermost atmosphere of the sun called “corona”. The corona is
visible during solar total eclipses and in soft x-rays. Corona is concentrated around
solar equator in loop-shaped structures and these connect areas of strong magnetic
fields called active regions. Sunspots are located within these active regions.

Flare classes are classified based on their output of x-ray brightness in the wave-
length range of 1 to 8 Å. There are four categories of solar flares that in turn are
classified into 9 subclasses. X-class flares are the largest energetic transient having
intensity greater than $10^{-4}$ W/m$^2$. M-class flares are medium sized energetic events
with intensity lying between $10^{-5}$ and $10^{-4}$ W/m$^2$. C-class flares are small sized
with intensity lying between $10^{-6}$ and $10^{-5}$ W/m$^2$. Finally, B-class flares have in-
tensity less than $10^{-6}$ W/m$^2$. The structure of magnetic field around sunspot gives
an idea of understanding and predicting flares. If this structure becomes twisted
and sheared then magnetic field lines can cross and reconnect with the explosive
release of energy.

We study flares because these high energetic phenomena provide an opportu-
nity to study physical processes in nature that are similar to those that occur in
laboratory devices designed for the purpose of achieving controlled thermonuclear
fusion.

1.4 Sun’s magnetic field

During the solar total eclipse, one can notice from the white light picture that sun
is pervaded by a large scale dipole like magnetic field structure. Strength of large
scale magnetic field structure is $\sim 1$ G, whereas sun also consists of localized strong
($\sim 10^3$ G) magnetic field structure such as sunspots.
The sun with a strong and complex magnetic field structure which may impact (Hiremath & Mandi 2004; Hiremath 2009b) weather and climate on Earth. The sun’s magnetic field give rise to many effects such as sunspot, flares which are collectively called solar activity. Much of solar activity seems to be directly connected with the properties of magnetic field. In a precise and direct manner the magnetic field of sun can be probed, because in the presence of magnetic field the energy levels of atoms, ions and molecules are split into more than one level. This causes the spectral lines to split into more than one line and amount of splitting is proportional to the strength of ambient magnetic field. This physical process is called Zeeman effect.

One can measure the strength of magnetic field structure by measuring the amount of Zeeman splitting. The number of sunspots and levels of solar activity vary with an 11 year period known as solar cycle.

The magnetic field of sun extends far out of space and it is called “interplanetary magnetic Field” (IMF). The solar wind, the stream of charged particles that flows outward from sun, carries the IMF to planets and interact with planetary magnetic fields in complex ways and thus generating phenomena such as aurora. Active regions are places on solar surface where the magnetic field is strong and these regions produce sunspots. Plasma interacts strongly with sun’s magnetic field. Due to this gaseous nature and convection in the outer part of 30% of radius, sun does not rotate uniformly but rotates differentially such that different latitude of sun rotates at different rates. At its equator, sun’s period of rotation is 25 days whereas at poles it is 36 days.

1.4.1 Surface magnetic field

Solar magnetism is mainly observed via the Zeeman splitting of the photospheric Fraunhofer lines. The source of surface magnetism in sun probably lies in the convection zone, the layer of solar interior just below the photosphere. Sunspots which are the regions of intense magnetic field structures on the solar surface are visible component of magnetic flux tubes that are formed in the sun’s convective zone. Due to differential rotation and cyclonic turbulence, the dynamo mechanism is supposed
to wind the poloidal magnetic field structure into toroidal magnetic field structure leading to the formation of sunspot structures.

It is believed that the solar cycle and activity phenomena are produced and maintained by such dynamo mechanism, although recently many doubts (Hiremath 2009a) are raised regarding such a process. Coronal loops formed from magnetic field lines from the sunspot stretch out into corona. The toroidal magnetic fields linked to sunspots and coronal loops are linked to flare activity and are also associated with CMEs. Surface magnetic activity appears to be related to age and rotation rate of sunspot.

Features occurring above the solar surface i.e., photosphere, is divided into chromospheric features and coronal features. Chromospheric features include chromospheric network, plage, prominences or filaments and spicules. While coronal features consist of coronal holes, coronal loops, coronal mass ejections, helmet structures, polar plumes and solar flare. Granulation and super granulation patterns observed on the surface of the sun are the result of underlying convective processes.

