Chapter 1

INTRODUCTION

1.1 General Introduction

The physical properties of the stellar atmosphere can be studied only through the photons received from them. The photon has three basic principle properties which contain the information about the source,

- The energy content of the photon for different wavelength bands like Ultra Violet (UV), Visible, Infra Red (IR) etc.
- The relative absorption of photons at a spectral line because of atoms present in the atmosphere.
- The polarisation state of the light.

The first principle which is known as photometry in general gives information about the temperature of the source. The second principle known as spectroscopy gives a wealth of information about the abundance of different elements present in the stellar atmosphere. These two put together is used to test all the stellar theory including the behavior of stars of different mass at different stages of evolution in the
HR diagram. The third principle, which was later employed, added more information about the magnetic fields present as well as the scattering processes involved in the atmosphere. In effect, it decides the validity of certain assumptions used in the general stellar theory. The assumption of no magnetic field and LTE can become very crude in certain regime. For example, photosphere of the sun has different structures primarily due to the presence of magnetic field and the assumption of LTE is no longer valid in chromosphere and corona. Hence, for refined models, study of the influence of magnetic fields and the non-LTE theory is important.

### 1.2 Representation of Polarised Light

The polarisation state of light can be completely specified by four quantities called the Stokes parameters. They are represented as $[I, Q, U, V]^T$ where superscript ‘T’ represents the transpose operation. These four parameters have the units of intensity and corresponds to a time-averaged intensity which is the observable in any experiment. The first parameter ‘I’ is the total intensity of the light which contains both polarised part and unpolarised part in partially polarised light. $Q$ and $U$ represents the linear polarisation state of the source whereas $V$ represents the circular polarisation state.

Any partially elliptically polarised light, which is the most general case, can be expressed in terms of the sum of a completely unpolarised component and a completely elliptically polarised component. The former component will have only intensity $I_{up}$, where the subscript ‘up’ means ‘unpolarised’, whereas the later component will have all the four components with non-zero values. The intensity, $I_p$ corresponds to the polarised intensity and is related to the other three components as,

$$I_p = \sqrt{Q^2 + U^2 + V^2}$$

(1.1)

The completely elliptically polarised component can in turn be split into a linear component plus a circular component and hence $Q$, $U$ and $V$ will have non-zero values.
1.2.1 Mueller Matrix

This is the most general case and the specific case of completely linearly polarised light can be represented by zero value of V and the circularly polarised case by zero values of Q and U. Hence, the complete specification of the polarisation state requires the measurement of all the four Stokes parameters.

**1.2.1 Mueller Matrix**

Any optical system used to measure the polarisation state of the light can be represented by a $4 \times 4$ matrix called Mueller matrix (Gerrard and Burch, 1975; Mueller, 1948). The output and the input Stokes vector for the optical system is related through this Mueller matrix as,

$$I_{out} = MI_{in}. \quad (1.2)$$

Where $I_{out}$ and $I_{in}$ are the four component input and output Stokes vector. Each of an optical element say polaroid, quarter-wave plate (QWP), and etc. can be represented by a single Mueller matrix for polarisation measurement. If an optical system has a train of optical elements say $\epsilon_1, \epsilon_2, \ldots, \epsilon_n$ with the first element close to an input source, the overall Mueller matrix of the optical system can be constructed by multiplying in order, the Mueller matrix of each element. i.e.,

$$M = M_n \ldots M_2 M_1. \quad (1.3)$$

$M$ is the combined Mueller matrix & $M_1, M_2, \ldots, M_n$ are the Mueller matrices of the optical elements $1, 2, \ldots, n$ respectively.

Mueller calculation makes the calibration of the optical system much easier for polarisation measurement. To calibrate any optical system, the combined Mueller matrix need to be calculated. Ideally, an identity matrix is preferred for the optical setup in order to get the input Stokes profile exactly at the output. However, in practice, the Mueller matrix is never going to be an identity matrix. This deviation from the identity matrix can be corrected off-line by multiplying the inverse of the
measured Mueller matrix with the observed Stokes parameters. From Equation 1.2, it can be seen that,

\[ I_{in} = M^{-1} I_{out} \]  \hspace{1cm} (1.4)

