# STUDIES ON DYNAMICS OF ACTIVE REGIONS AND SUNSPOTS

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## DECLARATION

I hereby declare that the matter contained in this thesis is the result of the investigations carried out by me in Indian Institute of Astrophysics, Kodaikanal under the supervision of **Dr. R. Thiagarajan**, Head of the Department of Physics, Post Graduate and Research Centre, Urumu Dhanalakshmi College, Tiruchirapalli, India. This work has not been submitted for the award of any degree, Diploma, Associateship, Fellowship, etc., of any other University or Institute.

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Dedicated to

***TO MY BELOVED PARENTS***

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## PREFACE

Earth's environment is largely dominated by influences arising from transient active phenomena occurring on the Sun. It is not surprising, therefore, that a large part of the current endeavour in the new science is being devoted to the measurement of particle fluxes, magnetic-fields, and electromagnetic radiation of all kinds in the space between the Earth and the Sun, and to their correlation with visible phenomena on the solar disk. The transient active phenomena on the Sun occur within localized regions known as active centres that include sunspots, photospheric and chromsopheric plages, flares, prominences, and coronal condensations. It is now generally accepted that these diverse and spectacular phenomena owe their origin to the presence of magnetic fields.

Sun is full of mysteries. This makes solar research exciting. There are gaping holes to be filled in the fundamental laws of science before we can explain what happens. The very existence of sunspots itself is intriguing. They should be heated quickly from the sides and disappear. They should have never formed - but they do form. We are still far from arriving at a single theory that can explain solar activity and its relationship with other phenomena which comprise it. The other spectacular feature is the huge prominences which are concentrations of remarkably cool coronal gas. Prominences are only 10,000 K, in contrast to the million- degree corona. They form in a variety of shapes. Their associations with active region magnetic-fields remain one of the coronal curiosities.

Sunspots and other active regions claim our interest because they are often associated with the much enigmatic explosive phenomena (flares). Flares are the most spectacular changes associated with active regions and are the characteristic manifestation of solar activity. It is believed that flares are triggered by the instability created in the magnetic fields of the active region and release tremendous amount of energy in a matter of seconds. This transient phenomena is initiated by the dynamical processes in the solar atmosphere where the relative motions of the magnetic structures are more important rather than the actual field strengths and the interactions of these field line system is probably the triggering mechanisms of flares. Bright areas seen in chromospheric photographs show flares to their best advantage. The whole show typically lasts for about an hour or so. Energy released by flares are the source of heat for a parcel of coronal gas, which then expands explosively and brightens. In the process burst of high-speed charged particles spiraling around magnetic field lines are ejected out. These particles that travel at speeds approaching to the speed of light produce a burst of radio radiation that can be detected on the Earth. Collision between these fast particles and the coronal gas, in turn, produce burst of X-rays. The detection of X-rays and radio bursts is another way of studying the activity that accompanies solar flares.

The physicist usually has the opportunity of making direct physical measurements in the laboratory on the system in which he/she is interested, but the solar physicist has to rely purely on observation and inference. Solar studies are now advancing towards space craft and satellite bound observations. But still the ground based telescopes and their auxiliary equipment provide many ideas in basic solar research that has produced many practical applications, and no doubt will continue to do so in the future. This thesis is an outcome of the research work carried out in the area of Observational Solar Physics at Indian Institute of Astrophysics, Kodaikanal, India using the ground based optical solar telescopes and spectrographs. Most of the observations presented in this study are taken by the author and some of the data obtained in the past (in 1970s) are also utilised for the analyses.

The thesis consists of seven chapters. A brief outlook on the Sun as a star, its atmosphere, solar activity, and other activity centres, flares and the relevant optical instruments to observe these spectacular features are discussed in the introductory chapter. Chapter 2 describes flare related magnetic field changes, prominences and their activation, and associated velocity flow and Evershed effect. The results of the studies made on the basis of the data obtained in respect of dynamics of active regions and sunspots are presented in the 3rd, 4th, 5th and 6th chapters. Interesting cases of flares associated with the filament eruptions are analysed in chapter 3. Flare cases where filament eruption is not involved are taken in chapter 4. Chapter 5 addresses the rotational motions of plages and sunspots playing a crucial role in the evolution of a prominence and its fine structure. A dynamical phenomena common to all sunspot is the Evershed effect. Flare conditions are often indicated by the bipolar fields where the polarities are opposite with a twisted and kinked neutral line. The line emissions are analysed in chapter 6 to trace the photospheric velocity field in the regions between the bipolar sunspots.

The final chapter summarizes the results and attempts to present the results in a cohesive way.

## LIST OF PUBLICATIONS

1. Filament Activity in a Quiet Region Flare, K. Sundara Raman, S.S. Gupta, R. Selvendran, *Journal of Astrophysics and Astronomy*, **14**, 45, 1993.

2. The Variation of Filament Direction in a Flaring Region, R.R. Rausaria, K. Sundara Raman, P.S.M. Aleem, Jagdev Singh, *Solar Physics*, **146**, 137, 1993.

3. Effects of Magnetic Shear, Spot, and Plage Rotation on Prominence Evolution, R.R. Rausaria, S.S. Gupta, R. Selvendran, K. Sundara Raman, Jagdev Singh, *Solar Physics*, **146**, 259, 1993.

4. Hα flare on 14 March, 1984 - Evidence for Reconnection ?, K. Sundara Raman, P.S.M. Aleem, Jagdev Singh, R. Selvendran, R. Thiagarajan, *Solar Physics*, **149**, 119, 1994.

5. On the Triggering of Quiet Region Flares without Filament Activation, K. Sundara Raman, R. Selvendran, R. Thiagarajan, *Bulletin of Astronomical Society of India*, (in press), 1997.

6. Sunspot Motions Associated with Flares, K. Sundara Raman, R. Selvendran, R. Thiagarajan, *Solar Physics*, (submitted), 1997.

# CONTENTS

# CHAPTER 1

# INTRODUCTION

## 1.1. Sun as a star, and its core

Sun is an average star of spectral type G2 having absolute magnitude 4.8 and falls in the middle of the main sequence. Because of its close proximity to the earth, Sun's image can be projected and a resolvable disk of high intensity makes it easier to study the solar structure in great detail which is not possible for other stars. Hence, Sun is the only star whose physics we can probe. Stars on the main sequence are those that have interior structures quite similar to the Sun. These stars must have great central pressures to hold up the enormous weight of their envelopes, and this central pressure yields a high central temperature. Thanks to the high central temperature, nuclear reactions proceed in the cores of these stars and they become hot and luminous. Direct observations of the interior of the Sun is not possible and most of the information available concerning the core of the Sun are based on hypothetical conclusions arrived from studying the surface and outer atmospheric features. It has been suggested that Sun and other stars may still have rapidly spinning cores left over from the time of formation. Also the structure of the outer layers is modified by the existence of convection, which is difficult to model. There has been renewed interest in solar interior because we can now probe it by solar seismology and neutrino observations. Sun is the only star for which such observations are possible and these observations have greater importance for understanding the physical processes of other stars.

## 1.2. Solar atmosphere

### 1.2.1. Photosphere - Sunspots

By projecting a full-disk image from even a small telescope, we can see the Sun's 'surface' features. The Sun's 'surface' is known as photosphere, seen in ordinary white light. The telescope shows the surface not to be a perfect white mosaic disk, but rather it is strongly textured with granulations. The granulation is a rice grain like pattern covering the photosphere with a scale of 1000 km and its structure suggests the presence of convection underlying the photosphere. In addition, solar surface can also be seen with the presence of occasional sunspots which are the centres of activity on the solar disk visible in white light. Sunspots are the dark cool localized regions surrounded by hot gases of the photosphere. The apparently unchanging Sun in fact changes daily in the form of sunspot activity. Sunspot activity varies greatly from a minimum (sometimes zero in number) to a maximum and down to a minimum again in about 11 years. This is called the sunspot or solar cycle. Delicate fibrils stretching out radially from a dark core (the 'umbra') form the lighter or greyish 'penumbra' in most of the sunspots, when observed at high resolution. The umbra covers about half of the spot diameter and has a temperature of 4000 K well below the average photospheric temperature of 5770 K, with a magnetic field strength to the level of 4000 Gauss. Sunspots usually have bipolar structure. Also, the gas pressure in the sunspots is observed to be low. A sunspot remains cooler because the magnetic pressure plus the reduced gas pressure balances the higher gas pressure of the surrounding photosphere. Some sunspots are symmetrical, but in others the penumbra and even the umbra can be irregular. The sunspots near the limb are accompanied by bright plages which cannot be seen at the disk centre.

### 1.2.2. Solar cycle

The presence of sunspots tells us about magnetic fields which play a vital role in every activity of the Sun. From the mappings of the sunspots made on successive days, it can be seen that the Sun rotates with a 27 -day period, and on close scrutiny, Sun's differential rotation can also be found. The rotation period varies from about 24 days near the solar equator to 33 days near the pole. We do not know whether the differential rotation is a deep-lying phenomenon or a surface effect, nor if it varies with the solar cycle. Some models of solar activity suggest, it generates the solar magnetic field by dynamo action. The presence of the convection underneath the photoshpere coupled with the differential rotation is thought to be responsible for the formation of sunspots.

### 1.2.3. Solar oscillations

The interior of the Sun is in radiative equilibrium from where the energy is carried outward by photons. But in the outer envelope the opacity due to neutral helium and hydrogen impedes radiative transfer and in the process, convection occurs ; the outer 20 % or so is in convective equilibrium. Many surprising surface phenomena are due to these convective motions and one of these is the pattern of non-radial oscillations. The Sun oscillates in hundreds of normal modes of small amplitude. The dominant modes have a period of five minutes and velocities around 0.3 km per second. The motion is a longitudinal sound wave thought to be excited by the convective envelope.

## 1.3. Chromosphere

### 1.3.1. Chromosphere in the light of Hα and Calcium K lines

Chromosphere is the solar atmosphere lying immediately above the photosphere. Chromosphere means 'coloured zone'. It appears for a few seconds as a pinkish colour at the beginning and end of a total solar eclipse. Though it is highly rarefied to emit white light, it still emits some spectral lines. As the density falls off rapidly with height, most of the visible spectral lines disappear within 1000 km, leaving only a few of the very strongest lines, e.g. the red Hα and blue Hβ lines of hydrogen, and the violet H and K lines of calcium. These give chromosphere its colour. The most remarkable property of the chromosphere is the complete dominance of its structure by the magnetic-field, resulting in features of great beauty entirely different from what is observed at lower levels.

The chormosphere can be observed readily on the Sun's disk with a spectroheliograph or a narrow-band filter, both of which isolate the light from a spectral line and produce images of the chromosphere without the Sun's blinding glare. Of all the lines in the visible solar spectrum, hydrogen Hα and calcium- K lines are mostly used to take pictures of the solar chromosphere. The Hα pictures tell us about the lower chromosphere whereas the K line pictures give the upper layers of the chromosphere. We can identify features typical of both the active and quiet Sun from these chromospehric pictures.

### 1.3.2. Chromospheric features

There is a close correspondence between the magnetic field pattern and chromospheric structures. Sunspots, of course, look dark in the chromosphere also; but every other region of vertical magnetic field is marked by a bright plage or facula. Thus the centres of activity in the higher layers are seen as bright plages surrounding the dark sunspot groups. These are the active regions where brilliant, short lived flares occur from time to time. Another interesting feature is the dark thread like structure called filament which occurs at the inversion, or neutral line between regions of opposite magnetic polarity. These filaments are cool dense material suspended against the solar gravity and also shielded from the surrounding hot regions. Also seen are small horizontal structures containing cool material connecting directly places of opposite fields, and these features are called chromospheric H$\alpha$ fibrils. Their shapes resemble closely to the field lines shown by iron filings near strong and weaker magnets. Thus three different types of structures - (i) bright plages, (ii) long dark filaments, and (iii) a jungle of almost horizontal fibrils covering the whole surface are seen in the chromosphere. In addition, small jet like structures called spicules are observed in the limb choromosphere which owe their shape to the magnetic-field. When the filaments approach the limb of the Sun due to solar rotation, they may appear as 'prominences' if the lines of force looping between its foot points become somewhat sheared. The prominences thus seen on the limb are huge volumes of cool, denser gas extending out to 50,000 km or more from the surface. Their location, shapes, and very existence are the direct result of the magnetic field. These prominences which evolve from the chromospheric filaments are considered to be part of the corona.

## 1.4. Corona

### 1.4.1. Observations of the solar corona

Corona is the outermost atmosphere of the Sun that becomes visible only during total eclipse time. At the time of totality a narrow strip of the Earth's surface is shielded completely by the Moon from the brilliant disk of the Sun. The faint corona is then only visible with all its splendour. This part of the solar atmosphere is few thousand km above the photosphere, where the temperature rises sharply at over a million degree. The coronal density is very low, $10^{-12}$ times the Earth's atmosphere. Because of the low density, corona is a million times fainter than photosphere and can be best seen only during total eclipse. Since the coronal temperature is high, the conductivity is high, and the temperature falls off very slowly in the corona. As a result the gas farther from the Sun cannot be contained, but flows out into space as a solar wind. In the corona the outward flow is dominated by sources with open magnetic fields, called coronal holes, where no coronal emission is seen because the magnetic structure cannot hold the gas. The appearance of the corona varies greatly between the maximum and minimum of the solar cycle. Thus, the structure of the entire solar atmosphere is governed by the magnetic fields that are deep rooted in the Sun.

Since the hot corona emits X-rays very intensely, and the cool photosphere emits very little X-radiation, it is also possible to photograph the corona by taking X-ray Sun pictures. Thus, modern space research has made it possible to observe corona from the X-ray and UV emissions of the hot outer layers without waiting for an eclipse, so the solar corona is now much more familiar to us. The X-ray photograph of the corona shows the irregular distribution of the coronal gas. The coronal emission reaches its maximum intensity in a few bright points. These bright regions last only for a few hours, and they are generally connected with sunspot groups. The dark areas in the X-ray picture where no coronal gas appears are 'coronal holes' and the recent works have shown that the solar wind probably flow, out of these coronal holes.

### 1.4.2. Solar wind

Photographs of the solar corona show only the part nearest to the surface of the Sun. In fact, the solar corona extends throughout the solar system and is observed near the Earth's surface as solar wind. These outward motion of the corona is the result of its extremely high temperature, which creates a relatively high coronal pressure. Since the coronal pressure is greater than the pressure of the interstellar gas outside the solar system, the corona flows outward. Recent evidences indicate that much of the outward flow is continuously replenished by matter flowing through the coronal holes at the solar surface. It is the solar wind that creates and shapes comet tails and provides particles that become part of the radiation belts around magnetically active planets such as Earth and Jupiter.

## 1.5. Solar flares - early studies

On September 1, 1859, Carriangton and Hodgson independently observed a group of localised brightenings on the solar surface (Carriangton 1860, Hodgson 1860), the first observed solar flare. Since that time, our understanding of the physics underlying the phenomenon they observed has increased remarkably. Solar flares may be due to some unknown process that occur below the photosphere. But aspects involving structures like filaments are closely related to flares. The introduction of magnetograph showed the clear association of flares with magnetic field. Probably the first theoretical analysis that take account of the high conductivity of solar atmosphere was that of Giovanelli (1946), who proposed that flares are electrical discharges due to changing magnetic fields. Dungey (1953) showed that the electrical field due to change in the magnetic field leads to a current at an X-type neutral point, which in turn tends to enhance the change in the magnetic field. Dungey introduced two concepts namely magnetic instability and reconnection. These concepts have dominated theoretical studies of solar flares ever since.

In 1950s rocket-borne experiments made it possible to detect X-rays from solar flares (Chubb et al 1961). X-ray images obtained from the space crafts have shown that flares are primarily coronal phenomena; the chromospheric response is now regarded as a 'secondary' aspect of these flare process. In the late 1950s and 1960s a variety of flare models were proposed (Sweet 1958, Gold and Hoyle 1958, Carmichael 1964, Sturrock 1968). According to these models an instability is created in a metastable magnetic field configuration that would suddenly release free energy associated with coronal currents. This energy release was identified during the impulsive phase of solar flares. Subsequent research indicates that there are more phases of energy release that need to be considered. It has long been recognized that flares occur in active regions where magnetic field is predominant. One of the important environmental aspect of solar flares is that large two-ribbon flares are invariably associated with filaments. Smith and Ramsey (1964) pointed out that filaments are typically 'activated' before a flare. It was found that X-ray brightenings typically occur in an active region shortly before a flare and this process is referred to as pre flare heating. It would be interesting to know what relationship if any, exists between filament activation and pre flare heating.