1.4.1.1 Small scale magnetic fields

Howard (1967) classified the surface magnetic fields into small scale and large scale magnetic field structure. The small scale magnetic field structures are associated with small-scale structures of solar atmosphere, the development of active regions and the decay of active regions. The large scale field consists of background-field, large scale distribution of solar activity and polar fields.

Hale (1922a,b) discovered small regions on the sun where the magnetic field measured was several hundred guass. He named these “Invisible Sunspots”. Many of these features later developed into sunspots, or the remains of sunspots and some were not connected with sunspots even though they were within active regions.

Solar magnetic field structures are not smoothly distributed over the surface, but appear as small scale and concentrated in bundle. Most of these clumps are bipolar and typical sizes of these clumps are $\sim 100 \text{ Kms}$, with field strengths $\sim 1 - 2 \text{ KG}$. Stenflo (1989) has observed that, nearly 90% of the total magnetic flux penetrating the photosphere outside the sunspots occurs in such clumps. Since,
the sizes of these clumps are near the angular resolution limit, the mechanism of formation and evolution is poorly understood. It is believed that magnetic flux which appears to emerge from the solar interior as large coherent structures (example sunspots) decay by fragmentation at a rate of $10^{15} \text{ Mxsec}^{-1}$ (Gokhale & Zwaan 1972). The fragmentation implies transferring of flux from smaller to larger spatial wave numbers (Harvey & Harvey 1973; Stenflo 1976) leading to sizes of $\sim 100$ Km flux tubes.

The magnetic field structure in the photospheric layers is concentrated in active regions and in a network distributed over the whole sun (Solanki et al. 2006). In active regions (outside sunspots) the magnetic field is concentrated in faculae or plage areas. In the quiet sun (i.e., outside active regions) the magnetic flux elements form a network along the borders of super granular cells with a length scale of $\sim 20-40$ Mm. Another type of magnetic feature in the quiet sun located in the interiors of super granular cells are the internetwork elements that have horizontal magnetic field structures. Recent spectropolarimetric observations (Lites et al. 1996; Harvey et al. 2007; Lites et al. 2009) from Hinode show that: (i) horizontal fields are ubiquitous on the surface of the sun; (ii) they have structural dimension that are smaller than granules and larger than vertical fields; (iii) horizontal fields are spatially separated from the vertical fields; (iv) these horizontal magnetic field structures have strengths ($\sim 55$ G) five times larger than vertical fields and (v) strong horizontal fields in plages appear as small islands with strength $\sim 600$ G.

Another magnetic feature present on the solar surface is sunspot. Sunspot covers only a fraction of a percent of solar surface even at the times of greatest solar activity. Other magnetic activities are pores that have diameters a couple of thousand of kilometers and are dark. Smaller and more common structures that appear on the solar surface are magnetic elements and bright structures that have diameters smaller than a few kilometers. High resolution observation shows magnetic features having spatial resolution of $\sim 150$ km (Keller 1992). Indirect observations suggest the existence of internetwork field structure of diameter 50 km (Lin 1995). Observations also indicate the presence of omnipresent turbulent field structure in photospheric layers (Solanki et al. 2003). Magnetic elements have many features in common with
sunspots. These two structures together with pores are thought to be manifestations of intense magnetic flux and are described by the theory of magnetic flux tube. The magnetic structure both in active and quiet sun are similar and magnetic field is concentrated in less discrete elements of magnetic flux separated by regions with comparatively little magnetic flux.

1.4.1.2 Large scale magnetic fields

Howard (1967) showed that there exists large-scale monopolar and bipolar magnetic field structure in the of photosphere with sizes $\sim 10^3$ times larger, field strengths $\sim 10^3$ times weaker ( $\sim 5$ G ) and fluxes of the same order as those of active regions. The unipolar regions seem to be created by breaking up the ‘following’ polarity parts of the active regions. These unipolar regions seem to migrate pole ward and to build up a general polar magnetic field.

These photospheric large-scale fields lead to the large-scale structures in the corona which are seen in the white light photographs and in the x-ray pictures. The examples of these are: (i) prominences, (ii) coronal loops, extending up to one solar radius, (iii) coronal streamers, extending often beyond $\sim 10R_\odot$ and (iv) coronal holes extending up to $0.1R_\odot$.