### 1.3 Solar Magnetic Fields

It is now realised that most of the physical processes happening on the outer layers of the sun are governed by magnetic fields. All the manifestations of solar activity like sunspots, plages, pores, flares, prominences, spicules, are caused by magnetic fields. Apart from these structures, there are diffuse magnetic structures like a background magnetic field on the sun (Stenflo, 1973). The presence of bright points associated with magnetic activity proposes the need for high-resolution studies since the observed bright points have sizes smaller than the diffraction limit of the biggest telescope available currently (Muller, 1985). These small scale magnetic features are predicted to be associated with the heating of the upper layer of the solar atmosphere (Van Ballegooijen, 1986). The physical processes behind the formation of these different scale structure is not yet clearly understood (Thomas, 1992). Whether the large scale structure like sunspot is formed by the segregation of small-scale fields or the small-scale structure is formed by the breaking up of the large scale structure is not yet clear.

However, it is well understood that the magnetic field plays an important role in the energy balance of the atmosphere of sun as well as stars, particularly, the solar-type stars. It is now generally believed that solar magnetic fields are produced by dynamo processes at the base of the convection zone and they emerge in the form of flux loops giving rise to the observed magnetic activity (Parker, 1955; Zwann, 1978; Parker, 1984). In order to understand the various physical mechanisms which form different structures on the solar surface at different scales, it is necessary to quantitatively study the magnetic fields. Although qualitative information on the presence
of magnetic fields and the shapes of the field lines can be obtained by observing the shapes of the emission structures with filters at various wavelengths, quantitative information requires polarisation measurements.

1.4 Solar Polarimetry

Solar polarimetry is the study of the polarisation state of light received from the sun. The only consistent way of studying the magnetic fields on the sun is through polarimetry (Stenflo, 1994). There are two possible mechanisms adapted until now to study the magnetic fields present on the sun. They are,

- Zeeman effect, to study the strong magnetic fields.
- Hanle effect, to study the weak diffuse background magnetic fields.

1.4.1 Zeeman Effect

Zeeman effect is the splitting of a spectral line when an atom emitting or absorbing light is subjected to a magnetic field (Zeeman, 1896; White, 1934). The magnetic field causes the splitting of atomic energy levels due to precession of the atom around the magnetic field axis. In other words, the Zeeman effect capitalises on lifting of the degeneracy of atomic eigenstates by magnetic fields. Figure 1.1 shows a schematic picture of the classical analogue of an atomic system as a three-axis damped oscillator having a resonant frequency \( \nu_0 \) of the spectral line. The atomic oscillator is represented by a system consisting of a linear oscillator along the direction of the magnetic field vector \( \mathbf{B} \) (called as the \( \pi \) component) plus two circular oscillators of opposite directions, both lying in a plane perpendicular to \( \mathbf{B} \) (called as the \( \sigma \) components and represented as \( \sigma_R \) and \( \sigma_L \)).

Figure 1.1 shows two different configurations of interaction of the oscillator with incident electromagnetic radiation, one is called as longitudinal Zeeman effect (top
1.4.1: Zeeman Effect

Figure 1.1: A classical analogue of the atom as an oscillator to illustrate the Zeeman effect. This figure is obtained from the High Altitude Observatory (HAO) website (http://www.hao.ucar.edu/public/research). See the text for details.

The longitudinal Zeeman effect occurs when a plane wave propagating in the direction of B excites both circular modes, $\sigma_R$ and $\sigma_L$, corresponding to right- and left- circular polarisation respectively. This excitation leads to the absorption of circularly polarised light at $\nu_0 \mp \nu_L$ where $\nu_L$ is the well known Larmor frequency ($\nu_L = eB/4\pi mc$, $e$ and $m$ are the electronic charge and mass respectively). In this special case, the incident electromagnetic wave has no oscillatory component along the linear oscillator parallel to B (since the electromagnetic waves are transverse in nature). Hence, absorption of the $\pi$ component cannot occur. Because the background continuum is unpolarised, the absorption of right-(left-) circular polarisation results in an excess of left-(right-) circular polarisation as shown in Figure 1.1. In the other special case of transverse Zeeman effect, the propagating wave excites both the $\sigma$ and $\pi$ components. The
1.4.1: **Zeeman Effect**