### 1.6. Phases of solar flares

The simplest flares involve a sudden brightening in Hα on a time scale of minutes. This is usually referred to as the 'impulsive phase'. Earlier studies used the terms 'flash phase' and 'expansion phase'. However, it is not clear whether the impulsive phase itself provides the secret of the entire flare phenomenon. There is often activity in the active region just before a flare occurs. Various sequences of energy release phases seems to take place in different classes of flares. The following minimum number of energy release phases are identified.

**a) activation phase :** This phase subsumes filament activation and pre flare heating and represents the sudden conversion of energy from one form to another.

**b) impusive phase :** This is the most dramatic phase of a solar flare. In Hα, it appears as a sudden brightening that rapidly extends along the length of the filament. It may be accompanied by a rapid hard X-ray burst, line gamma-ray emissions, and by a microwave radiation. It appears that magnetic free energy is suddenly converted into the process of heating and acceleration of electrons and ions. The various form of radiation may then be interpreted as secondary process due to this heating and acceleration. Beginning with impulsive phase, but extending much later, there may be soft X-ray burst that can be interpreted as 'bremsstrahlung' from a hot dense coronal plasma. The current view is that this 'flare plasma' is produced by chromospheric evaporation in response to the sudden flux of energy from the corona to the chromosphere.

**c) Gradual phase :** Bai (1986) showed that in some flares, there is a second more gradual period of particle acceleration after the impulsive phase. It may come five or ten minutes after the impulsive phase and lost for five or ten minutes or more. Hence, acceleration of particles to very high energies may take place and such flares may be 'microwave rich '. Flares that exhibit a gradual phase of particle acceleration appear to be associated with coronal mass ejections.

**d) Late phase :** Soft X-ray emission that begins during or before the impulsive phase typically extends considerably after the impulsive phase. The energy content of the flare plasma increases after the impulsive phase showing that there is continued energy release after the impulsive phase. The time scale of this energy release was of the order of hours. It is this process that is referred to as the 'late phase' of energy release. Hα observations alone give evidence for such a late phase of energy release in the form of flare ribbons slowly separating with speed of the order of one km per second and this drift can continue for hours.

### 1.7. Flare precursors

A precursor is a transient event preceding the impulsive phase, possibly even before the onset and not necessarily at the site of the flare itself (Priest et al 1986). Precursors signal some early destabilization of the magnetic field prior to the onset of a flare. It proves very difficult to trace a casual link between a specific pre flare change and a particular flare because similar brightenings or transients occur in active regions even in the absence of any flare.

Observations of coronal precursors at much shorter wavelengths insist that interaction between multiple magnetic structures are an essential feature of flare process. For flare related coronal mass ejections (CMEs) there is usually a weak soft X-ray enhancement tens of minutes prior to flare onset in one foot of a pre-existing large coronal arch (Harrison et al 1985, Simnett, Phillips, and Bentley 1986, Harrison 1986). The coronal magnetic structures at the site of the energy release comes independently from (a) imagery in soft and hard X-rays (Machado, Duijveman, and Dennis 1982, Machado et al 1983, 1986, Simnett, Phillips, and Bentley 1986); (b) imagery in UV and soft X-rays (Woodgate et al 1981, Cheng et al 1985); (c) imagery at microwave frequencies (Willson and Lang 1984, Kundu and Shevgaonkar 1985, Shevgaonkar and Kundu 1985, Lang and Willson 1986); (d) simultaneous observations at hard X-rays and meter radio waves (Raoult et al 1985).

There is at cm wavelengths a great diversity of coronal precursors. These include polarisation reversals (Kundu, Schmahl, and Velusamy 1982), the formation of quadrupolar structures (Velusamy and Kundu 1982), step-like changes in polarisation (Hurford and Zirin 1982), pre burst heating of loops observed at 20 cm (Willson and Lang 1984), narrow-band continuum emission (Hurford, Read, and Zirin 1984), and pre burst activity at 17 GHz. (Kai, Nakajima, and Kosugi 1983). It is impossible to discern from among these phenomena whether any consistent sequence of pre flare events is occurring in identifiable coronal structures.

The bulk of the energy released during a flare may be associated with kinetic or coronal transients. Coronal transients are closely related to chromospheric filament eruptions. Hence, it is difficult to entangle the flare process from filament eruption. The association of erupting filaments with two-ribbon flares receives considerable attention because of the geometry of the situation that leads to theoretical modeling with predictive capabilities. According to theoretical models, the specific mechanism which destabilises the filament is magnetic reconnection, but direct evidences from observations are seldom available. It must be emphasized however, that not all the flares are accompanied by erupting filaments, nor do all flare-related eruptions have pre flare phase.

The absence of a single precursor that could reliably foretell a flare, even though observers have sought them assiduously for years, and the disparity among flares observed in different active regions, means that pre flare transient behaviour does not always arise from the same mechanism. The exact nature of process depends upon the coupling between the structures adjacent to the flare and the rest of the activity complex. This wide spread dependence increases the scope for variety among pre flare phenomena.

## 1.8. OPTICAL FLARE

### 1.8.1. The importance of optical observations

Optical observation present considerable information of the flare process. The concept of optical flare (brightness, duration, surface) is essentially based on Hα brightening. The optical flare gives most of the information right from the pre flare magnetic field changes in both photosphere and chromosphere to the late phase of the flare. Most of what we know about flares is the result of optical observations though the initial flare energy release may occur in very high temperature material invisible in the optical range.

Some of the advantages of the optical observations are : high resolution telescopes for optical work are easy and cheap to build ; magnetic fields can be easily measured ; the pre flare conditions that are invisible to X-rays or radio waves and the flare origin can be well studied in the optical ; almost all high energy flare effects are reflected in optical flare.

The optical observations alone first demonstrated the location of flares occurring on neutral lines in the longitudinal fields (Severny 1958). The pre flare events like spot motions, flux emergence, flux submergence, flux cancellation, filament activation, and finally the post flare two-ribbon drifts are all well documented by the optical flare studies. The filament that is part of most of the flare is in fact the seat of energy release, hence it is possible to see the flare energy release process in the visible region. In fact Hα filament is a prominence embedded in the corona overlying an inversion line of photospheric magnetic field, anchored either near a sunspot or near between plages. The transition region between prominences and corona is very thin and in general similar to chromosphere-corona transition region (Yang, Nicholls, and Morgan 1975, Orrall and Schmahl 1976, Schmahl and Orrall 1980, 1986, Rabin 1986). Hence the studies of the prominences indicate the conditions prevailing in the lower corona. The fine structures and dynamics of the prominences are well exhibited by high resolution optical observations. Thus optical observations make it possible to study most part of the flare activities that take place at different atmospheric levels of the Sun.

### 1.8.2. Optical flare classifications

When the Sun is observed in Hα line, active regions in the chromosphere appear as bright plages surrounding and overlying the sunspots which characterize the active region in the photosphere. A flare appears either as a brightening of part of the existing plage or as the formation of new bright areas in places where plages did not exist before. In the regions where the activity is peak, brightness variations in the plage regions almost occur continuously. The characteristic feature of actual flare brightening is a very vast increase in brightness followed by a much slow decay.

Regular observations in optical region is carried out in Hα with a passband of 0.25 to 0.5 Å in the centre of the line. Thus we observe the most intense and optically thick portion of the flare in the core of the Hα line. According to the appearance of the flare in the core of the Hα light, they are classified in four groups by their importance 1, 2, 3, and 4. Their area at the time of maximum brightness is the primary criterion for this important classification.

A transient brightening in Hα light is called as a flare if its area in the chromosphere exceeds $3X10^8$ sq km. Smaller events are called sub flares and their importance is denoted by the letter S. For the flare of importance S, the area in terms of millionths of hemisphere of visible Sun is less than 100. For the flares of areas 100-250, 250-600, 600-1200, and more than 1200 millionths of the visible hemisphere of the disk, the flares are classified as 1, 2, 3, and 4 respectively. Also according to the brightness of the area of the flare, a suffix F, N, or B is added to the class importance. That is F = faint, N = normal, and B = brilliant. The lower limit for sub flares is obviously far below the resolving power of solar flare patrol telescopes. Thus all lists of sub flares are incomplete and also greatly inhomogeneous, because different solar observatories set different lower limits to their reports. The complete list of flares can be found in Solar and Geophysical Data published from Boulder, U.S.A.

The duration of flares in Hα light varies from few minutes for sub flares to more than several hours for the most powerful flare of importance 4. Initially when the activity starts commencing, the brightness of the plages slowly start increasing and this period is called as initial flare rising phase. This can be observed in Hα. Thermal X-ray and gradual microwave bursts have durations similar to the Hα flare. Hα emission is only one aspect of the complex flare phenomenon and it does not necessarily reflect the flare behaviour at other wavelengths.

## 1.9. Optical instruments

### 1.9.1. Solar tower telescope-spectrograph

For solar astronomer, success depends upon the perfect definition of the solar image. An image resolution of 1 arcsec or better is required for effective observations of the fine details in the solar surface that can be distinguished both visually and on direct photographs taken with a short exposure time. Hence the principal facility required from a solar tower telescope is a high solar image resolution. That is, the image of the Sun should be large and bright. The f-ratio of an optical system - the ratio of the focal length of the image forming element (generally lens) to its aperture (diameter) - provides a convenient measure for the telescope resolution. Large values of the f-ratios are invariably in use where solar structure of the smallest size (of the order of 1 arcsec or less) is under investigation. Smallest f-ratios give the brightest image and so are used in general as detecting element for tapping the solar energy. In solar towers, fused quartz are used as light gathering mirrors to minimise the effects of heat.

Of the many accessories used in conjunction with solar towers, the spectrograph is the main auxiliary instrument common to all solar towers. The spectrographs that accompany solar towers have very large dispersion compared to any other laboratory spectrographs. The telescope-spectrograph combination works at maximum efficiency when the f-ratio of the image forming objective is equal to the f-ratio of the collimating lens of the spectrograph. A plane grating with a lens that perform both collimator and camera are the most commonly used design of the spectrograph (Littrow arrangement).

### 1.9.2. Optical facilities at Kodaikanal

The sites for the solar studies are chosen either in high mountains or near the lakes where the dust and pollution levels are less. This will produce good seeing conditions that are needed to study the fine details of the Sun. Indian Institute of Astrophysics, popularly known as Kodaikanal Observatory is located on the Palani Hills ($10^\circ$ 14' N, $77^\circ$ 29' E), at an elevation of 2343 meters above the mean sea level. As is common among many mountain solar observatories, the best seeing for the day exists 3 to 4 hours after sun rise. During the monsoon session, the overnight showers eliminate the dust in the air and in case the sky is clear in the morning, the definition is the best for the day. Nearly 250 days of observations are possible in a year at Kodaikanal.

**a) Solar tower-tunnel telescope-spectrograph**

The solar tower at Kodaikanal was built in 1959 and commissioned in 1960. It went into regular observation in 1962 after several modifications have been made to the solar telescope and spectrograph. A two-mirror fused quartz mirror coelostat 61 cm diameter, mounted on a 11 meter tower, reflects light on to a third quartz flat, which sends the beam in the horizontal direction into a 60 m long underground tunnel. The parallel light falls on a 38 cm achromatic objective of 36 m focal length. This yields a 34 cm diameter solar image that has a scale of 5.5 secs of arc per mm. The spectrograph is of Littrow type and utilise a 20 cm aperture lens, 18.3 m focal length. The lens is in conjunction with a 600 lines per mm Babcock grating of ruled area 200 X 135 mm and blazed in the fifth order green. Examination of the iodine absorption spectrum near $\lambda$ 5330 Å in the fifth order show the doublets clearly having a separation of 0.009 Å. The spectrograph has a very high dispersion of 11.7 mm per Å in the fifth order near $\lambda$ 5900 Å. The f-ratio of both the image forming objective and the collimating lens of the spectrograph is f-96 and are designed in such a way to make the highest possible resolving power available for solar research.

**b) Spectroheliograph**

In many types of solar research, the object under observation is visible only in monochromatic light. If a second slit is placed in the focal plane of a solar spectrograph, the instrument becomes a monochromator and is known as spectroheliograph. Provisions must be made for fine movement of the entrance slit of the spectrograph across the solar image and for a synchronize motion of the second slit. If a photographic plate receives the light emerging from the second slit, it will record monochromatic intensity variations in the field of view swept over by the entrance slit of the monochromator. Such pictures are called as spectroheliograms.

Spectroheliograph building houses two spectroheliographs and a Hale spectrohelioscope. A Foucault siderostat with a 46 cm diameter mirror reflects sun light on to a 30 cm lens. A 60 mm image is formed at the focal plane of this lens. The K-spectroheliograph is a two-prism instrument with a dispersion of 7 Å per mm near $\lambda$ 3930 Å . The exit slit admits 0.5 Å about Ca II K. The daily disk and prominence spectroheliograms obtained with this instrument date back to 1904. The H$\alpha$ spectroheliograph is a Littrow grating instrument. The exit slit isolates 0.35 Å about H$\alpha$, and daily series of pictures of the Sun with this instrument go back to 1911.

**c) Photoheliograph**

A 6" refractor telescope is available at Kodaikanal through which white light photoheliograms having a size of 8" are recorded daily. These observations date back to 1900.

### 1.10. Importance of studies on active regions

Electrically charged particles like electrons and ionized atoms are always in random motion and permeate through solar atmosphere. Obviously electric and magnetic currents are generated and traced throughout the Sun. The discovery of mass motions, and the presence of strong magnetic fields in the active regions of the Sun opened up new lines of investigations in the physical processes occurring in the hot plasma of the solar atmosphere. It is also strikingly evident that the magnetic field is the knitting factor for most of the solar eruptions, mass motions, flares, etc. that occur at different atmospheric levels of the Sun. In this thesis we have focused our attention on the enigmatic eruptive phenomena that takes place in the active regions of the Sun.

Solar flares are explosions in magnetized plasma where a sudden outburst of energy of the order of $10^{32}$ ergs is released in a short interval of time. Flares accelerate particles up to relativistic energies and produce electromagnetic radiation in the range from radio to γ-ray wavelength. Energy released during solar flares is generally accepted to be a result of the stressing and subsequent partial relaxation of active region magnetic fields. However, mechanisms which are responsible for the gradual build-up of magnetic energies which is converted into kinetic and thermal energies at the time of a flare is not yet fully understood. It is interesting to note that the physical strengths and sizes of the active regions do not appear to be crucial factors in triggering a flare. Hence, we have given close attention to the dynamics of active regions and sunspots and the factors which are responsible for creating the instability in the magnetic field lines. Photoheliograms, spectroheliograms, and line emissions are analysed to identify the properties for flare eruptions and prominences.

# CHAPTER 2

## FLARE RELATED MAGNETIC FIELD CHANGES

### 2.1. Flares and magnetic field in active regions

The primary condition for any of the dynamical phenomena in the Sun is the presence of one or more active region. Flares occur in association not only with large, complex active regions but also with the smallest resolvable active regions. Active regions are the manifestations of magnetic fields in the solar atmosphere, and initial investigations of the relationship between flare productivity and magnetic fields are made by Giovanelli (1939), Kleczek 1953), and Bell and Glazer (1959).

Flares do not occur at random locations within an active region, but invariably are related to boundaries between positive and negative fields. These boundaries are often referred to as 'neutral lines'. Earlier studies of flare positions relative to photospheric magnetic fields showed that flares occur near polarity inversion lines (Severny 1958, 1960, Martres et al 1968, Smith and Ramsey 1967, Michard 1971). The chromospheric part of the flare also bears a very specific relationship to these polarity boundaries. These specific and invariable associations of flares within the magnetic fields of active regions affirm the generally accepted view that flares derive their energy from the magnetic fields of active regions. Theoretical studies emphasize that the detailed physics of the magnetic field conversion depends on the changes associated with magnetic field configuration and this process is recognized as magnetic reconnection (e.g., Priest 1981). It is generally observed that at least slow changes in the magnetic fields of active regions accompany or precede a solar flare.