1.4.1.3 Solar magnetic activity

Interaction of sun’s convection, differential rotation and magnetic field plays an important role in the generation of solar activity and solar cycle. But the exact mechanism of solar activity is not understood. Sunspots act as tracers of solar magnetic activity cycle. Active region of the sun consists mainly of the sunspots and the magnetic loops connecting them. The magnetic field in the sun is continuously altered and the active region is always varying which means that number of sunspots observed on the sun is not a constant but vary with time. Time variation is predominantly cyclic, i.e., mean period is 11 years. However, there are large amplitude fluctuations. This cyclic phenomenon is termed as sunspot cycle.

Early in solar cycle, sunspots appear at higher latitudes and at the end of the cycle appear closer to the equator. When a new cycle starts again sunspots appear at
high altitudes. The latitude distribution of sunspot is a good method to determine the time of sunspot minimum for a given cycle. This recurrent behavior of sunspots give rise to the butterfly pattern and was discovered by Edward Maunder in 1904 and it is shown in Fig 1.2. Butterfly diagram shows equatorward migration of sunspots, poleward migration of weak surface radial field, pole reversal at the time of sunspot maximum and both have an average periodicity of 11 years. The reason for this sunspot migration pattern is unknown. Understanding this pattern could tell us something about generation of sun’s internal magnetic field structure.

Most of the sunspot groups are bipolar which contain two principal members, the one which leads the group in the direction of sun’s rotation is called leader and the other is called the follower. In general, leader spot is found to be larger than the follower. The leading and following parts in a spot group have opposite polarities. The most remarkable feature observed in a bipolar spot group is the reversal of magnetic polarities in either hemisphere with the beginning of the new cycle. Thus, when magnetic polarities are taken into account, a complete sunspot cycle has a period of about 22 years. This is known as 22 year magnetic cycle. Magnetic interaction can sometime trigger sudden explosions called solar flares and coronal mass ejections (CMEs) which are the biggest explosions in the solar system.
and these eject magnetized plasma and charged particles into the space. These disrupt satellite operations and telecommunications facilities, electrical power grids, air-traffic on polar routes etc.

1.4.2 Internal magnetic field

Direct measurement of strength of internal magnetic field is impossible. Hence internal magnetic field structure can be studied only by theoretical modelling and comparing the consequences at the solar surface with the observed photospheric field (Hiremath 1994).

Many theoretical models have been developed for explaining the surface field structure that has near 22 periodicity. According to turbulent dynamo theory, the surface time varying field structure is maintained and periodically reversed by cyclonic turbulence and rotation inside the sun (Parker 1955a; Krause 1976; Raedler 1974; Yoshimura 1972; Gilman 1974). In order to produce a dynamo field structure a weak seed field is required. High conductivity of solar plasma suggests that the sun
might have retained some of the fossil field structure from the collapse in its proto-star phase (Cowling 1953; Hiremath 1994; Hiremath & Gokhale 1995). In fact, only on theoretical grounds such a field of primordial origin is possible (Cowling 1953; Bahcall & Ulrich 1971). Chitre et al. (1973) and Dicke (1977, 1979) had postulated the existence of fields of $\sim 10^8$ G in the central regions of the sun to explain the dearth of solar neutrinos. The meridional circulation can be induced by large scale internal magnetic field resulting in mixing of material in the solar interior. This could possibly explain the deficit of observed solar neutrinos and splitting of acoustic modes of oscillations, although recent observational evidences suggest a solution in neutrino physics.

The presence of a ‘steady’ quadrupole toroidal field structure of $\sim 2 \pm 1$ MG at the bottom of convection zone was derived by Dziembowski & Goode (1991) by analyzing the Libbrecht’s (1989) data on rotational splittings of acoustic frequencies. Mestel (1968) suggested that a field of $\sim 1$ G is required for uniform rotation. The deficit of lithium with a normal beryllium abundance in the solar atmosphere was explained by Parker (1984) and Moss (1987) by proposing that a strong magnetic field $\sim 10^6$ G may be existing below base of the convection zone. Dudorov et al. (1989) concluded that the presence of a weak large-scale magnetic field in the radiative zone could lead to the establishment of rigid-body rotation in a short time scale compared with the age of the sun. The oscillatory theories of solar magnetic cycle also require large-scale weak magnetic fields $\sim 100$ G in the radiative interior of the sun.