The latter is unshifted in wavelength by the magnetic field. The former is shifted in wavelength according to the Larmor frequency but is linearly polarised rather than circularly polarised. The direction of linear polarisation for this transverse case is depicted in the bottom figure of Figure 1.1. In general, where B can be in any direction, both longitudinal and transverse Zeeman effects act together. The shapes of the Stokes profiles of Zeeman sensitive spectral lines contain the information about the full vector B. However, there is an uncertainty of 180° in the calculation of the azimuthal field since the transverse Zeeman effect is similar for an azimuthal field configuration separated by 180°. Note that this classical picture is applicable only to the normal Zeeman effect where the transition is from J = 0 to J = 1 which makes the spectral line split into three.

For a normal Zeeman effect, the amount of splitting, $\Delta \lambda_B$ (in Å) is proportional to the magnetic field strength and is given by,

$$\Delta \lambda_B = 4.67 \times 10^{-13} \lambda_0^2 g B,$$

where $\lambda_0$ is the central wavelength in Å and B is the field strength in Gauss. ‘g’ is the Landé factor of the upper energy level. Under the Russel-Saunders coupling (Condon and Shortley, 1935; White, 1934),

$$g = 1 + \frac{J(J+1) + S(S+1) - L(L+1)}{2J(J+1)}.$$

Where L, S and J are the angular momentum, spin angular momentum and total angular momentum quantum numbers of the atomic states involved in the transition, respectively.

The Zeeman effect studied in the laboratory, which is called here as direct Zeeman effect, can be applied only to emission lines. Fraunhofer lines formed in the solar atmosphere are absorption lines. They display the so called *inverse Zeeman effect*, where the polarisation sense is reversed. The Zeeman pattern shown in Figure 1.1
14.1: Zeeman Effect

actually corresponds to the inverse Zeeman effect. The differences between the direct and the inverse Zeeman effect are (Ye Shi-hui, 1994),

- For the longitudinal magnetic field, the direction of circular polarisation for the corresponding two $\sigma$ components are opposite.

- In the transverse magnetic field, the direction of polarisation of the $\pi$ and $\sigma$ components provided by the direct and inverse effects are perpendicular to each other.

- In the transverse field, the two $\sigma$ components of the inverse Zeeman effect are only partially polarised, while for the direct effect the polarisation is complete.

- In the case of inverse Zeeman effect, the azimuth of the observed polarisation is the same as that of the magnetic field present.

In this thesis the magnetic field is studied using absorption lines and we have used the term Zeeman effect rather than the term inverse Zeeman effect. The actual situation in stellar atmosphere is more complex than the case of pure Zeeman effect. This is due to the following reasons,

- Stellar atmosphere can simultaneously absorb, scatter and re-emit radiation and also the scattering need not be coherent.

- The magnetic fields are not strong enough to completely split the line, at least in the optical region, for the observation of sun where the Doppler broadening is more than the magnetic splitting.

- The inhomogeneity of stellar atmosphere and the presence of magnetic field makes it much more difficult to infer the physical conditions present in them.

For the sun, the direct way of finding the splitting is possible only in IR wavelength region because the Doppler broadening in the visible region is more than the magnetic field splitting. As shown in Figure 1.1, in Zeeman effect, apart from the splitting of the
spectral line, the \( \sigma \) and \( \pi \) components exhibit a characteristic circular (Stokes V) or linear (Stokes Q & U) polarization. The state of polarization depends on the strength of the magnetic field and its orientation with respect to the line of sight. Hence, the Zeeman effect is a method of choice for diagnosing the presence of magnetic fields that are sufficiently strong (in excess of a few hundred Gauss) to compete with the micro-turbulent Doppler broadening of the line profiles.

### 1.4.2 Hanle Effect

A different class of polarization effects, due to coherent scattering can also be used for magnetic field diagnostics. Like the blue sky is polarised due to Rayleigh scattering by molecules, certain lines in the solar spectrum become polarised when they are partly formed by coherent scattering. When a magnetic field is present in a coherent scattering system, the precession of the atom induces a modification called the Hanle effect of this scattering polarisation. Hanle effect reduces the degree of polarisation produced by the coherent scattering and rotates the plane of polarisation. Figure 1.2 shows a picture of the classical analogue of an atom as an oscillator to illustrate the Hanle effect.