### 2.2. Sunspot motions and flares

The association of flares with observed photospheric magnetic field are in terms of magnetic field configurations and evolutionary changes (Mayfield and Lawrence 1985). The development and decay of sunspots are certainly important indicators on the evolution of active regions, since they represent the highest concentrations of magnetic flux. If evolutionary changes may provide the necessary conditions for flares to occur, then it is quite possible that sunspot motions and changes could be significant observable factors in the energy build-up of at least some solar flares. Unfortunately no comprehensive studies are made by comparing sunspot changes prior to flares with the frequency of the same changes in the absence of flares. Although convincing statistical analyses are still lacking, we cannot rule out sunspot motions prior to some of the flares. Collisions or approach between evolving sunspot groups have been associated with important flares (McIntosh and Donnelly 1972, McIntosh 1969, 1971). This process naturally results in very steep magnetic field gradients between spots of opposite polarity. McIntosh (1970a,b) has noted that even small sunspot groups may be associated with major flares if their spot motions are especially large and lead to an increasing gradient across the neutral line. It is also shown that the separation of sunspots decreased prior to a large flare and increased after the flare (McIntosh 1969). Sunspot rotation and partially developed vortices in penumbral and fibril structure also accompany especially flare rich regions (Zirin and Tanaka 1973, McIntosh 1969, 1970b). These properties are additional consequences of the mutual approach of sunspots of opposite polarity. The fibrils of approaching adjacent regions of opposite polarity always turn away from each other and towards the direction of the polarity boundary often called the neutral line of longitudinal component of observed magnetic fields (Martin 1973, Foukal 1971a,b). It is now well established that flares occur as the result of sunspot motions and also that the parallel boundary is established by sunspot motions. Therefore, flare is a consequence of a particular evolution of the magnetic structures near an inversion line prior to the start of the flare onset (Martres and Soru-Escaut 1977). Most of the major flares are associated with regions of complex magnetic field structure found in large sunspot groups (Švestka 1968), and only a small percentage of two-ribbon flare events are found to occur in nearly 'quiet' or spotless regions of the solar disk.

### 2.3. Emerging flux regions

According to Heyvaerts, Priest, and Rust (1977), the process of reconnection is responsible for flare trigger and it is driven by magnetic flux emerging vertically from beneath the photosphere or by pores and satellite spots moving laterally within sunspot groups at the surface. This model provides the storage of pre flare energy through the formation of a current sheet at the interface between oppositely directed magnetic fields of an existing active region and a new one growing besides it. Forbes and Priest (1984) experimented further with numerical simulations of reconnection between an emerging flux region and an overlying horizontal magnetic field. Martin et al (1982) find that two-thirds of the flares in a complex group are intimately related to new emerging magnetic flux within the same configuration. These new regions interact with existing flux in a variety of ways (Martin et al 1984), including one which suggests that emerging flux might stimulate reconnection from distance. Old flux patterns of opposite polarity are pushed together by a rapidly expanding new region at a 'neutral line' filament and a flare erupts at their interface (Martin et al 1984). Flux emergence prior to the occurrence of three major flares was reported by Quanshi, Aidi, and Xiezhen (1985). In many flares, photospheric motion deforming the magnetic field structure of a complex group or emerging opposite flux seem to build-up unstable configurations with higher energy thresholds. In the case of a well documented two-ribbon flare of 21 May, 1980 (de Jager and Švestka 1985), the destabilization of a highly stressed filament prior to a flare is attributed by Hoyng et al (1981) to the appearance of a new magnetic flux in the form of a pore directly beneath the filament. The same case analysed by Harvey (1982) with vector magnetogram suggests that the pore formed not by emergence but by the compression of existing flux at the surface. New flux did appear but in such a way that the net flux at a location beneath the activated filament actually decreased. In the case of a flare studied by Kundu et al (1985), emerging flux did not figure as a direct trigger of the flare preceded by an erupting filament but this does not rule out the possibility of emerging flux elsewhere in the surrounding region of the activated filament playing an indirect role by modifying the global magnetic structure. However, there are cases where the emergence of flux in the way idealised by Heyvaerts, Priest, and Rust (1977) without resulting any flare activity. Thus the role of emerging flux triggering instability in an overlying stressed filament also remains ambiguous. Therefore something extra is needed to produce large flares besides flux emergence pushing the overlying flux. Also it is very much essential to confirm whether a changing feature is a decisive flare trigger or a mere coincidence.

### 2.4. Homologous flares

Homologous flares repeat at the same locations in the same active region. Their X-ray, optical, and radio emissions follow similar patterns in space and time. Within complex active regions there may be several locations with different characteristics of magnetic field, each one generating its own series of homologous flares (Gaizauskas 1982). Homology provides an opportunity to isolate essential pre flare factors by comparing many series recurrent of events. Woodgate et al (1984) identify some pre flare flow patterns in the photosphere and chromosphere but not all the homologous flares investigated by them followed similar pre flare patterns. Machado (1985) finds that homology correlates clearly with the presence of magnetic topology changes in the corona after the flare though post flare changes at the level of photosphere and chromosphere are negligible.

The rate of repetition of flares belonging to the same homologous series can be as rapid as a few hour or as frequent as one in several days (Martres et al 1984). Past observations indicated that a rapid repetition was characteristics of homologous sub flares whereas longer delays were experienced for homologous great flares (Ellison 1963). Therefore, it can be inferred that lengthening delays associated with flare strength may be due to the process of magnetic energy build-up which is eventually released by flares. Numerous incidents of repeated flare patches erupting in close succession were reported even though they were spaced far apart in a complex active region (Ogir 1981, Golovko, Kasinskii, and Klochek 1981, Mogilevski 1981, Gaizauskas 1982).

## 2.5. Magnetic shear

### 2.5.1. Stressed magnetic fields and flares

It is generally accepted that flares derive their power from the free energy stored in the stressed magnetic fields (Švestka 1976). The rapid transformation of magnetic energy into plasma heating and particle acceleration is believed to occur through magnetic reconnection when the stresses exceed a critical threshold. Hence, the most important questions to be settled from pre flare observations concern the geometry of magnetic field, the stresses applied to them from photospheric to coronal heights, and the changing physical properties of the plasma trapped in those fields.

As stresses gradually develop, the magnetic field configuration in the active region becomes non-potential. Therefore, a study of the non-potentiality of solar magnetic fields is essential to understand the physics of solar flares and other dynamical phenomena as well. As an active region evolves, stresses in the coronal magnetic field may build-up in response to changes taking place at the photospheric level, such as sunspot motions, emerging flux, etc. Free energy of these stressed, non-potential fields is considered to be available for release in flares. Thus, it is important to study magnetic fields in solar active regions in order to understand solar flares. Measurements of magnetic fields at coronal level which is considered to be the flare site is relatively difficult. However, magnetic field measurements at the photospheric and chromospheric levels provide vital information about the sites of complex polarity, steep magnetic field gradients, and non-potential or sheared structures in active regions.

**2.5.2. Magnetic shear at the photosphere**

The concept of magnetic shear has occupied a central position in the study of flare associated changes in the magnetic field since early 1970s (Zirin and Tanaka 1973). To understand the development of magnetic shear is most important but not much work has been done so far with regard to what actually causes shear development. Because regions tend to cluster in complexes of activity rather than form in isolation (Gaizauskas et al 1983), their expanding motions within a cluster lead to interactions between initially uncoupled magnetic features and to local deformations of the magnetic field. By using a MHD model of a sheared archade of magnetic loops to investigate flare build-up of energy in an active region, it has been shown that magnetic energy sufficient to power solar flare is accumulated near the polarity inversion line, as the shear of the fool points in the magnetic archade increases (Wu et al 1984). These foot points are anchored in the photosphere where concentrations of magnetic flux, say, sunspots are present. Thus sunspot motion is frequently reported as causing magnetic shear at the photosphere (Nagy 1983, Gesztely and Kalman 1986, Neidig et al 1986, Kovacs and Deszö 1986). Shear motions of umbrae in a δ - spot (i.e. umbrae of opposite magnetic polarity contained within the same penumbra) before a flare is reported due to emergence of magnetic flux rope (Kurukowa et al 1987). Convincing evidences of shear generation by successive emergence of magnetic flux in δ - spots are often reported (Kurokawa 1991, Zirin and Wang 1993, Wang 1994). The formation of flare-rich δ - spots is attributed by Tang (1983) to near collisions of previously unconnected spots. Even a direct collision of opposite polarity sunspots can eventually, and with surprising suddenness, leads to magnetic shear by a process which is not unidentified (Gaizauskas and Harvey 1986) whereas collisions of sunspots from interacting bipoles have given rise to development of magnetic shear (Gaizauskas, Harvey, and Proulex 1994). The shear observation has become one of the most important aspect of flare research after the introduction of a quantitative measure of magnetic shear at the photospheric level by Hagyard et al (1984). It has been realized that flare-related photospheric shear is generally associated with mechanisms which are common in centres of complex activity like flux emergence (Zirin 1983), flux submergence (Rabin, Moore, and Hagyard 1984), and flux cancellation (Martin, Livi, and Wang 1985).

### 2.5.3. Transverse magnetic fields and flares

Thus the process of magnetic energy storage is attributed to the shearing of magnetic fields due to motions at or below the photosphere where hydrodynamic forces dominate. According to this view point, the longitudinal magnetic fields can remain virtually unchanged throughout the evolution of shearing, or in other words longitudinal fields are not stressed. So the transverse component of stressed magnetic field is closely related to solar flares and not the longitudinal fields (Lin, Wei, and Zhang 1993). Direct evidences of the non-potential nature of the observed field at the photosphere is best displayed by the alignment of transverse field along the neutral line (Hagyard et al 1982, Hagyard, Moore, and Emslie 1984, Priest et al 1986). Based on this, the concept of angular shear or twist is defined as the difference between the directions of observed transverse field, and potential field (Hagyard et al 1984). Thus necessary conditions arrived for the eruption of large flares are large angular shear and strong transverse field over an extended length along the neutral line (Hagyard, Moore, and Emslie 1984, Neidig et al 1986, Machado, Orwig, and Antonucci 1986).

However, counter examples are also observed when no flares occurred even when necessary conditions existed (Hagyard and Rabin 1986).

## 2.6. Magnetic shear at the chromosphere

### 2.6.1. Magnetic topology of Hα fibrils and filaments

The sheared field in fact is the signature of atmospheric currents. Traditionally the shear is represented by a bundle of strong transverse fields or a set of flux loops which align with the magnetic neutral line. Magnetic shear at the chromosphere was first recognized from the morphology of Hα fibrils or filaments which were in alignment with the magnetic neutral line (Zirin and Tanaka 1973). It is believed that the Hα fibrils at the chromosphere generally trace the transverse components of the photospheric vector field (Zirin 1974). Thus high resolution observations of fibril patterns provide a unique opportunity to study the chromospheric magnetic fields and its changes (Bruzek 1968, 1975, Nakagawa et al 1971, Zirin 1972).

The term 'fibrils' refers to dark strands that are only ~2 arcsec wide, <20 arcsec long (Bruzek and Durrant 1977). Substantial evidences exist that the direction of magnetic fields in the chromosphere parallels the fibril structure (Tsap 1965, Smith 1968, Bruzek 1969, Foukal 1971a, b, Zirin 1972). When studied in conjunction with magnetic field maps, they appear to run parallel to transverse field, $B_\perp$ (Veeder and Zirin 1970, Nakagawa and Raadu 1972). Filaments on the other hand are generally >5 arcsec wide and <30 arcsec long. Filaments invariably follow the boundaries between positive and negative regions on the maps of the longitudinal component of the magnetic field. Also, there are strong evidences for the association of filaments with photospheric neutral line (Babcock and Babcock 1955, Smith and Ramsey 1967, McIntosh 1972, Martres et al 1981). Fibrils may incline at any angle to nearby filaments, although close to the filament they turn to be aligned with it (Martin 1973) and high resolution images show that many filaments are nothing more than a fused chain of fibrils. It is shown that filaments form only where fibrils form strongly sheared paths (Harvey et al 1971, Martin 1973), although they may also form along polarity boundaries in bright plages where few or no fibrils are present. It is also observed that filaments are occasionally connected by fibrils with the bright elements of the chromospheric network. Rust (1984) showed the filament structure breaking down into several fibrils that terminate in different plage features before and after a flare. Tanaka (1976) also studied the evolution of filaments and fibrils associated with flares and concluded that after each large flare, the long filament was replaced by a set of short fibrils that bridged the neutral line. The common feature is that the variations detected seem to involve reorientation of fields and these changes in fibrils and filaments have similar pattern. Hence, it is assumed that filaments and fibrils, in flaring regions outline $B_\perp$ (Rust 1984). Also it is emphasized by Martin (1980) that pre flare fibril changes and the pre flare changes in filament, are not mutually exclusive events.

### 2.6.2. Energy changes during a flare

The attempts to find whether any decrease in magnetic energy after the flare have indicated time and again that such indications are difficult to observe. The transverse component $B_\perp$ of the magnetic field is a better indicator of the energy change, but it is difficult to measure this component which is perpendicular to the line of sight component. $B_\perp$ is still more difficult to obtain in the chromosphere and corona where the flares occur. Lacking Zeeman effect measurements, Veeder and Zirin (1970) and others have tried to measure the energy changes from chromospheric filaments and fibrils which may outline $B_{\perp}$. It is also quite often assumed that the site of increased transverse component becomes the filament (e.g., see Livi et al 1989). In uncomplicated spot groups, such results agree well with theoretical models (Nakagawa and Raadu 1972).

When a filament disappears completely during a flare nothing can be said about changes in $B_{\perp}$. Perhaps $B_{\perp}$ returns to the pre flare state. Many cases of permanent filament changes other than complete disappearance have been reported (Nolan, Smith, and Ramsey 1970, Bruzek 1975, Rust, Neupert, and Nakagawa 1975, Zirin and Tanaka 1981). Illustrative calculations by Tanaka and Nakagawa (1973) indicated how such a permanent filament change may reflect a significant reduction in magnetic field energy, even though the variations in Hα structures may appear slight. However, except for very large flares, flare associated magnetic field changes in the chromosphere are not detected. Magnetic field disruptions occur during flares is beyond question, but the net effect of flare energy released in the chromosphere, as in the photosphere (Rust 1976b) is below the sensitivity of present methods of detection. Though direct measurements are difficult to make, filaments are widely regarded as useful indicators of energy storage.

### 2.6.3. Magnetic cancellation

Emerging flux and magnetic shear both suspected of causing flares, yet neither factor is a sufficient condition. Some missing stimulus like flux cancellation, i.e., by the mutual loss of magnetic flux at sites where fragments of opposite polarity encounter one another (Martin, Livi, and Wang 1985) are considered to be the link for flare trigger. The polarity inversion lines in an active region is an obvious location for these encounters. Martin (1986) has recognized the importance of cancelling small-scale fragments of magnetic flux to the formation and eruption of active region filaments.

### 2.7. Filaments and sheared magnetic field configurations

#### 2.7.1. Filament eruption

Many solar flares are associated with the eruption and disappearance of dark Hα filaments (Bruzek 1975, Rust 1976a). Erupting filaments undergo twisting and bowling motions which give impression that the supporting magnetic fields are similarly moving. Since solar plasma in the filaments is highly ionized, and therefore, 'frozen in ' to the magnetic fields, we know that magnetic fields erupt when filaments erupt. After a flare, or even in the late stages of flare decay, a new filament may appear in place of one that is erupted. This means that the magnetic field may reconstitute itself after the flare with much the same form and strength as before. Since flares probably derive power from free magnetic energy in or near the filaments, there could also be differences between pre flare and post flare filament structures.

It has been shown time and again that one of the necessary condition for the flare production is sheared magnetic field configuration. The filaments are generally recognized to represent sheared magnetic field configurations and this is even expected because of the observation that filaments form at cancellation sites (Martin 1986). In addition, there are many studies that have shown associations between filament orientation, sheared configurations, filament eruptions, and flares. By interpreting cancellation as magnetic reconnection at the photosphere, Van Ballegooijen and Martens (1993) developed a model whereby part or all of the disappearing photospheric line-of-sight component is reconfigured into an increased transverse magnetic field component, and hence, disappears with continued cancellation, and as a result the magnetic field in the filament expands outward, eventually becomes unstable, and erupts.