A large-scale weak field in the radiative core was proposed by Stenflo & Vogel (1986) and Gough (1986) based on the analysis of global magnetic resonances. A large-scale poloidal field ($\sim 10^{-5}$ - 1G) was suggested by Rosner & Weiss (1985) from the analysis of rotational frequency splittings. Spruit (1990) suggested the existence of a large-sale field of $\sim 1$ G, with poloidal and toroidal components of similar strengths on the grounds of evolution of sun’s angular momentum.

With reasonable assumptions and approximations, recently steady part of poloidal magnetic field structure in the solar interior is modelled (Hiremath 1994; Hiremath & Gokhale 1995) as an analytical solution of the equation for magnetic
diffusion in an incompressible medium of constant diffusivity such that field lines must isorotate with solar plasma. Characteristic diffusion time scales are estimated to be $\sim 10.6$ and $2.7$ billion year respectively.

1.4.3 Solar MHD

Sun is in the fourth state of matter i.e., plasma. Specifically, plasma is ionized gas i.e., gas that has been given an electrical charge by stripping of electrons. The theory of plasma involves the study of interaction between magnetic field and plasma, treated as a continuous medium. Large scale plasma structure like sun can be defined by magnetohydrodynamics (MHD) equations. MHD describes the dynamics of macroscopic plasma where magnetic field $\mathbf{B}$ and velocity field $\mathbf{V}$ are coupled using a simplified set of Maxwell’s equations along with Ohm’s law, the ideal gas law, equations of continuity, equations of motion and equations of energy. Any movement of conducting material in a magnetic field generates an electric current $\mathbf{j}$, which in turn induces a magnetic field, $\mathbf{B}$. Each unit volume of liquid having $\mathbf{j}$ and $\mathbf{B}$ experiences MHD forces approximately equal to

$$\mathbf{j} \times \mathbf{B},$$

known as Lorentz force.

Alfven was the first to introduce the term MHD. MHD applies quite well to astrophysical objects since 99% of baryonic matter of the universe is made up of plasma, including stars, the interplanetary medium, the interstellar medium and nebulae. Solar atmosphere is dominated by magnetic fields. Sunspots are the source of intense magnetic field. To understand the surface activity of sun and solar cycle it is necessary to outline the principles of MHD. The basic building blocks of MHD are Maxwell’s equations, fluid dynamic equations and Ohm’s law. The properties of electromagnetic field is described by the following Maxwell’s equations:

Ampere’s Law

$$\nabla \times \mathbf{B} = \mu \mathbf{j} + \frac{1}{c^2} \frac{\partial \mathbf{E}}{\partial t},$$

(1.3)
Chapter 1

Introduction

Faraday’s Law
\[ \nabla \times \mathbf{E} = \frac{\partial \mathbf{B}}{\partial t}, \]  
(1.4)

Coulomb’s Law
\[ \nabla \cdot \mathbf{E} = \frac{q}{\epsilon}, \]  
(1.5)

and divergence of magnetic field
\[ \nabla \cdot \mathbf{B} = 0, \]  
(1.6)

where \( \mathbf{B} \) is the magnetic field, \( \mathbf{E} \) is the electric field, \( \mathbf{D} \) is the electric displacement, \( \mathbf{j} \) is the current density and \( c \) is the velocity of light. If \( \mu_0, \epsilon_0 \) are permeability and permittivity of free space respectively, then for most gaseous media in the universe,

\[ \mathbf{B} = \mu_0 \mathbf{H}, \]  
(1.7)

and

\[ \mathbf{D} = \epsilon_0 \mathbf{E}. \]  
(1.8)