Three criteria must be fulfilled in order for the Hanle effect to be operative,

- The Larmor frequency must satisfy the condition, \( \nu_L \approx A_{ij} \), where \( A_{ij} \) is the spontaneous emission rate of the atomic transition.

- The plasma densities must be low enough and the radiation intensity must be high enough that radiative excitation of the atom is more common than collisional excitation.

- The radiation field incident upon the scattering atoms must be anisotropic.

Figure 1.2(a) represents a scattering system illuminated anisotropically by a plane wave propagating along the x-axis. Assume the magnetic field is along the y-axis and
Figure 1.2: Classical analogue of the atom as an oscillator to illustrate the Hanle effect. This figure is taken from the HAO web page. See the text for details.

The observer is positioned along the z-axis. Similar to Zeeman effect, the atomic system is represented by a combination of a linear oscillator along y-axis and two oppositely rotating circular oscillators in the x-z plane. For pure scattering in the absence of magnetic field, the observer would measure a linear polarisation parallel to the y-axis. In the presence of magnetic field, the field-aligned state mixes with the circular states causing some re-emission polarised along the x-axis and hence reduces the net polarisation of the scattered radiation. In the case of Figure 1.2(b), the magnetic field mixes the radiatively excited circular oscillator states into linear oscillator state aligned with the magnetic field and hence depolarisation occurs. A very interesting special case is depicted in Figure 1.2(c) where the field is aligned along
the line of sight (along z-axis). A pure scattering in the limit of no magnetic field, results in observed linear polarisation along y-axis since both the circular states are excited in phase with the resultant oscillation perpendicular to the line of sight. The magnetic field alters the phase relation between these two oscillators, and the finite life time of the re-emission process causes the damping of both circular oscillators. This time-dependent variation of the oscillators results in both a reduction of net polarisation and a rotation of the plane of polarisation.

For a complete understanding of the Zeeman and Hanle effect applied to the sun, refer to the book by Stenflo (1994). This thesis deals only with the Zeeman effect and hence Hanle effect will not be discussed anymore except in the last chapter highlighting the potential application of Hanle effect in diagnosing weak magnetic fields in the solar atmosphere.

1.5 Solar Polarimetry: Techniques

The first detection of magnetic field on heavenly bodies was done by Hale, 1908 even though it was predicted by several authors before him (Bigelow, 1889; Schuster, 1892; Stromer, 1892). Hale measured the magnetic field in a sunspot by measuring the amount of circular polarisation in the wings of a spectral line. From observations of the magnetic field on the entire sun, he first arrived at the conclusion that the general magnetic field of sun is about 50 Gauss. The observations of Hale were put on a sound theoretical basis by Sears (1913). He developed the Sears formula to understand the magnetic configuration of sunspots from the observed Stokes profiles.

The technical developments of the instrument for the vector magnetic field study is very interesting to look at. After the demonstration of the Zeeman effect in the sunspot by Hale, the real improvement in the measurement accuracy was given by Babcock in 1953 (Babcock, 1953) with his longitudinal magnetograph. The famous Babcock magnetograph measures the line of sight magnetic field with greater accu-
racy and better technique compared to the earlier techniques. The development of an electro-optic modulator using a birefringent crystal, helped Babcock to design an instrument which operates as fast as 50MHz to beat the seeing variations and hence in the improvement of the polarisation accuracy. In his work, the polarisation of the beam was modulated at the entrance slit of the spectrograph with the help of an electro-optic modulator followed by a polariser to alternately isolate the right and left circular polarisation from the spectral line wings. Photomultipliers at the exit slits detected the circular polarisation which was then fed to a differential amplifier whose output signal was proportional to the magnetic field. Babcock's magnetograph was able to measure fields up to about 20 G in the lower limit. Using the magnetograph, he produced maps of the general magnetic field on the sun. Instruments similar to Babcock's magnetograph has been developed since then and used in several observatories until now. However, the limitation of his system is that it can produce only the line of sight magnetic field.