### 2.7.2. Formation of current sheet

The occurrence of flares in either simple bipolar configuration, or complex magnetic field configuration seems to require the prior development of a current sheet or a strongly sheared magnetic field. An active region develops from the eruption of twisted sub-photospheric flux tube. After the tube penetrates the photosphere to extend into corona, it is essentially favourable for the sub-photospheric portion to unwind and transmit the subphotospheric twist through the photosphere into the corona. This has the effect of producing rotations at the photosphere, including in particular a high shear along the neutral line. Such shear is the notable property of flare-producing regions. There is certainly a relationship between the photosphere and filaments, since they are observed to be connected to the photosphere by foot points. Hence, the photospheric twist is transmitted to the filaments and the geometry and structure of filaments in the close vicinity of flares develop strongly sheared fields. Furthermore, such shear is indicated by the fine scale-structure of filaments. Thus, the field in the filament is greatly sheared and therefore highly non-potential (McIntosh and Willson 1985, Priest 1989, Engvold 1989). As a result of the eruption of a filament, the overlying coronal field lines will form a current sheet below the erupting filament. The sheared loop configuration is possible even at spotless regions where magnetic fields are weaker. The sheared loop is the filament which will be heated to soft X-ray emitting temperatures (Cheng and Pallavicini 1984). Hence, the presence of filament is indicative of the existence of a current sheet or strongly sheared fields. The frequent association of flares with filaments thus demonstrate the importance of sheared fields or current sheets to the flare process even though direct observations of sheared fields in the chromosphere is not possible.

### 2.7.3. Magnetic reconnection - Theoretical models

It has been proposed (Sturrock et al 1984, Cliver et al 1986) that the slow reconnection of this current sheet is responsible for soft X-ray emission and in the drifting two-ribbon topology of large flares. A reconnection has two consequences. One is that energy is released that may lead to heating of the atmosphere, resulting in X-ray emission from the coronal level and H$\alpha$ brightening at the chromospheric level. The other effect is that the balance of forces is changed, so that part of the filament can move upwards, and more stress is placed on the remaining of the filament which may lead to further reconnection which may disconnect the roots of the filament almost entirely from the photosphere. It is possible that the acceleration of electrons and ions during the impulsive phase also is due to such a mechanism since it has proved difficult to explain particle acceleration as a direct result of magnetic reconnection.

Different models have been proposed to account for the destabilization of filaments (Priest et al 1986). When the MHD stability of a large flux tube anchored at its ends to the photosphere surrounded by a magnetic arcade, Hood and Priest (1980) find that the configuration becomes unstable when the length, twist or height of the flux tube is too great. Van Tend and Kuperas (1978) show that non-equilibrium results if the filament current or height exceed a critical value. Extensions of this electrodynamic model show that the global free flare configuration determines the amount of energy which is stored for a given pre flare current independently of the internal structure of the filament (Martens 1986) and of the actual acceleration mechanism (Kaastra 1985). A new unified theory of fast, steady-state reconnection has been set up by Priest and Forbes (1986) with many new regimes of reconnection, some of them preceding at much faster rates. Van Hoven and his colleagues have developed a new integrated theory for the unstable process which give rise to filaments and flares in sheared magnetic fields (Van Hoven, Steinolfson, and Tachi 1983, Van Hoven 1985). In all this scenarios, the onset of the flare begins when the stretched-out field lines start to reconnect beneath the already rising filament.

### 2.8. Scope of the present study

In spite of strong shears measured from magnetograms, coincide with major flares, they also persist for a long time without concurrent production of flares (Athay, Jones, and Zirin 1986). Also no distinctive difference in the degree of shear has been observed at the sites of flares of large energy difference, viz., intense gamma-ray events and the flares of lesser magnitude (Hagyard, Venkatakrishnan, and Smith 1990). It may be because of the fact that the studies from vector magnetograms mostly concentrate on the angular shear at the photospheric level near the magnetic neutral line. Build-up of magnetic shear is expected to be associated with the overall development of the entire active region. Moreover, extended areas of non-potential structures have been observed in many cases, covering large areas away from neutral lines (Gary et al 1987). Also magnetic shear is visualized only in photosphere, the shear also must have been present in the vertical extent above the neutral line. In view of this, it appears desirable to study the morphology of the entire flare active regions in photosphere and in chromosphere without restricting the shear analysis only along the photospheric neutral lines. Hence we feel that high resolution Hα pictures are still most important in the study of magnetic shear.

In the present study we have given specific attention to the variations observed in the configuration of active regions due to the stresses applied to them from photospheric to coronal heights. Based on the details given in sec. 2.6.1 and 2.6.2, we have assumed that the pre flare filament changes are the regions of increased transverse components representing highly sheared fields ( refer also sec. 2.7.1 and 2.7.2 ) and have argued that the value of shear can be derived from the Hα filaments which assume the azimuth of the neutral line of the non-potential field. The cases of interesting events observed at Kodaikanal are analysed in this thesis. We have arrived at some exciting results which are to be discussed in the forthcoming chapters. A preview of the work done in this thesis is given below for a quick glance.

a) The photospheric plasma motions in active regions, such as shear motions of sunspots or the relative motions of the adjoining chromospheric plages (in the case of spotless flares) are found responsible for bringing in shear, which will in turn, change the structure and orientation of the Hα filaments. Hence, shear angle is measured in terms of changes observed in the direction of Hα filaments with respect to the opposite polarity sunspots or plages (in spotless flares) belonging to the same active region. In this way, the complete environment of the Hα filament is taken into account while evaluating the magnetic shear at the chromospheric level. Since, flare sites are considered to be close to the region of Hα filament, it is also felt that the shear angles thus calculated are more appropriate in representing magnetic shear in the absence of vector magnetograph.

b) In the case of flares that do not have any filament activation or even if there is no filament present in the flaring region, the change in the orientation of the primary photospheric field in sunspots or chromospheric plages (in spotless flares) are considered for shear measurements. The rotational motions in sunspots or plages (in spotless flares) are measured from the change in their orientation angles and are given as a measure of shear.

c) Zirker (1989) observationally has shown that prominences posses fine structures where the magnetic field configuration is greatly sheared. The cases of two dark Hα filaments evolving as prominences during their disk passage are analysed. It has been shown that the critical value of the shear is not only play an important role in the filaments to evolve as prominences but also responsible for resulting the fine structure of the two prominences studied.

d) Eversed (1909) at Kodaikanal Observatory made a remarkable discovery on the radial flow of matter in sunspots. A review of the work on Evershed effect shows that even though enormous amount of work are carried out to understand the velocity field in sunspots, many problems are yet to be solved concerning this dynamical phenomena. Also not much work has been done to find out the nature of flow near neutral lines of bipolar sunspots. Since flares are activated near the neutral regions of δ-type sunspots, it has been attempted in this study to find out the line of sight velocity in the regions between the opposite polarity umbrae of these spots. Also attention is paid to measure the velocity field in between the regions of opposite polarity sunspots having separate nuclei.

# CHAPTER 3

# FILAMENT ACTIVATED FLARES

## 3.1. Introduction

It is of great interest to look for the physical processes in individual flares, as we do not have any comprehensive or general theory of flares. However, in the case of active solar regions, it is plausible to accept the fact that the surplus energy released at the time of a flare is derived from the gradually stored energy from the surrounding magnetic fields. But observational evidence does not point to any drastic change in the magnetic field at the time of a flare. The eruption of flares is often related to the occurrence of sheared magnetic structures (Zirin and Tanaka 1973, Švestka 1981, Hagyard, Moore, and Emslie 1984). Zirin and Tanaka (1973), Tanaka and Nakagawa (1973) and Neidig (1979) reported relaxation of shears near the zero lines of magnetic fields prior to flares. Hagyard et al (1984) observed that the magnetic field in the area of flare activity exhibited much larger degree of shear than in the non-active areas of the region. Therefore, it is concluded that the excess energy released during a flare is drawn out of the magnetic energy stored in twisted or sheared magnetic loops (Martens and Kuin 1989). This situation has brought the interest to look for the factors that cause shear in the magnetic field structures. Flares normally occur in regions which show fast changes in the magnetic field structures. The complexity of the magnetic field gives rise to a non-potential state bringing shear to the field lines. The emerging magnetic flux at the photospheric level is attributed as one of the causes for producing shear to the field lines (Rust, Nakagawa, Neupert 1975). Now it is widely believed that photospheric plasma motion in active regions, such as shear motions of sunspots and rotational motion, can bring in non-potentiality, and can produce shear in the magnetic field. After reaching a critical value, the shear becomes untenable and the flare results.

Flares accelerate partciles up to relativistic energies and produce electromagnetic radiation in the range from the radio to $\gamma$ ray wavelengths. The important questions related to flares are : (i) cataclysmic release of the non-potential energy of the free-flare magnetic field configuration and (ii) the acceleration of particles, especially electrons, to energies of at least a few hundred KeV or MeV in a time interval of probably 1s. The release of energy and acceleration of particles are generally attributed to magnetic field reconnection in flares (Syrovatskii 1978, Priest and Milne 1980, Leroy, Bommier, and Sahal-Brechot 1983).

## 3.2. Orientation of H$\alpha$ filament in a flaring region

### 3.2.1. Observational data

Flares usually occur around the magnetic neutral line (Kruger 1974,). The variations in the orientation of field lines in a neutral line may indicate the presence of reconnection. Therefore, the orientation of the neutral line using H$\alpha$ filaments as proxies are given close attention. The analyses of the data show a significant change ( $5^{\circ}$ ) in the orientation of the filament over a half minute.

In the present analysis, spectroheliograms taken for every half a minute are used and the observations are restricted to 30s each owing to instrumental limitation. The photoheliogram of the flaring region taken at Kodaikanal on

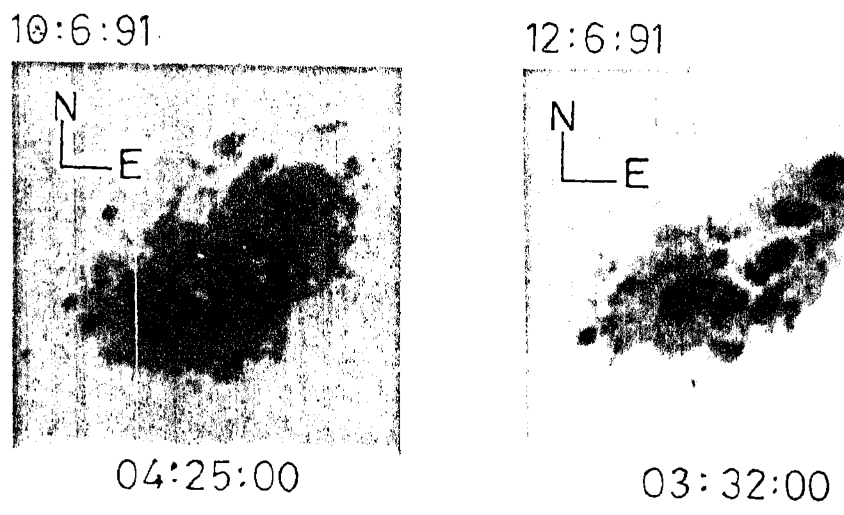



Fig.3·1 a. Pre & Post-flare white-light photoheliograms on 10 and 12 June, 1991.

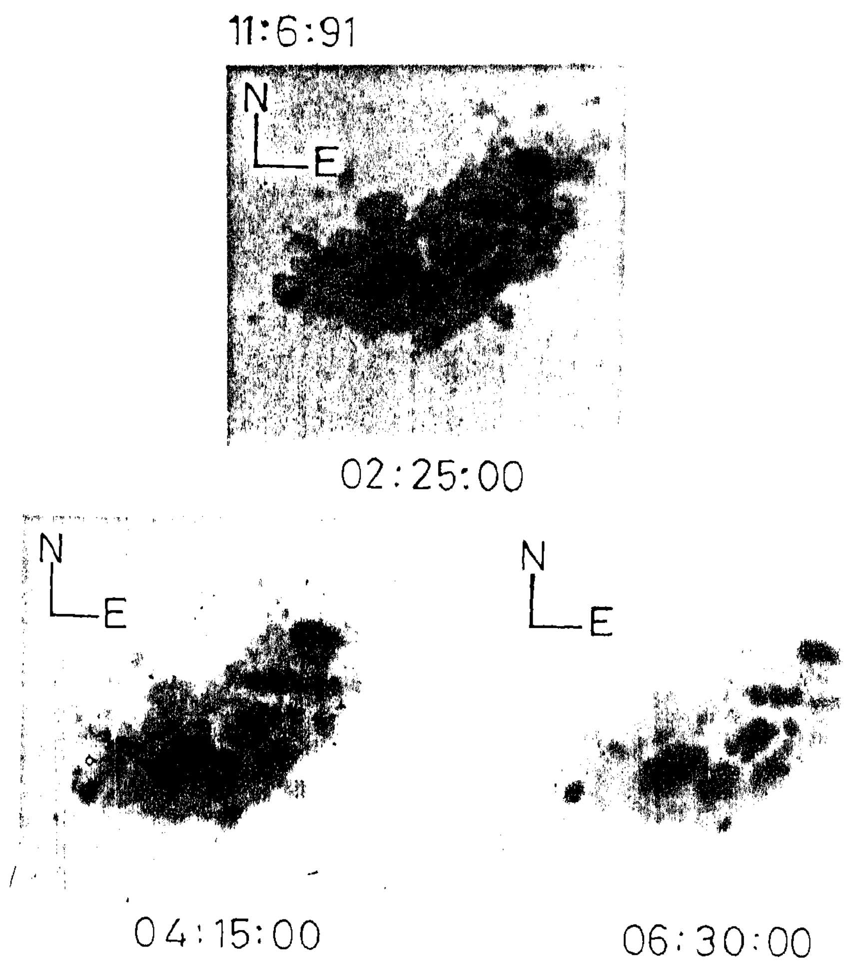



Fig. 3·1 b. White-light photoheliograms on the flare day, June 11, 1991.

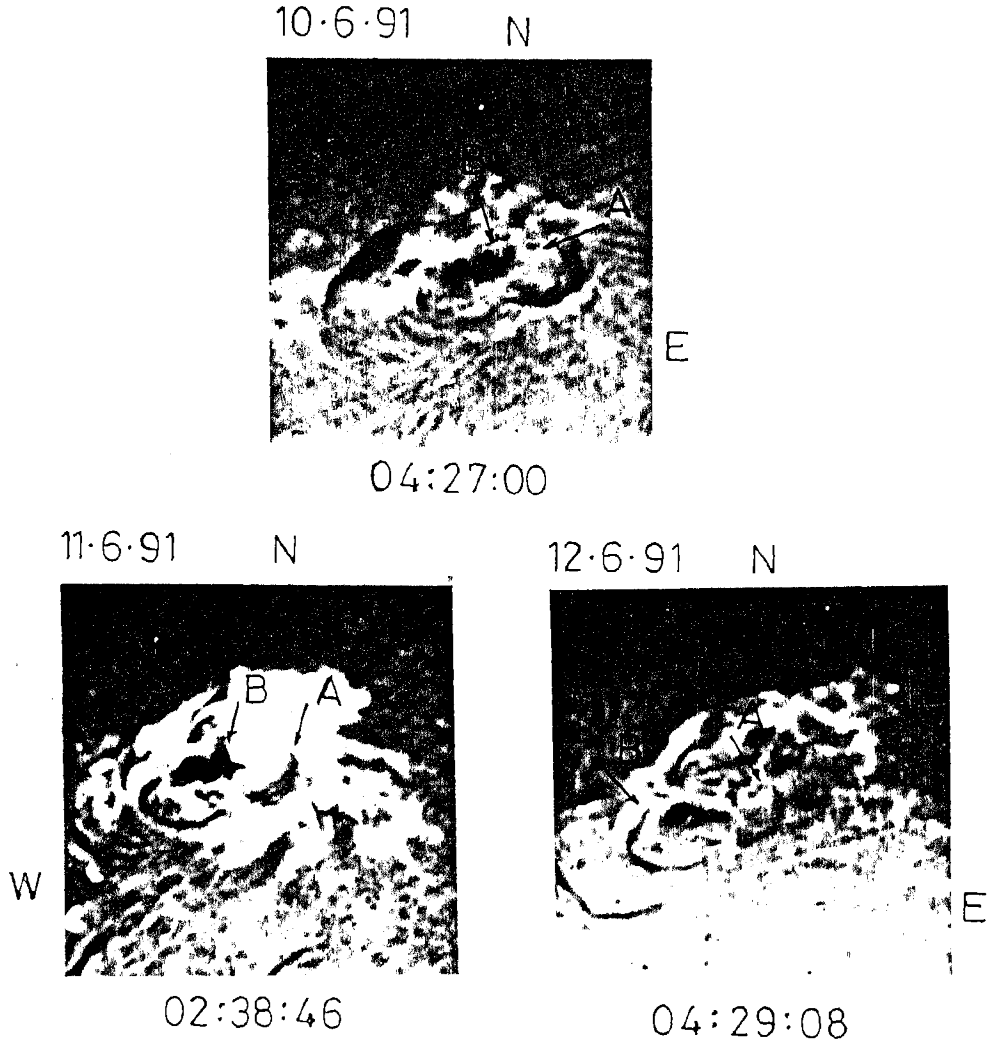



Fig.3·1c. Hα spectroheliograms from 10 to 12 June, 1991 showing the evolution of the filament and its subsequent eruptions as a flare on June 11, 1991. The time of observation is indicated on each frame.