Generalized Ohm’s law is
\[ \mathbf{j} = \sigma [\mathbf{E} + \mathbf{v} \times \mathbf{B}], \]  
(1.9)

where \( \sigma \) is the electrical conductivity and \( \mathbf{v} \) is the velocity of the plasma and it relates the electric current density to the fields producing it. In fluid mechanics, equation of motion is
\[ \rho \frac{d\mathbf{v}}{dt} = -\nabla p + \rho \mathbf{g}, \]  
(1.10)
equation of continuity is
\[ \frac{d\rho}{dt} + \rho \nabla \cdot \mathbf{v} = 0, \]  
(1.11)
perfect gas equation is
\[ p = \frac{R \rho T}{\mu}, \]  
(1.12)
where \( p \) is the pressure, \( \mathbf{g} \) is acceleration due to gravity, \( R \) is the universal gas constant, \( \mu \) is the permeability, \( \rho \) is the density and \( T \) is the temperature. The equation of motion is given by Navier-Stokes equation extended by including Lorentz force which is
\[ \rho \frac{d\mathbf{v}}{dt} = -\nabla p + \mathbf{j} \times \mathbf{B} + \rho \mathbf{g}. \]  
(1.13)
Lorentzian force \((\mathbf{j} \times \mathbf{B})\) can be decomposed into two terms. The first term represents the change of \(\mathbf{B}\) along a particular field line and is therefore a magnetic tension force whose strength is proportional to \(B^2\). The second term is the magnetic pressure force. The last term \(\rho g\) in equation\((1.13)\) is a force due to gravity.

Magnetic induction equation follows from the Maxwell’s equations and the generalized Ohm’s law under the non-relativistic approximation as follows

\[
\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) - \nabla \times (\eta \nabla \times \mathbf{B}) \tag{1.14}
\]

with

\[
\nabla \cdot \mathbf{B} = 0, \tag{1.15}
\]

and the magnetic diffusivity \(\eta\) is defined as

\[
\eta = \frac{1}{\mu \sigma}, \tag{1.16}
\]

or

\[
\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B} \tag{1.17}
\]

if \(\eta\) is uniform. The first term on the right hand side of magnetic induction equation is due to convection, i.e., due to fluid motion and second term represents field diffusion. The ratio of convection term to diffusion term gives magnetic Reynold’s number, i.e., \(\frac{\nabla \times (\mathbf{v} \times \mathbf{B})}{\eta \nabla^2 \mathbf{B}} \sim \frac{\mathbf{v} \mathbf{B}}{\eta L^2} = \frac{V L}{\eta} \equiv R_m\), where \(V\) is the velocity, \(L\) is the length scale.

When \(R_m \ll 1\), then induction reaction reduces to \(\frac{\partial \mathbf{B}}{\partial t} \simeq \eta \nabla^2 \mathbf{B}\), i.e. induction equation reduces to a pure diffusion equation and therefore typical diffusive time scale is \(\tau = \frac{L^2}{\eta}\).

When \(R_m \gg 1\), then induction reaction reduces to \(\frac{\partial \mathbf{B}}{\partial t} \simeq \nabla \times (\mathbf{v} \times \mathbf{B})\), such that the frozen flux theorem of Alfven applies (Priest 1981) which states that in a perfectly conducting fluid, i.e., in ideal MHD, the magnetic lines move with the fluid or the field lines are frozen into plasma. Some basic assumptions of MHD are

1. The plasma is treated as a continuum.
2. The coefficients $\eta$ (the magnetic diffusivity) and $\mu$ (the magnetic permeability) are assumed to be uniform. Also most of the plasma properties are assumed to be ‘isotropic’. The exception is the coefficient of thermal conductivity, whose value along and normal to the magnetic field may differ greatly.

3. The plasma is assumed to be in thermodynamic equilibrium with velocity distribution function close to a Maxwellian. This holds for time-scales much larger than the collision time scales and length-scales much longer than the mean free paths.

4. The equations are written for inertial frame. The extra terms that arise for a frame rotating with the sun may be important for large-scale processes.

5. ‘Relativistic’ effects are neglected, since the flow speed, sound speed and Alfven speed are all assumed to be much smaller than the speed of light.

6. The simple form of ‘Ohm’s Law’ is adopted for most applications, rather than more general version.

7. The plasma is treated as a ‘single fluid’ although two or three fluid models may be more relevant for the coolest or rarest parts of the solar atmosphere.

1.5 Sun’s Rotation

Nearly 400 years ago (soon after the discovery of the sunspots), sun’s rotation was discovered from the movements of the sunspots over the sun’s disk, since sunspots serve as tracers that help us to compute the rotation of sun. Pioneers of this discovery were Galileo Galilei (1564-1621), Goldschmidt (1587-1615), Thomas Harriet (1560-1621) and Schiener (1575-1650).