The first transverse magnetic field was measured by Severny and his co-workers at the Crimean astrophysical observatory (Stepanov and Severny, 1962; Severny, 1964a; Severny, 1964b; Severny, 1965). This transverse magnetograph was a modification of an existing longitudinal magnetograph at the $\lambda 5250.2\text{Å}$ spectral line. A quarter-waveplate (QWP) was introduced in addition to the existing quarter wave electro-optic modulator, to achieve, a half-wave modulation to detect the linear polarisation. The signals from the photomultipliers located at the wings of the Zeeman sensitive spectral line was added instead of subtracting them as in the Babcock's scheme.

Leighton (1959) invented a method to get the longitudinal magnetic fields at one-stroke of the entire sun. He used two spectro-heliograms recorded simultaneously in each wing of the spectral line on a photographic plate. While one spectro-heliogram is for the right circular polarisation intensities, the other is for the left circular polarisation intensities. By adding one negative photograph with the other positive photograph, the circular polarisation intensity is produced over the whole sun. The
limitation of the technique is a poor calibration of the magnetic field even though the magnetic field of the entire disk of the sun could be measured in few minutes. Apart from these, there are different techniques developed in this period to consistently study the magnetic field on the sun. The technique by Trenor, (1960) and Adams (1963) are few examples.

With the development of Fabry-Perot spectrometer (FP) and narrow band filters, it is becoming increasingly easier to record longitudinal magnetic fields almost instantaneously over an entire active region on the sun. Instrument which uses an FP or a birefringent filter to record both transverse and longitudinal magnetic fields is called a vector magnetograph. Regular maps of vector magnetic field in the form of transverse and longitudinal contour maps can be produced using the vector magnetograph (Hagyard et al., 1982; Hagyard, Cumings, and West, 1983; Makita, Hamana, and Nishi, 1985; Mickey et al., 1996). However, the prime limitation of this method is that the complete information is not fully extracted. Zeeman saturation occurs because of non-linear behavior of the Stokes V with the line of sight component of the magnetic field. The physical nature of the spectral line forming region is not completely extracted. However, there were attempts to use such an instrument to get the polarised line profiles in order to extract the complete physical picture of the line forming region (Balasubramaniam and West, 1991; Leka, Mickey, and LaBonte, 1999).

The other type of instrument which uses a spectrograph to record the full Stokes line profiles has the advantage of extracting the complete information including the macroscopic physical parameters like temperature, pressure etc. of the observing region. Instruments which use the full Stokes polarised line profile measurements are called Stokes polarimeters. In this case, the image or the slit of the spectrograph has to be stepped to map the two-dimensional region of interest. Hence, one complete vector magnetograph of an active region requires considerable amount of time. Currently, these two different instruments are used in different types of studies. Any
fast changing field configurations like flares can be studied through the filter magnetograph. In this case, only the change in the morphology of the field structure were studied and not the intrinsic field strength variations. The Stokes polarimetry is used to study magnetic fields which are fairly stable over a considerable amount of time. Lites, Martinez Pillet, and Skumanich (1994) discusses, the advantages and disadvantages of these two different techniques.

1.5.1 Radiative Transfer

It has been pointed out that the actual situation in the stellar atmosphere is quite complicated than the pure Zeeman effect. After the measurement of the polarised line profiles, it is needed to interpret the polarisation in terms of the magnetic field parameters like the field strength, line of sight inclination and the azimuth of the field vector. The theoretical formulation of the Zeeman effect in different atmospheric conditions were developed in the 1950's. Unno (1956) first developed the theory of polarised radiative transfer of a spectral line formed in a magnetic field. His theory is based on pure absorption and a Milne-Eddington model atmosphere. Stepanov (1960), Rachovsky (1962) and Beckers (1969) improved the theory to include the physical conditions like the magneto-optical effect. Numerical studies to include both LTE and non-LTE was made by Moe (1968) and Rees (1969).

Wittman (1974a, 1977) was the first to develop radiative transfer codes to generate the solar spectrum using a detailed model atmosphere. Starting from the basic atomic physics and quantum mechanical formulations, Landi Degl' Innocenti and Landi Degl' Innocenti (1972) developed the equations for the polarised radiative transfer in the most self consistent way, that included all possible physical processes. One of the problem with the spectrograph based Stokes polarimetry was the extraction of the vector magnetic field and other physical parameters from the observations by comparing it with a model atmosphere. Wittman (1974b) synthesized the Stokes profiles
and compared with the observed data. Since, the synthesis itself is a laborious, time consuming and involved process, it has not appealed as a quick and a relatively less model dependent method.