10 June, 1991 at 04:25:00 UT is shown along with the post flare photoheliogram of 12 June, 1991 in Figure 3.1a. Its location was N31 W07 on 10 June, 1991. It is a very complex δ - spot group with 5 to 6 umbrae in one common penumbra. The umbral positions are quite twisted, indicating the presence of shear and proper motion. The location of the region on 11 June, 1991 at 02:25:00 UT was N31 W19 and on 12 June, 1991 was N32 W31 at 03:32:00 UT. The photoheliogram on 11 June, 1991 is shown in Figure 3.1b. At 02:38:46 (Figure 3.1c) UT on 11 June, 1991 the flare was already in progress in the region marked 'A'. This flare developed into a 4B flare at 02:52:30 UT and is the biggest flare recorded at Kodaikanal in recent years. The spectroheliograms from 10 to 12 June, 1991 and the time sequence of the flare in Hα on 11 June, 1991 are given in Figures 3.1c and 3.1d.

### 3.2.2. Data reduction

Vector magnetic field measurements in the photosphere provide direct evidence for the twisted or sheared nature of magnetic loops. In the absence of such measurements, the sheared configuration may be inferred from the Hα filaments, which align along the neutral line positions dictated by the sheared magnetic loops. A quantitative measure for the magnetic shear at the photospheric level was proposed by Hagyard et al (1984), from a detailed study of one active region. They defined the degree of shear as the angle in azimuth between the directions of the observed magnetic field and of the potential field.

Comparisons of Hα pictures and the magnetic field measurements of the active regions have shown that the path traced by a filament indicates the magnetic neutral line and lies along the dividing line between the regions of oppo-

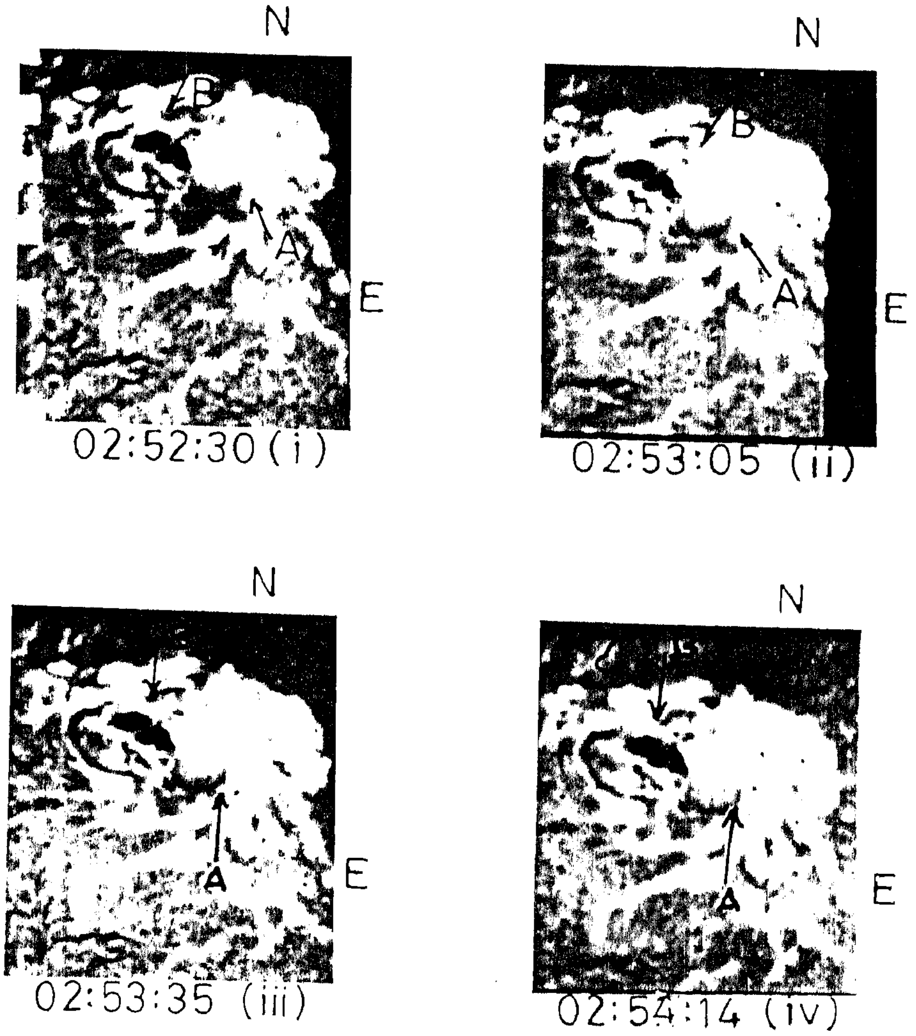
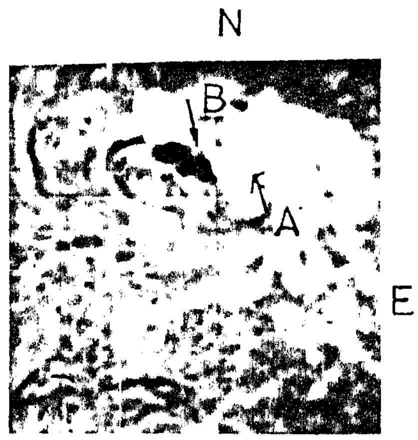
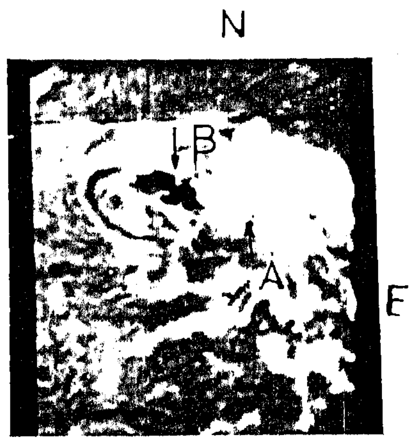


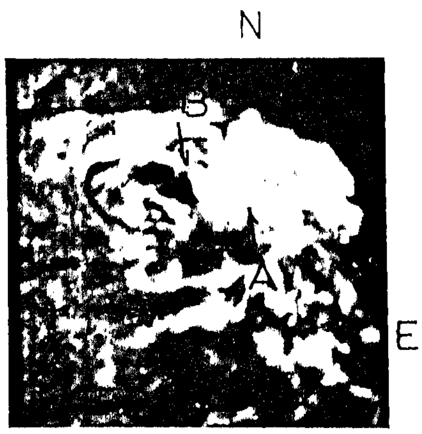

Fig. 3·1d (i – ix) The time sequence Hα spectroheliograms on the flare day June 11, 1991.



02:54:45 (v)



02:57:15 (vi)



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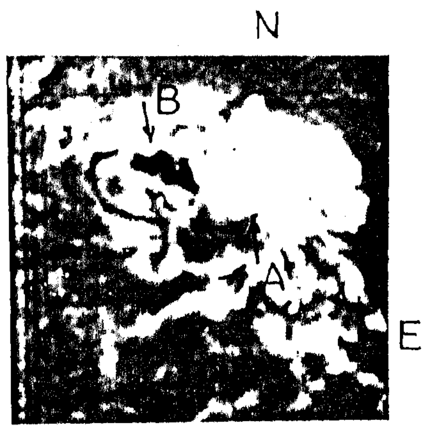
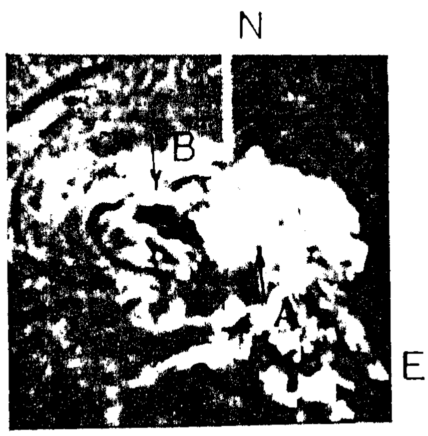


02:58:10 (viii)



02:58:35(ix)

site polarity. It appears that the position, structure, and orientation of a filament is controlled by magnetic field configuration. Changes in magnetic field structures due to magnetic shear may change the orientation of Hα filament. It is therefore assumed that the orientation of the Hα filament and magnetic shear are closely associated with each other, but without simultaneous data, it is hard to prove it.

Hence, we have used the argument that the value of shear can be derived from the Hα filaments which assume the azimuth of the neutral line of the non-potential field. The following data reduction procedure is adopted to derive the angle of shear. The spectroheliogram image (60 mm diameter) is enlarged and projected through an enlarger on to the photographic print of its photoheliogram mate, with perfect alignment using the (N-S) and (E-W) pole markings. The position of the Hα filament is then sketched on the photogheliogram print. To measure the shear angle, the line joining the centre of gravity of one sunspot to the centre of gravity of the other spot of the bipolar group is taken as X-axis. It has been possible to define the centres of gravity of the spots precisely in the case that is studied here. The point of intersection of the neutral line (Hα filament) and the X-axis is chosen as the origin of the coordinate system and the Y-axis is orthogonal to the X-axis. Now, the shear angle '$\gamma$ ' is the angle between the Y-axis and the neutral line (i.e., Hα filament). Using this procedure, Sivaraman, Rausaria, and Aleem (1992) showed that a change in the shear in a 24 hour interval, not the large value of the shear, is the forerunner criterion for the onset of flares. However, the shear and flow velocities may change significantly over a short period before the onset of a flare. Therefore, a detailed study of shear change with very high time resolution is carried out in the present analysis. The variation of shear angle 'γ' in the regions marked 'A' and 'B' are given in tables 1 and 2 respectively, on various days and times.

### 3.2.3. Results

The shear angle 'γ' for both the regions 'A' and 'B' have very large variations from 10 to 11 June, 1991. On 11 June, 1991 when the flare is already in progress, the filament orientation of the region 'B' shows considerable change at a half a minute interval. The region 'A' is blown up and the reference lost due to film saturation. As a result, the measurement of the shear angle is not possible. On 12 June, 1991 the filament orientations of both the regions have returned to almost the normal position of 10 June, 1991. Based on the analysis of the variation of shear angle 'γ' on different days and time for this region, the following conclusion may be drawn. "The umbral positions on 10 June, 1991 look to be quite twisted, the region indicated by the arrow mark on Figure 3.1a and broke into parts on 11 June, 1991. The changes in the structure of the umbrae are quite clearly visible in Figures 3.1 a,b of 10 to 12 June, 1991. This results in an increase of shear angle of both the regions 'A' and 'B'. The shear undergoes almost a $60^{\circ}$ change from 10 to 11 June, 1991, which introduces a non-potential character in the field lines, and after reaching a critical value this becomes untenable and results in the flare onset. Thus, it is felt that the observations presented here are representative of the onset of a flare due to variations in the filament orientation at a high time resolution, and after the flare is over, the field lines, regain their original position".

**TABLE 1**

Variations of shear angle as function of time

| Date | Time in UT | | Spot area in millionth of solar disk | Flare area in millionth of solar disk | Region A |
|---|---|---|---|---|---|
| | SHG | PHG | | | Shear angle |
| 10 June, 1991 | 04:27:21 | 04:25:00 | 2310 | — | 50 |
| 11 June, 1991 | 02:38:46 | 02:25:00 | 2607 | 3510 | 10 (opposite direction) Region blown up and filament position undergone considerable change and has shifted downward at the location marked 'C'; measurement in subsequent frames not possible due to blowing up of the reference point. |
| 12 June, 1991 | 04:29:08 | 03:32:00 | | | 30 |

**TABLE 2**

Variations of shear angle as function of time

| Date | Time in UT | | Region B | |
|---|---|---|---|---|
| | SHG | PHG | Shear angle | |
| 10 June 1991 | 04:27:21 | 04:25:00 | 60 | |
| 11 June, 1991 | 02:38:46 | 02:25:00 | 5 | flare already in progress |
| | 02:52:30 | | 10 | |
| | 02:53:05 | | 20 | increase in flare area |
| | 02:53:35 | | 25 | and intensity |
| | 02:54:14 | | 30 | |
| | 02:54:45 | | 25 | slight decrease in flare |
| | 02:57:15 | | 20 | area and intensity |
| | 02:57:42 | | 15 | |
| | 02:58:10 | | | |
| | 02:58:35 | | 30 | increase in area and |
| | | | 35 | intensity of flare |
| 12 June, 1991 | 04:29:08 | 03:32:00 | 50 | |

### 3.3. Evidence for reconnection ?

#### 3.3.1. Filament eruption and field line reconnection

Generally flares occur in complex magnetic regions where a high field gradient exists, and also where the magnetic polarity of the area is reversed. The plasma motions in the solar atmosphere lead to the complexity of the magnetic field. Information on the change of magnetic fields in such complex regions may be inferred by continuous monitoring of the Hα filaments. As the flare sites are the region around the magnetic neutral line, variations in the orientation of field lines in a neutral line may indicate the presence of reconnection, the direct evidence of which is difficult to obtain. It is believed that the reconnection which is happening at the photospheric level is marked by the dynamic activity of the filament in a region at the photosphere-chromosphere interface. Thus we have used the argument that the Hα dark filament, which assumes the position of the neutral line, is dictated by the sheared nature of the magnetic loops. Hence, the change in the Hα filament direction from one day to the next is measured with respect to the sunspot positions in the same active region, by using the same method reported in the earlier section 3.2.2. The case of the 4B flare of 14 March, 1984 is analysed wherein the opposite polarity field lines are pushed together in a region close to the newly emerged field at the photosphere. This, in turn, develops shear and starts reconnection, and it is argued that out of various processes, field line reconnection is responsible for the onset of the flare. Spectroheliograms in Hα and white light photoheliograms taken at Kodaikanal from 11 to 15 March, 1984 are used in this study and are given in Figures 3.2a and 3.2b.