Study of sun’s rotation started systematically from 1850 AD onwards. It was Richard Carrington and Gustav Sporer who carried out observations of the apparent motion of sunspots. From the study of sunspots, it is seen that sun rotates differentially at its surface and extends throughout the convective zone. Below the base of convection zone, i.e., in the radiative zone and core, there is an abrupt change in
rotation, with rotation like a solid body. On the surface sun’s rotation is observed to be fastest at the equator and tend to decrease as latitude increases, i.e., equatorial region rotates faster than polar region. At the equator, the solar rotation period is about 25 days and at the poles it is about 36 days. The sun’s rotational axis is tilted by about 7.25 degrees from the axis of the earth’s orbit. Since sun is in plasma state and due to convection, it exhibits differential rotation. The 11-year sunspot cycle and associated 22 year magnetic solar cycle phenomena are believed to be due to this differential rotation and convective motion of sun.

### 1.5.1 Surface Rotation

By observing the positions of stable and long-lived structures, tracers such as sunspots, faculae and filaments, super granules and coronal features etc., solar rotation can be determined. Doppler velocity measurements are also used to measure sun’s surface rotation which reveal narrow bands of weakly slower and faster rotation rate as a function of latitude that migrate towards the equator (Howard & Labonte 1980). These variations are known as torsional oscillations. Measurements from Doppler velocity also reveal nonrotational flows on the surface. These include flows from the equator towards the pole which may represent meridional flow in the convection zone (Hathaway 1996; Hathaway et al. 2003). Sun’s rotational profile on the surface can be derived by measuring the apparent motions of sunspots over the sun’s disk (Newton & Nunn 1951; Ward 1966; Balthasar & Woehl 1980; Godoli & Mazzucconi 1979). For example, a typical rotational profile of the Sun on the surface using sunspot as tracers is given by Gilman & Howard (1984) as follows:

\[ \Omega(R_\odot, \phi) = 467.0(\pm 0.2) - 91.4(\pm 1.4)\sin^2 \phi \text{ nHz}, \]  

(1.18)

where \( R_\odot \) is the observed radius of the sun and \( \phi \) is the heliographic latitude. Sun’s rotational profile can also be derived by measuring the Doppler shift in the spectral lines east and west limbs (Snodgrass 1991) and is given as follows:

\[ \Omega(R_\odot, \phi) = 453.8(\pm 1.0) - 54.6(\pm 0.8)\sin^2 \phi - 75.5(\pm 1.1)\sin^4 \phi \text{ nHz}. \]  

(1.19)
This is \( \approx 4\% \) slower than the rotation rate of sunspot groups. This significant difference, amounts to \( \approx 80 \text{ msec}^{-1} \) in relative velocity at the equator. Later measurements (Livingston & Duvall 1979; Duvall 1982) also confirm this result. The rotation of photospheric magnetic fields outside sunspots was first examined by Wilcox & Howard (1970). This rotation is similar to the rotation of sunspots. Later studies (Stenflo 1974, 1977) confirmed this result. Snodgrass (1983) also determined surface rotation from the Mount Wilson magnetograph data as follows.

\[
\Omega(R_{\odot}, \phi) = 461.9(\pm 0.3) - 73.8(\pm 2.9)\sin\phi - 52(\pm 5)\sin^4\phi \text{ Hz.} \quad (1.20)
\]

### 1.5.2 Internal Rotation

Sun’s interior is not accessible to direct observation. But the advent of helioseismology helped us to understand the sun’s interior and solar activities. Helioseismic investigations of internal rotation rate of the sun reveal that latitudinal differential rotation seen at the surface extends up to the base of the convection zone. From base of convection zone to the center, sun rotates rigidly. Sun’s internal rotation can also be inferred from the rotation rates of the sunspots during their initial appearance on the surface (Hiremath 2002). Due to very high conductivity of solar plasma, sunspots isorotate with internal plasma, and due to buoyancy rise toward the surface along the path of rotational isocontours. This implies that sunspots are very good tracers of internal dynamics and magnetic field structure of solar convective envelope. Recent studies (Javaraiah & Gokhale 1997; Sivaraman et al. 2003; Hiremath 2002) have shown that variation of initial rotation rates of the sunspot groups with different lifespans is almost similar to the radial variation of internal rotation as inferred from helioseismology.