1.5.2 Inversion Techniques

The first non-linear least square method was developed by Auer, Heasley, and House (1977), called as AHH routine. In this routine, all the four observed Stokes profiles were attempted to fit with those of the profiles generated from the analytical solutions of the radiative transfer equations. The AHH routine incorporated several simplifications to the line formation in a magnetic field and had ignored the magneto-optical effects. They had effectively used a four parameter fit viz., Doppler width, the ratio of line center to the continuum optical depth, the magnetic field strength and the inclination of the magnetic field to the line of sight. Landolfi, Landi Degl' Innocenti, and Arena (1984), refined this technique to include the magneto-optical effects and the damping parameter and called it as ALL routine. This routine used a six parameter fit to their solution.

Skumanich and Lites (1987) self consistently derived the Stokes profiles using a simple classical theory approach. A slight modification to take an exponential chromospheric rise of the source function into account was presented by Lites et al., (1988). The main strength of this inversion technique lies in the simplicity of its assumption of a Milne-Eddington (ME) atmosphere. The solution of the radiative transfer equation for this atmosphere is analytic and hence it is easy to implement in a computer code. Nine parameters are used as free parameters for the inversion. The nine parameters are: two parameters to specify the source function, the constant magnetic field vector (described by three parameters), the line of sight velocity, the ratio of line-to-continuum absorption coefficients, the Doppler width of the line and the damping parameter. A tenth free parameter is added to account for a non-magnetic back-
ground in the observations, either by stray-light contamination or by lack of spatial resolution. This technique is used for the Stokes profiles observed with the Advanced Stokes Polarimeter (ASP) (Elmore et al., 1992). This high accuracy polarimeter has given 2D maps of four Stokes parameters with high spatial and spectral resolution of entire active and quiet regions (Skumanich, Lites and Martinez Pillet, 1994; Lites et al., 1995; Keppens and Martinez Pillet, 1996; Martinez Pillet, Lites and Skumanich, 1997; Lites et al., 1998).

The inversion technique developed by the Zurich group is discussed in Keller et al., (1990) and Solanki, Montana and Livingston (1994). They developed a methodology to use infra-red lines to measure the magnetic field (Solanki and Bruls, 1994; Solanki, 1997). This methodology allows for the variations of the physical parameters along the line of sight. They extensively used infra-red observations in order to understand the magnetic field topology (Solanki, Ruedi and Livingston, 1992a; Solanki, Ruedi and Livingston, 1992b; Solanki, Walther and Livingston, 1993; Ruedi, Solanki and Livingston, 1995).

The Stokes Inversion based on Response function (SIR) developed by Ruiz Cobo and del Toro Iniesta (1992) works independent of the initial guess value for the free parameters whereas all the other inversion technique discussed, do require a reasonable initial guess value. The distinctive feature of the SIR technique is the inclusion of the variation of the physical quantities. Inferences of stratification of all those quantities are sought. Through linearisation of the radiative transfer equation, the sensitivity of the Stokes profiles to such quantities in a first-order approximation is given by the so-called response function (RF) (Ruiz Cobo and del Toro Iniesta, 1994). RFs are indeed the main trunk of this inversion technique.

To accept a given model as a final solution, a quantitative reproduction of the Stokes profiles are needed for all the inversion techniques to check for the reliability. With the development of high polarimetric accuracy polarimeters (Elmore et al., 1992; Povel, 1995), it has been recognised that there are asymmetries in the observed Stokes
profiles. These asymmetries which have long been recognised in sunspots (Moe, 1967; Beckers and Schroter, 1969; Grigorjev and Katz, 1972; Makita, 1979) are currently seen practically everywhere in the sun particularly in the magnetic structures at all scales (Sanchez Almeida and Lites, 1992; Solanki, 1993; Martinez Pillet, Lites and Skumanich, 1997). A coherent explanation of the Stokes profile asymmetries constitute one of the most exciting and still unsolved problem to understand the dynamics of solar magnetic structures (Solanki, 1997). With the SIR technique this asymmetry problem has been addressed (Westendorp Plaza et al., 1997a). The LOS variation of the physical parameters of the observed region can now be calculated from the observed Stokes profiles. In effect, a tomographic picture of an active region can be made from these observed Stokes profiles (Westendorp Plaza et al., 1997b; Westendorp Plaza et al., 1998). However, this kind of inversion code needs enormous amount of computation time and hence used only in a limited way.