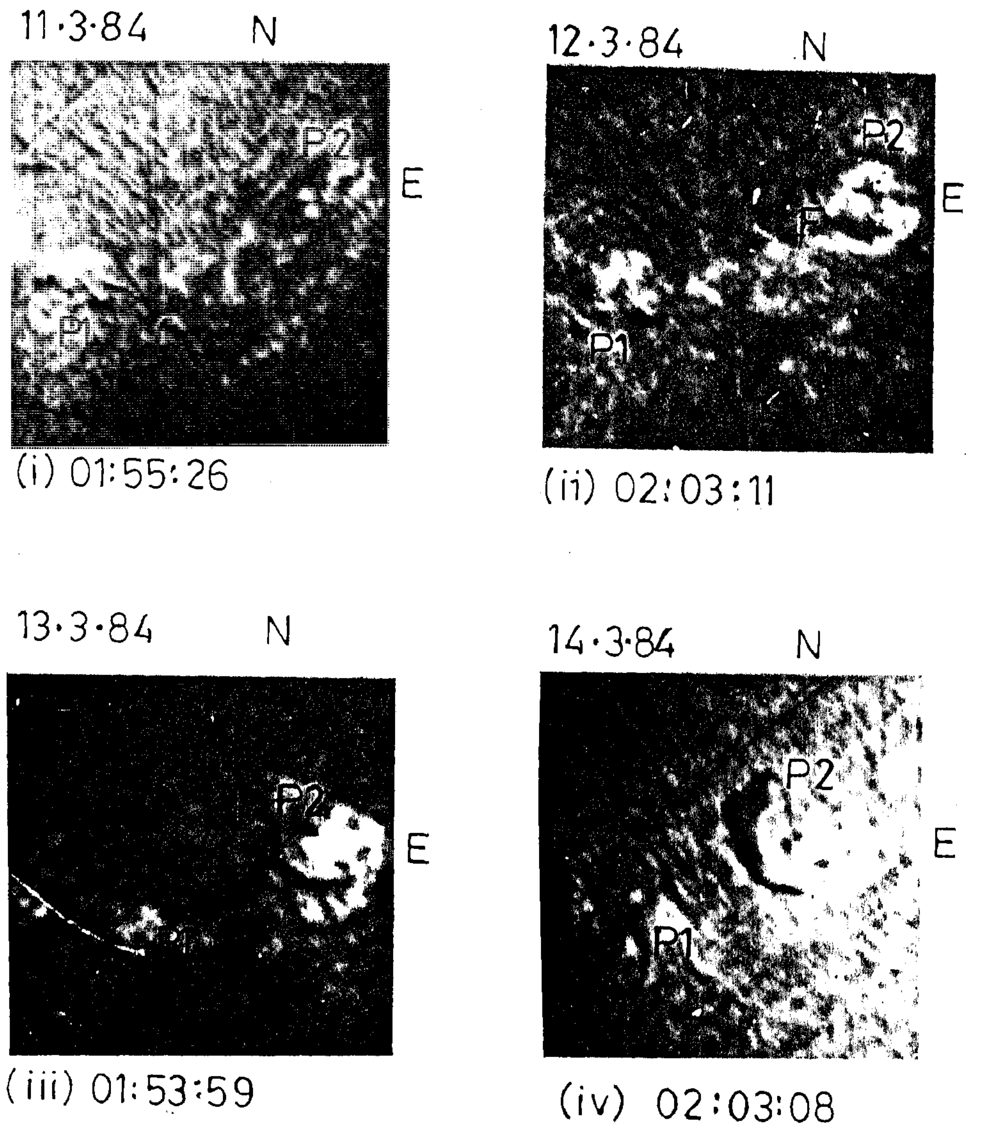
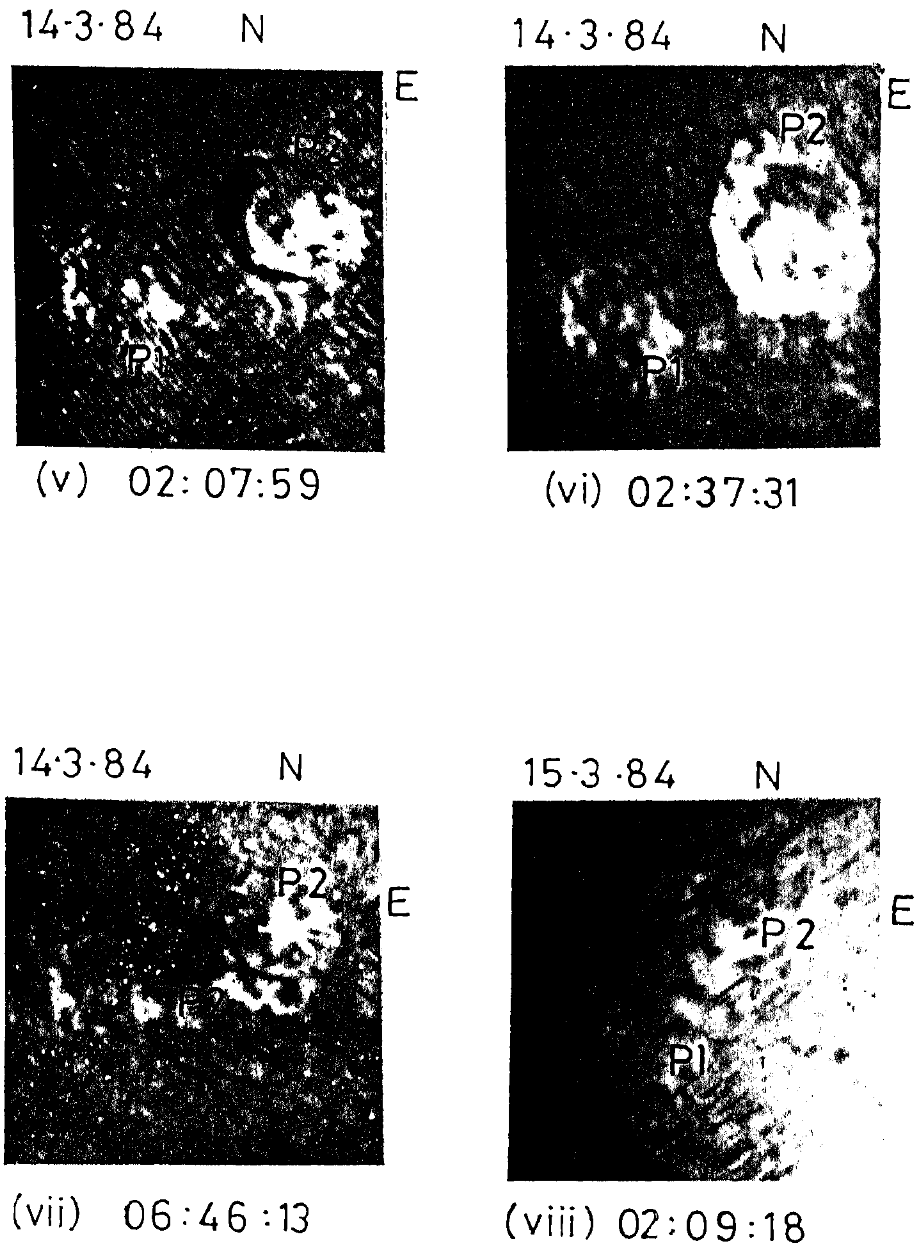



Fig.3.2a(i-viii). Hα spectroheliograms for 11 to 15 March, 1984 showing the evolution of the filament and its subsequent eruption as a flare on 14 March, 1984.




(v) 02:07:59

(vi) 02:37:31

(vii) 06:46:13

(viii) 02:09:18

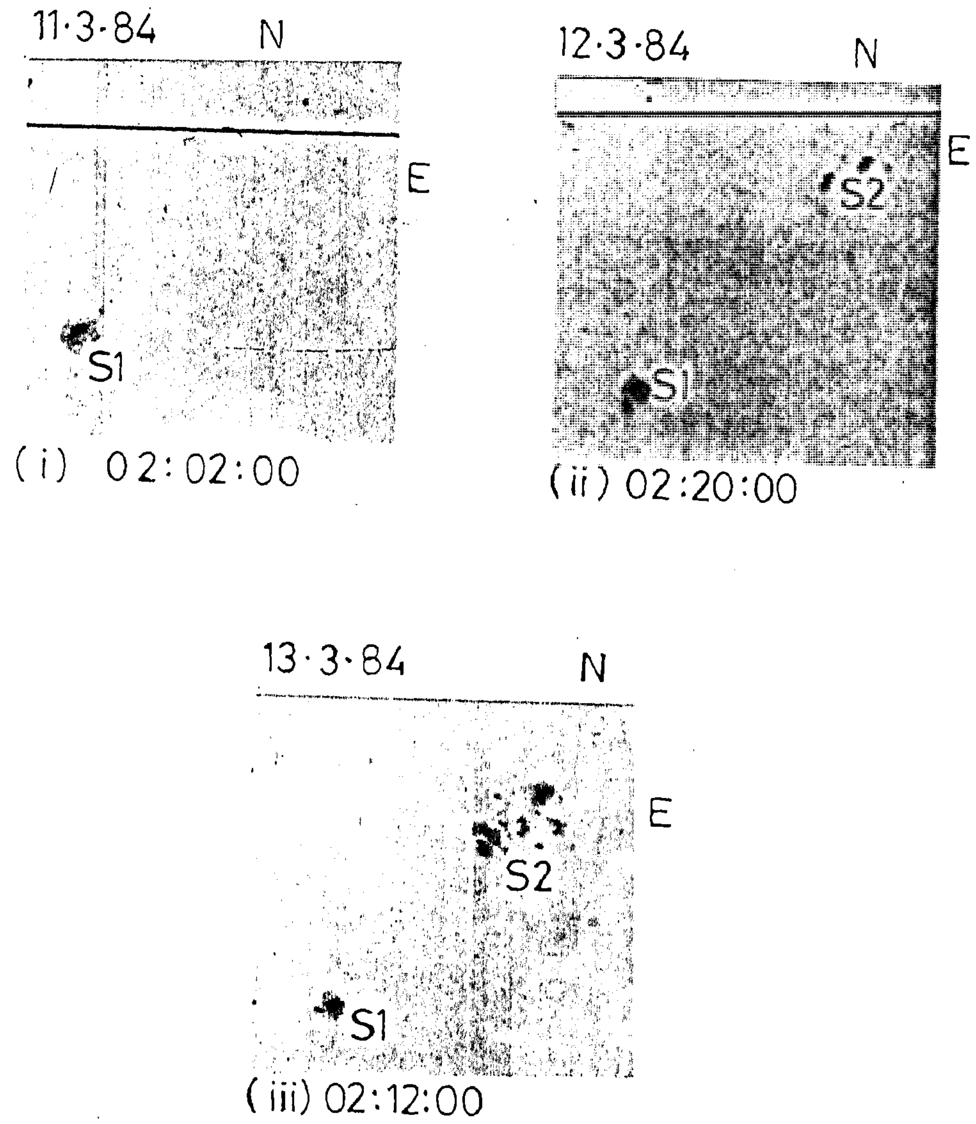
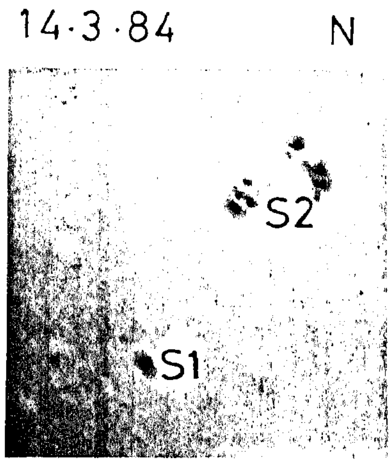
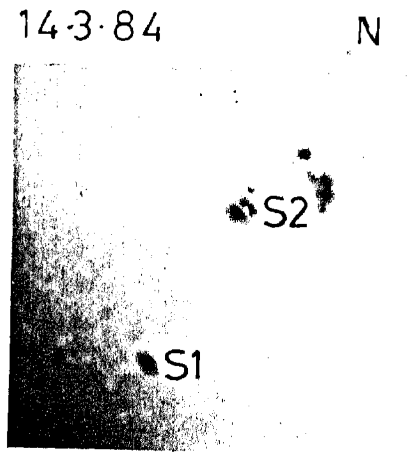


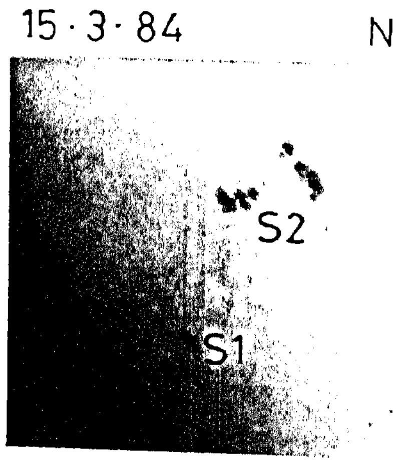

Fig. 3·2b (i-vi). White-light photoheliograms of the corresponding regions for 11 to 15 March, 1984. The development of the newly emerged spot group S2 is shown from 12 March, 1984.




(iv) 02:20:00




(v) 05:33:00




(vi) 02:00:00

### 3.3.2. Results

A plage elongation, which is representative of close active regions in the east-west direction across the centre of the solar disk, is seen in the spectroheliogram of 11 March, 1984. The following events resulted in a flare on 14 March, 1984 at 02:37:31 UT.

**a) 11 March, 1984 :** It is well known that the plage distribution is closely correlated with the magnetic field at the photosphere. The plage regions marked as P1 and P2 at the location S15 W16 and S09 E03 (Figure 3.2a (i)) became centres of activity in the next couple of days. The photoheliogram (Figure 3.2b (i)) shows the presence of a spot, S1, at S15 W17, but no spots are found near the region S09 E03.

**b) 12 March, 1984 :** A new spot group, S2, emerged in the form of pores in the location S08 W08 (Figure 3.2b (ii)) in the close vicinity of the plage region P2 (Figure 3.2a (ii)) in accordance with the fact that the chromospheric plage begins to form much earlier than the appearance of the sunspot. The location of the spot S1 is S15 W30. A feeble H$\alpha$ filament F as shown in the (Figure 3.2a (ii)) appears close to P2. The alignment of the H$\alpha$ filament is to be perfect with the neutral line (Švestka, 1981), and here it is present outside the active region P2, between P1 and P2. Hence, it appears in this case that emerging flux alone is not responsible for the filament formation and suggests that the emerging field, S2, is under the influence of the spot field, S1. As the filament is very weak, it is difficult to measure the angle '$\gamma$'.

**c) 13 March, 1984 :** The newly emerged spot group S2 has grown. The location of S1 and S2 are S14 W44, and S08 W24, respectively. The white light photoheliogram (Figure 3.2b (iii)) shows both the growth of spot group S2 and its relative motion with respect to spot S1, when compared with the photoheliogram of the previous day, 12 March, 1984 (Figure 3.2b (ii)). It is conspicuous that the emerging flux in the region S2 initiates relative motion between the spot groups S1 and S2. The Hα filament is very well marked and positioned closer to the plage P2 in a region between P1 and P2 (Figure 3.2a (iii)).

**d) 14 March, 1984 :** The spot group S2 has further grown. The relative and rotational movements of the spot groups S1 and S2 are well observed at 02:20:00 UT (Figure 3.2b (iv)), when compared with the previous day 13 March, 1984 (Figure 3.2b (iii)). The respective location of S1 and S2 are S14 W58 and S10 W40. The positions of the sunspot groups S1 and S2 from 12 to 14 March, 1984 lie almost in the centre of the disk. Hence, we feel that the conversion to the heliographic coordinates will not alter the centre of gravity of the spot groups S1 and S2. The difference between the centre of gravity of the spot groups S1 and S2 is 22 degree (March 12), 20 degree (March 13), and 18 degree (March 14), respectively. We believe that the strong emerging magnetic flux in the region S2 plays an important role in compressing and pushing it closer to S1 by a drift of 2 degree on each day. This has strengthened the interaction between the fields S2 and S1 and is observed in the form of filament acceleration at 02:03:08 UT and 02:07:59 UT (Figure 3.2a (iv & v)). The filament structure becomes much more pronounced, and it attains a semi-circular shape. Also the filament is positioned in a region slightly away from the emerging magnetic field of the preceding spot of S2, in a region between S2 and S1. Hence, we feel that the growth of the filament is due to the interaction of the growing magnetic field of S2 with its neighbouring field S1.

The photospheric plasma motion such as the relative and rotational motions of sunspots S1 and S2 brought the non-potentiality into the magnetic field. In the process the magnetic field at the chromospheric level in the filament was strongly sheared across the zero line of magnetic field. As a result, the Hα filament underwent a severe twist, became untenable and started unwinding itself, erupting into a spectacular circular flare of 4B importance, almost covering the entire region P2 in the location S10 W40 at 02:37:31 UT (Figure 3.2a (vi)). At the time of the flare, this region is blown off and the reference point cannot be identified for measuring 'γ '. Finally, in the post flare phase at 06:46:13 UT (Figure 3.2a (vii)), the ribbon loops are seen drifting away from each other. The filament acceleration declines, and the angle 'γ ' nearly relaxes to its original value.

e) **15 March, 1984 :** The filament has left its signature in the form of some faint fragments which are seen between the plage regions P1 and P2 (Figure 3.2 (viii)). The values of 'γ ' are shown in Table 3 as a measure of flare activity.

**Table 3**

Change in the orientation of the Hα filament as a measure of flare activity.

| No. | Date | Time in UT | 'γ' in degree |
|---|---|---|---|
| 1 | 12 March, 1984 | 020311 | Filament very weak |
| 2 | 13 March, 1984 | 015359 | 15 |
| 3 | 14 March, 1984 | 010308 | 26 |
| 4 | 14 March, 1984 | 020759 | 33 |
| 5 | 14 March, 1984 | 064663 | 15 |

### 3.3.3. Discussions

Priest and Heyvaerts (1974) outlined a model in which plasma instability could start where the emergent flux interacts with the overlying fields, and as a result, Hα pictures might show evidence for reconnection. In this case, we feel that the emerging flux is not the only condition for the flare onset. The event suggests that the emerging magnetic flux compresses the overlying field (S2) which, in turn, initiates its interaction with the neighbouring field (S1), and it is observed in the form of growing Hα filament close to the emerging field in a region between these two fields. When the emerging field (S2) and the existing field (S1) are brought together due to their relative motion, reconnection of field lines takes place in the neutral plane and the flare is triggered. The filament activation and its subsequent eruption as a flare are well observed in Hα, whereas the reconnection of field lines takes place in a region around the magnetic neutral line at the photospheric level. As the Hα filament is supposed to be on the neutral line, we feel that the reconnection is indicated by the dynamic activity of the filament at the chromospheric level. It is further confirmed by the eruption of the Hα filament, as this suggests that the flare has derived its energy from the magnetic field in or near the filament, the region which is identical with the position of the zero line of magnetic field. The change in the orientation of the Hα filament is reported here as a measure of flare activity. We believe that the observations presented here are representative of field line reconnection, and after the flare is over, the field lines regain their original position.

### 3.4. Filament activity in a quiet region flare

Solar flares occurring in quiet regions are interesting and exceptional events. Generally the spotless flares follow the activation and disappearance of dark Hα filaments (Moore and LaBonte 1980). The analysis of a Hα filament activation in a non-spot region attaining a circular/loop shape before the onset of a flare is reported in this section. The twist observed in the filament indicates the non-potentiality and it is believed that the plage motions set the beginning of this instability resulting a ribbon-type flare.

#### 3.4.1. Observation and data reduction

The advent of vector magnetograms have given a better understanding into the relationship between flares and magnetic fields. Even then much information is still based on sunspots and plage observations. To identify the apparent motions in the solar atmosphere which outline the storage of magnetic energy departing from a potential field for the flare onset, the Hα and Ca II K pictures from 6 to 9 May, 1979 are analysed here. The evolution of flare and Hα filaments are given in Figure 3.3a(i-v). Their corresponding Ca II K spectroheliograms are reproduced in Figure 3.3b(i-iv) and the white light photoheliogram of the flare day 9 May, 1979 is shown in Figure 3.3c. The following data reduction procedure is adopted to measure the angle '$\gamma$' which represents the filament activity. The Hα spectroheliogram image is enlarged and projected on to the photographic print of its Ca II K spectroheliogram mate and aligned for a perfect match using pole markings. The filament is then sketched on the Ca II K spectroheliogram print as shown in Figure 3.3d. The angle between the Hα filament and

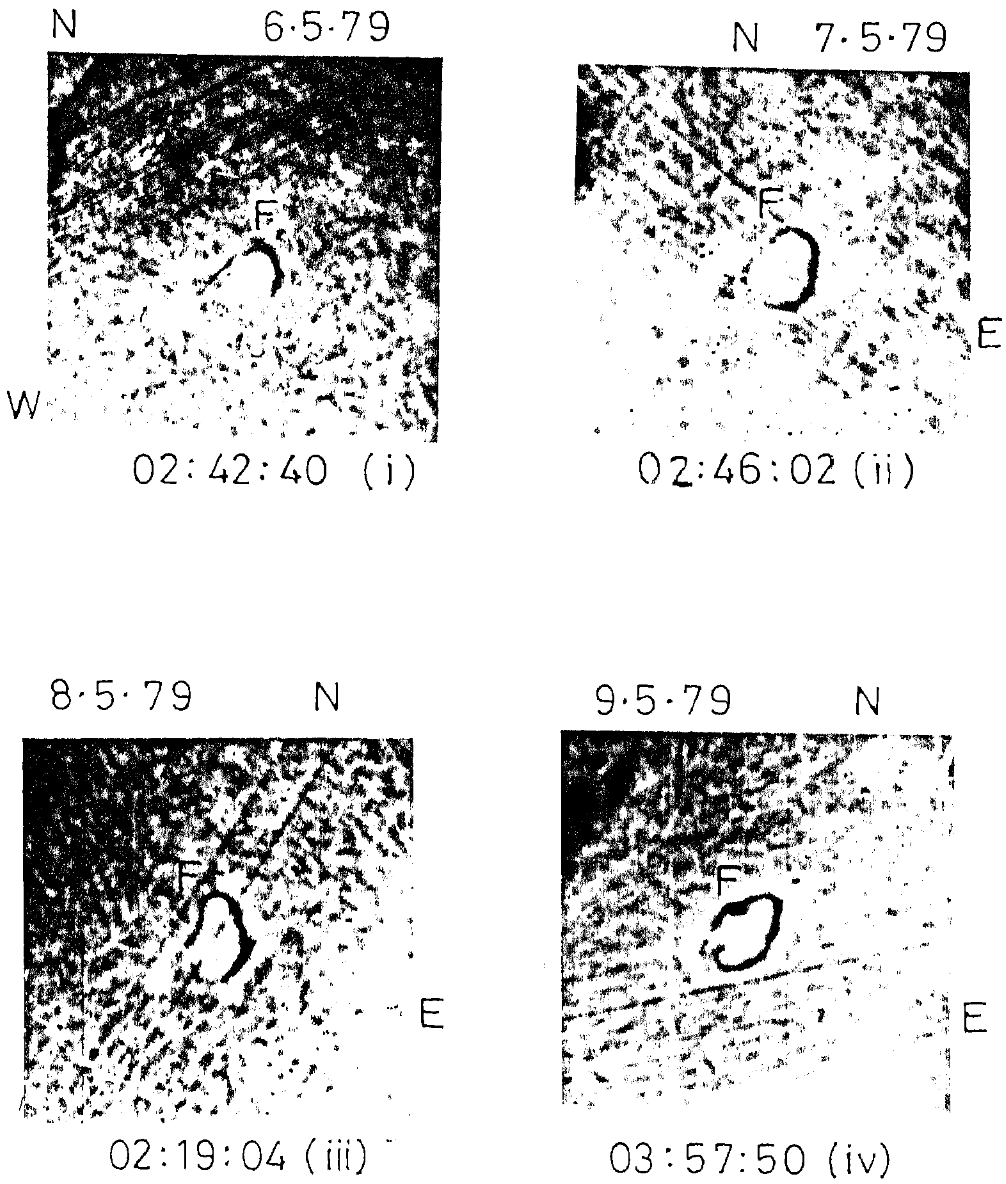
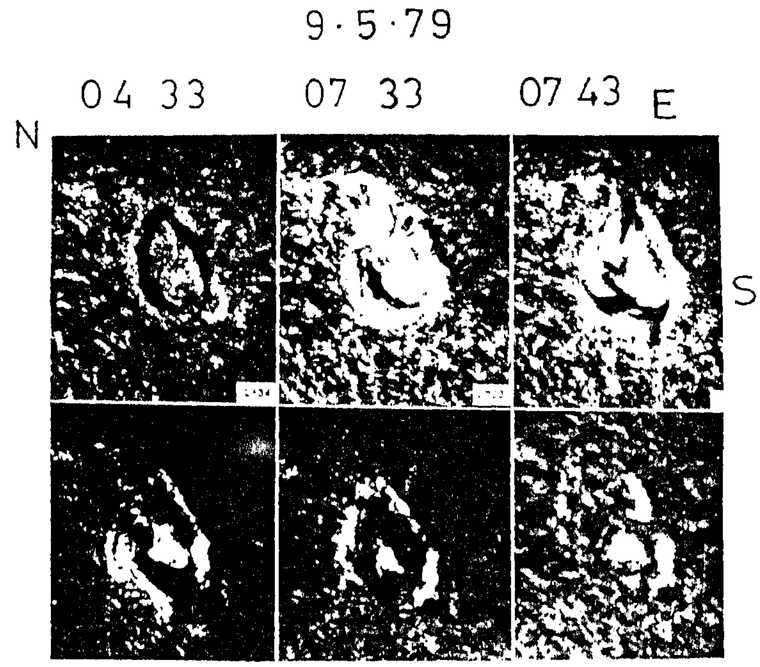



Figure 3·3a(i–v). $H_\alpha$ spectroheliograms from 6 to 9 May, 1979 showing the evolution of the filament giving rise to a flare.




(v)

an axis which is orthogonal to the line joining the centres of gravity of the plages P1 and P2 and the point of intersection of the Hα filament is defined as 'γ'.

### 3.4.2. Results and discussions

Generally the flares originate closer to the zero line of longitudinal field, dividing the magnetic polarities. The zero line of magnetic field is identical with the position of dark Hα filament (Švestka 1976). The plage corridors or dark lanes which delineate the magnetic neutral line show the opposite polarity plages (Gibson 1973). Any change in the structure and orientation of these adjoining plages may in turn alter the orientation of the Hα filament which may lay between these plages. Therefore, the variation in the orientation of Hα filament with respect to the position of the opposite polarity plages are taken as the shear developed in the active region. The centre of gravity of these opposite polarity regions are taken as reference for studying the variation of Hα filament direction ('γ') from one day to the other. This may represent a method of finding out the value of shear in the case of spotless flares.

On 6 May, 1979 a filament F (Figure 3.3a) appeared at N22 E23 in between the plages marked as P1 and P2 (Figure 3.3b). It is interesting to note the change in the orientation of the Hα filament on the next day. The area of the plage P2 has grown (Figure 3.3b Frame ii) and the filament looks to be anchored over the plage P1 attaining a semi circular shape. The area of the plage P2 and the filament have further grown on 8 to 9 May, 1979. At 03:57:50 on 9 May, 1979 the filament is at N22 W20 and the plage motions are visible compared to the previous day. This change in the plage orientation contributed the filament to attain a remarkable circular shape and became untenable resulting

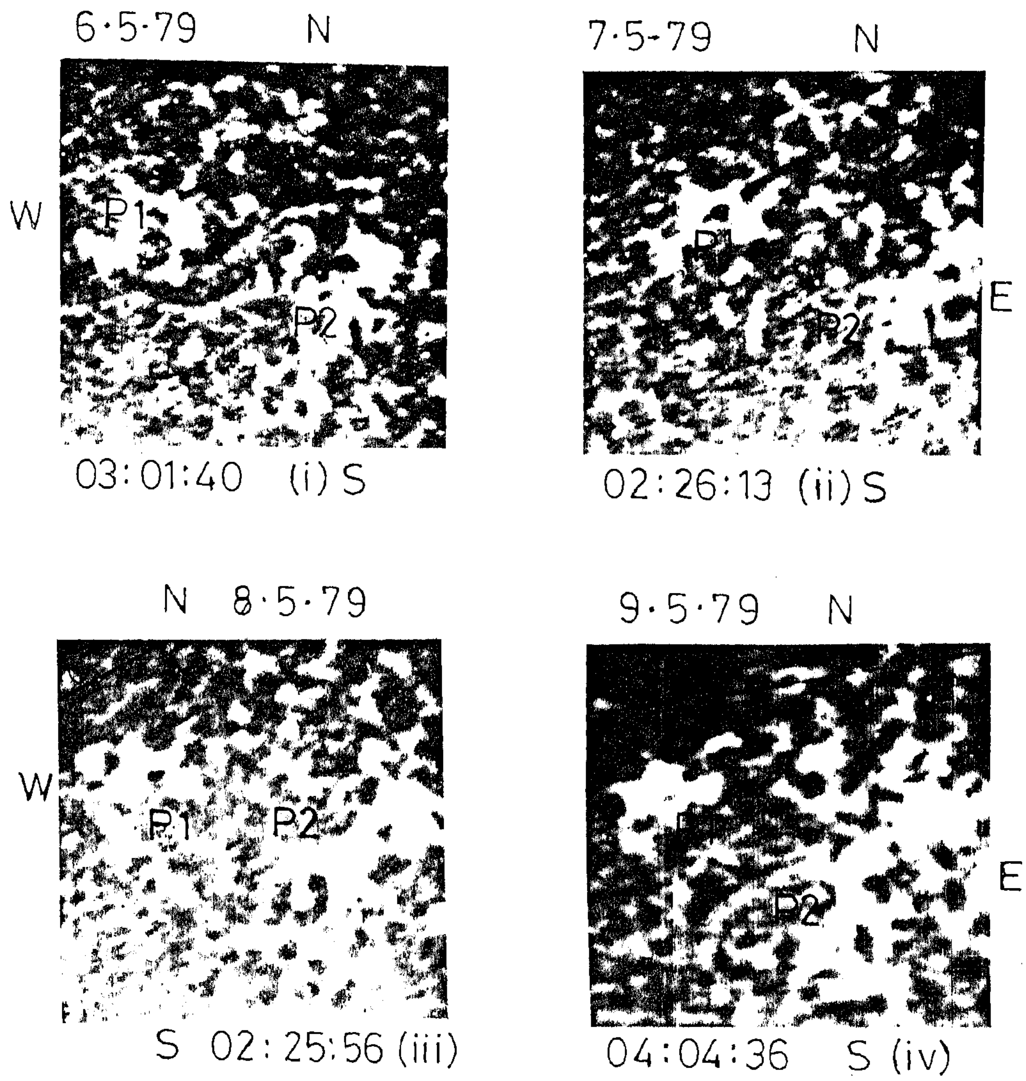



Figure 3·3b(i–iv). Ca II K spectroheliograms of the corresponding region from 6 to 9 May, 1979.

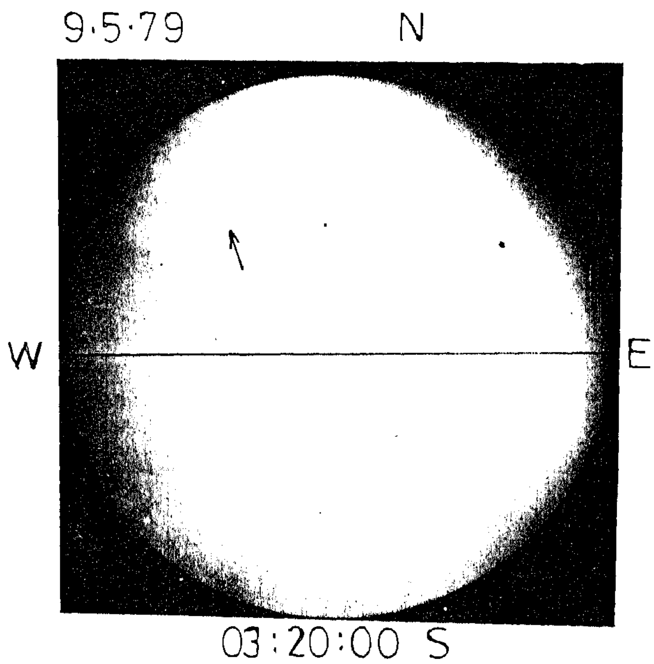



Figure 3.3c White-light photoheliogram of the flare day 9 May, 1979. The arrow mark indicates the flare region.

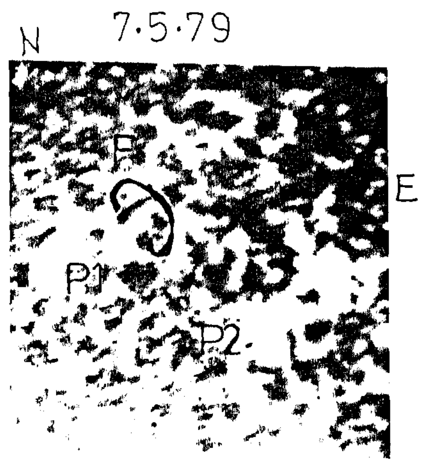



Figure 3.3d Hα filament superposed on the Ca II K spectroheliogram to measure " ".

in a flare. Large portions of the filament disturbed and the flare ribbons appeared at 07:33:00 UT (Figure 3.3a(v)) Dark loops joining the ribbon can also be seen. The filament material exhibited intense activity and finally the entire filament disappeared leaving its signature in the form of some faint emission patches. The flare sequence in Hα shown in Figure 3.3a Frame (v) is reproduced from the photographic atlas of the Solar Chromosphere edited by A. Ambastha and A. Bhatnagar of Udaipur Solar Observatory. The values of 'γ' are given in table 4.

**Table 4**

Change in the orientation of the Hα filament.

| No. | Date | 'γ' in degree |
|---|---|---|
| 1 | 6 May, 1979 | 87 |
| 2 | 7 May, 1979 | 60 |
| 3 | 8 May, 1979 | 8 |
| 4 | 9 May, 1979 | 2 |

A look at the table 4 shows that initially the change in the orientation of the filament is small. However, variation in the value of 'γ' from 7 to 8 May, 1979 becomes such more pronounced and the triggering of the flare had taken place on 9 May, 1979. Based on the analysis of the angle 'γ' on different days for this region, the following conclusions are drawn. "The changes in the filament direction is caused by the shear motions of the plages. The larger variations in the value of 'γ' alone are not sufficient conditions for the flare onset. The cumulative change in the filament direction coupled with the variation in the plage orientation on a specific day play an important role on the evolution of a spotless flare. It suggests that two oppositely directed fields in the form of plages are pushed together in a steady motion, as a result the lines of force reconnect in a neutral plane and trigger the flare".