1.6 Motivation for this Thesis

With the success of the inversion codes, the measurement of full Stokes profiles or the Stokes polarimetry brings out much more physical insight of the active region than the vector magnetograph based systems. With the possibility of a bigger ground based telescope like Advanced Solar Telescope (AST) (http://www.noao.sunspot.noao.edu/AST/) and the success of the Adaptive Optics system (Rimmele and Radick, 1998), fast vector polarimetric measurement will be possible in the near future. With all these developments discussed above, it can be realised that a Stokes polarimeter is essential in any solar observatory in order to understand the magnetic field structure on the sun. Since, the Kodaikanal Tower Telescope (KTT) (Bappu, 1967) has a high resolution spectrograph with spectral resolution comparable to the spectrograph used by ASP, we decided to build a Stokes polarimeter at KTT.

There were attempts to build a Stokes polarimeter in India (Balasubramaniam,
1.6: Motivation for this Thesis

1988; Ananth et al., 1994). However, until now there is no consistent measurement of vector magnetic fields even though the line of sight magnetic field measurements were done successfully (Bhattacharyya, 1965; Mathew, 1998).

In this thesis, I report on the development of a Stokes polarimeter using the KTT to consistently study the magnetic field of sunspot. The main difficulty in removing the telescope polarisation because of oblique reflection is successfully handled within a percent accuracy. The limits up to which the magnetic field measurement can be carried out at the KTT have been calculated. This puts the constraint on the kind of problems one can deal with using such kinds of oblique reflecting telescope. Several techniques were developed to study different contaminations coming into the measurement of the magnetic field and ways were developed to remove it from the observed Stokes profiles in order to study the magnetic field configuration of sunspot.

The structure of the thesis is the following:

The second chapter discusses the development of an optical method to measure the refractive indices of the mirror coatings of the KTT in order to calculate the instrumental polarisation produced by it. A computer simulation was carried out initially to understand the critical parameters involved in the measurement. The oxide layer formed on the mirror surfaces are detected.

The development of a Stokes polarimeter using a rotating Glan-Thomson prism polaroid (GTP) and a masked CCD as a detector is discussed in third chapter. The masked CCD is used to integrate the charges inside the CCD which increases the signal-to-noise ratio and also reduces the seeing induced spurious polarisation signal. The laboratory and the field testing of the polarimeter is explained. A CCD based polarisation interferometric technique is developed to measure the retardance of the quarter-waveplate used in the Stokes polarimeter.

Fourth chapter concentrates on the observation of Stokes profiles in the disk center to measure the daily variation of the instrumental polarisation. The model of
the KTT developed by Balasubramaniam, Venkatakrishnan and Bhattacharyya (1985) is modified to include the initial rotation from the sky plane to the plane of incidence of the first mirror. The measured data point is fitted with the model to derive the refractive indices of the coating which were then used to remove the instrumental polarisation produced during these observations. The model developed for the KTT now includes the oxide layer formed on the three mirrors of the KTT.

Chapter five discusses the observation of a sunspot KKL 21263 (NOAA 8516) and the inversion code used to get the physical parameters for this sunspot. The complicated profiles observed in the neutral line of this sunspot are fitted with a two magnetic component model. The observations of one another sunspot and the inversion results are given in this chapter and compared with the observations taken from the Mees Solar Observatory.

Chapter six discusses the polarisation profile obtained for the metallic lines Ti I and Sc I. These two lines are sensitive to temperature and forms only in the umbra of the sunspot. Also, this produces an anomalous Zeeman effect compared to the Fe I lines ($\lambda\lambda$ 6301.5Å and $\lambda\lambda$ 6302.5Å) which produces normal Zeeman effect. This chapter also summarises the thesis and discusses the future improvements that need to be made.

We conclude the thesis by discussing the potential use of this instrument and the limitation of the system. Even though the system as of now cannot be compared with the accuracies achieved by ASP and ZIMPOL, we suggest certain class of problems that can be studied with this instrument. Since each chapter is written in such a way that it can be understood independently, some of the repetition could not be avoided.