# CHAPTER 4

# FLARES WITHOUT FILAMENT ACTIVATION

## Part - I

## 4.1. Sunspots motions in flares without filament activation

### 4.1.1. Introduction

Solar flares are energetic phenomena involving a sudden conversion of magnetic energy into other forms of energy in the solar atmosphere. The primary condition usually for a flare to occur is the presence of one or more active regions and thus it is important to study the magnetic fields in the active regions to understand the flare onset and triggering. Coronal levels are considered to be the primary flare sites, but coronal magnetic field measurements are difficult to make. However, most of the results show that the magnetic field changes introduced in photosphere and chromosphere are responsible for triggering the flares at coronal level. It is even believed that the main reservoir of stored energy may be hidden beneath the photosphere and the released energy is loosely related to the amount stored. But observations do not show clearly, how and where, the energy is accumulated for flare production.

Studies of photospheric magnetic fields show the centering of flares around polarity inversion lines (Martres et al 1968, Smith and Ramsey 1967, Michard 1971) and relaxation of shears near the zero lines of magnetic fields (Zirin and Tanaka 1973, Tanaka and Nakagawa 1973, Neidig 1979). Priest (1991) has insisted upon the presence of high field gradients at the photospheric level before flares. In general the observed photospheric magnetic field prior to flare is associated with emerging as well as decaying magnetic fields interacting with a stable structure creating magnetic shear and has been studied by many authors (Rust and Bridges 1975, Canfield and Fisher 1976, Švestka 1976, Heyverts et al 1977, Zirin 1983, Priest 1991, Sundara Raman et al 1994). The complexity of the magnetic field and creation of magnetic shear are closely associated with flares (Rust, Nakagawa, and Neupert 1975, Gaizauskas 1989). Complexity in the magnetic field structure stresses the field, which in turn, induces magnetic shear in the form of changes in the magnetic field pattern. Also shear is induced by the relative motions of magnetic structures. These processes are likely to give the available energy for flaring.

As for the chromospheric environment of the flare is concerned, shear is often observed in Hα fibrils (Tanaka and Nakagawa, 1973). Sara Martin (1980) has stressed that most major flares have filament activation and eruption. Rausaria et al (1993) while analysing a 4B flare found large shear in the Hα filament prior to the start of the flare measured from the variation of filament direction with respect to the bipolar sunspot position belonging to the same active region. In a large flare the overall scenario is that during the pre flare phase a prominence and its high sheared field rise slowly and the flare is triggered by the rapid eruption of the prominence which probably occur because of the reconnection below the prominence (Priest 1981, Švestka 1976). These plasma motions of photospheric and chromospheric field structures are responsible for contributing shear, which in turn, produce non-potential character to the magnetic field lines. Therefore, flare must essentially be a process associated with dynamics of solar active regions. Most of the major flares are generally associated with filament eruptions. However, not all the flares are involved with filament eruption. There are cases of small flares driven by photospheric motion and mostly observed as brightening in H$\alpha$. In such cases, it is believed that photospheric plasma motion of sunspots and rotational motion can bring in non-potentiality and produce shear in the magnetic field. We have discussed here the shear developed due to the changes in the orientation observed in the spot groups and have found that once shear attains a threshold value, minor flares are triggered. These minor flares reported here are not associated with any filament activation.

### 4.1.2. Data reduction and analysis

As flares derive power from the non-potential fields, locating such kinds of fields are important to understand the flare process. The complexity in the magnetic structure stresses the magnetic field causing change in the magnetic field pattern. We feel that the changes observed in the magnetic field pattern in active regions indicate the plasma motions and outline the storage of magnetic energy departing from potential field. These changes induce shear and using vector magnetogram a quantitative measure of shear at the photospheric level was proposed by Hagyard et al (1984) from a detailed study of one active region. They defined the azimuthal difference between the directions of the observed field and of the calculated potential field as degree of magnetic shear and found large values of shear at the flare sites on the polarity inversion lines of bipolar active regions in the photosphere. In the absence of vector magnetogram facilities, we feel that information about the dynamics of active regions can be derived by studying the white light photoheliograms and spectroheliograms. We have taken simple cases of symmetrical sunspots of opposite polarities, the polarities inferred from bipolar group morphology, which appeared on a particular day as a group and have studied their evolution during their disk

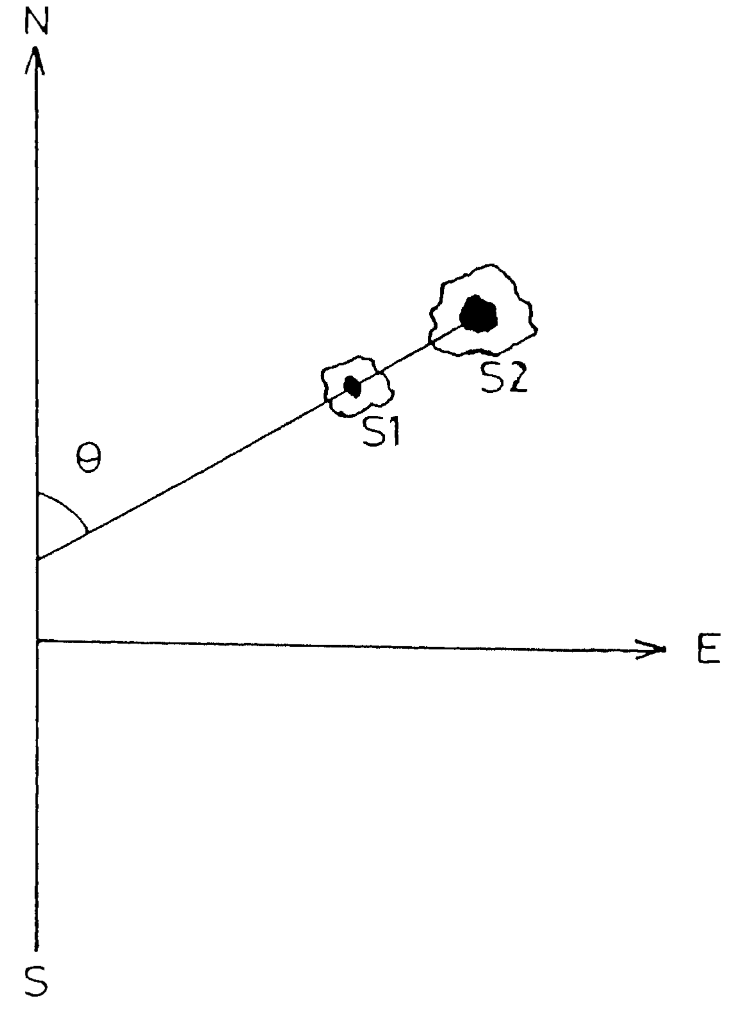



Fig.4. 1a. Details of the technique used to measure the shear angle in sunspots from their change in orientation. The two axes for the measurement of angle θ are(i) rotation axis of the Sun represented by the line NS and (ii) the line joining the centres of gravity of oppositely poled sunspots extended to meet the rotation axis of the Sun.

passage leading to minor flares. The orientations of the sunspots in the active region have changed indicating the presence of proper motion and stressed configuration. The translational motion of one sunspot around another of opposite polarity developed slowly before leading out to flares. The changes observed in the sunspots orientation are listed in table 5 and these changes correspondingly will alter the orientation of the neutral line of the active region in the photosphere.

The following data reduction procedure is adopted to measure the shear angle. We have sketched the positions of sunspots from the photoheliograms on the Sun charts by carefully noting the pole markings. To detect the changes in the orientation of the sunspots in a group on a particular day, the rotation axis of the Sun was chosen as a reference for measurement of angles as there is no filament present in the close region or in the region between the bipolar group. A line is drawn connecting the centre of gravity of one spot to the centre of gravity of the other spot of the same bipolar group. It is fairly easy to locate the centres of gravity of the spots chosen. The angle made by this line with the rotation axis of the Sun is measured from the north towards east direction after corrections for foreshortening. This angle '$\theta$' gives the orientation of the bipolar sunspot group on the solar surface on a particular day. Any variation in '$\theta$' from one day to the next indicates the shear developed due to the change in the orientation of the sunspot group. The most probable error in the measurements of angle '$\theta$' is $\pm 2^{o}$ for the spots closer to the limb. Figure 4.1a shows the technique used to measure the shear angle. White light photoheliograms showing the bipolar sunspot group which appeared during 12 to 14 June, 1970, 15 to 18 February, 1973, and 21 to 24 March, 1973 are given in Figure 4.1b, Frames i to iii. Figure 4.1c shows the white light photographs of the Sun giving the evolution of spot groups S1 and S2 from 10 to 17 March, 1973 leading to homologous flares. Figure 4.1d shows the flare in Hα occurred in the regions corresponding to the days in Figure 4.1b. Hα spectroheliograms showing homologous flares in the region corresponding to the days in Figure 4.1c are shown in Figure 4.1e. The arrow marks in Figures 4.1d and 4.1e indicate the flare region.

### 4.1.3. Results

**(a) 2F Flare on 14 June, 1970** Figure 4.1b, Frame i shows a simple bipolar sunspot group during its disk passage from 12 to 14 June, 1970. Pores appeared in between this spot group on 13 June, 1970. The pores close to the leading spot of the group have grown and also there is a change in the orientation of the main sunspots on 14 June, 1970. The change in the orientation of the umbrae of main spots is not appreciable ( $2^{\circ}$ ) on 13 March, 1970 but a change of $13^{\circ}$ is observed on the next day 14 June, 1970. These cumulative changes of spot growth and relative motion of sunspots have given rise to a 2F flare at location 18 N 01 W in a region between the main sunspots as shown in Figure 4.1d.

**(b) SN Flare on 18 February, 1973** Figure 4.1b, Frame ii shows the bipolar spot group from 15 to 18 February, 1973 leading out to a minor flare SN on 18 February, 1973 at location 18 S 16 W in the region close to both the polarities of the group as shown in Figure 4.1d. The spot group does not show any significant variation in its structure but gradually the rotation of the sunspots have taken place. The change in the orientation of $8^{\circ}$ observed in the sunspots on 18 February, 1973 compared to the previous day has triggered the flare.

Fig. 4.1b Fr i

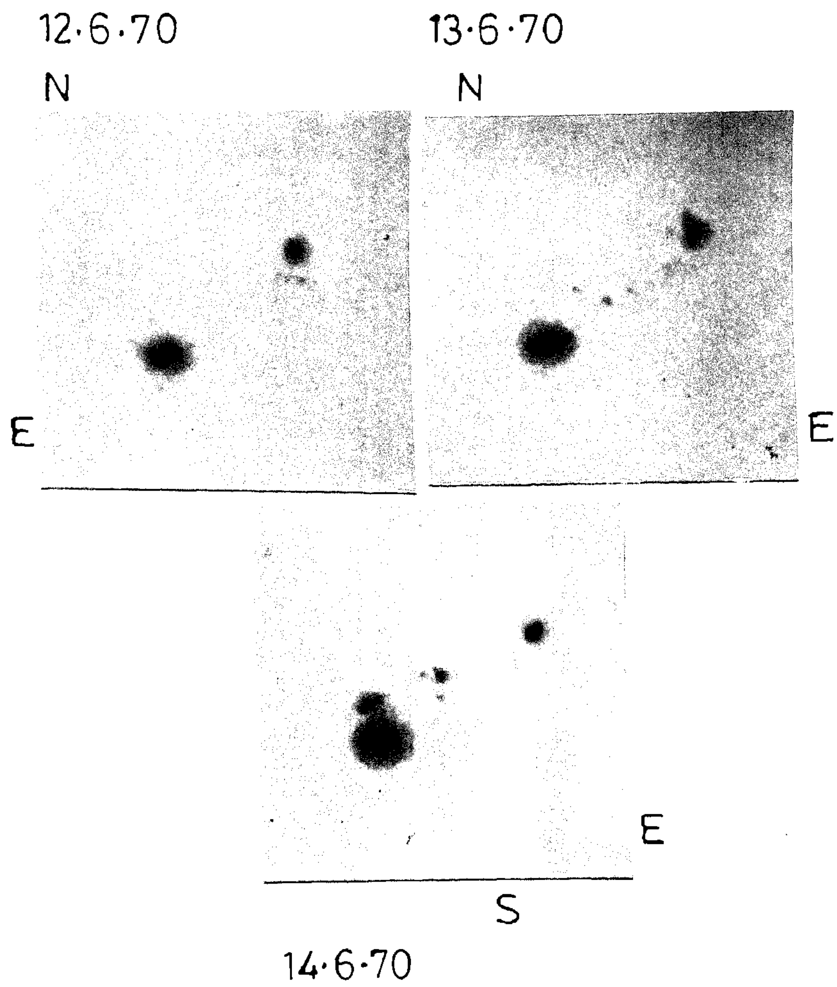



Fig.4.1b. Fr.(i) to (iii) White light photoheliograms showing the changes in the rotation of the sunspots umbrae in the groups which appeared during 12 to 14 June, 1970, 15 to 18 February, 1973 and 21 to 24 March, 1973.

Fig. 4.1b Fr.ii

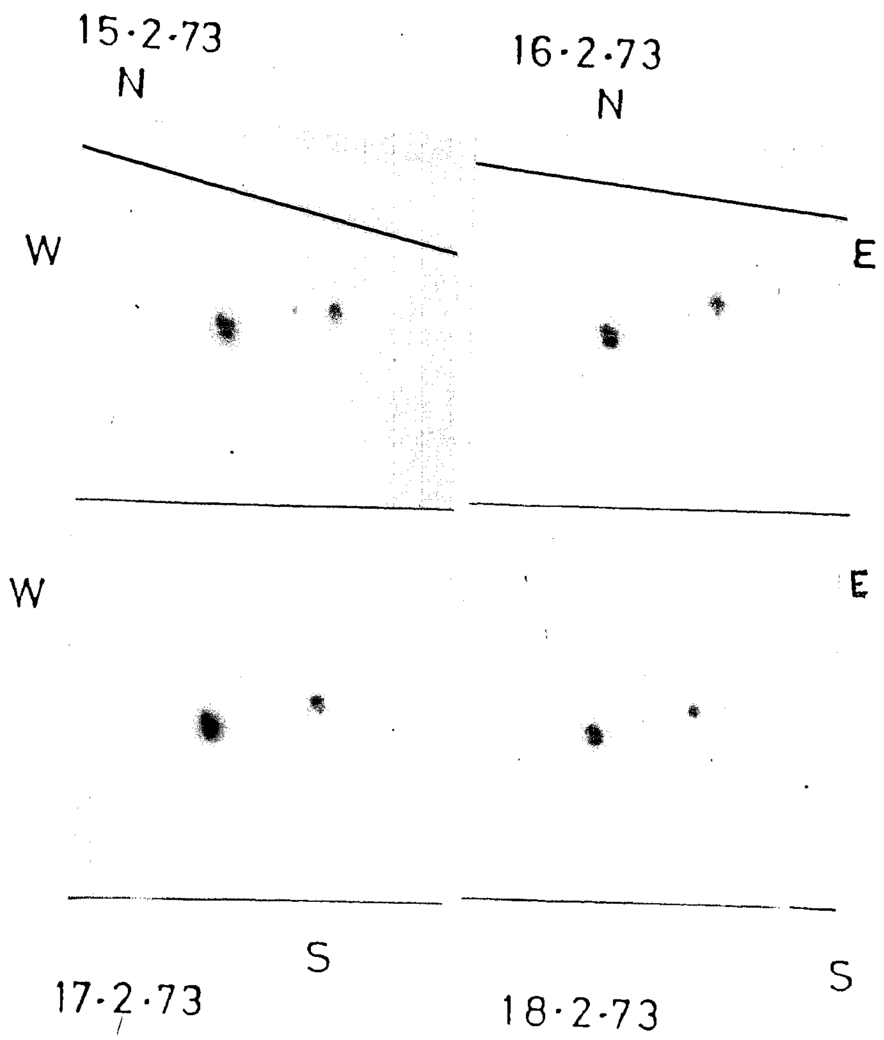
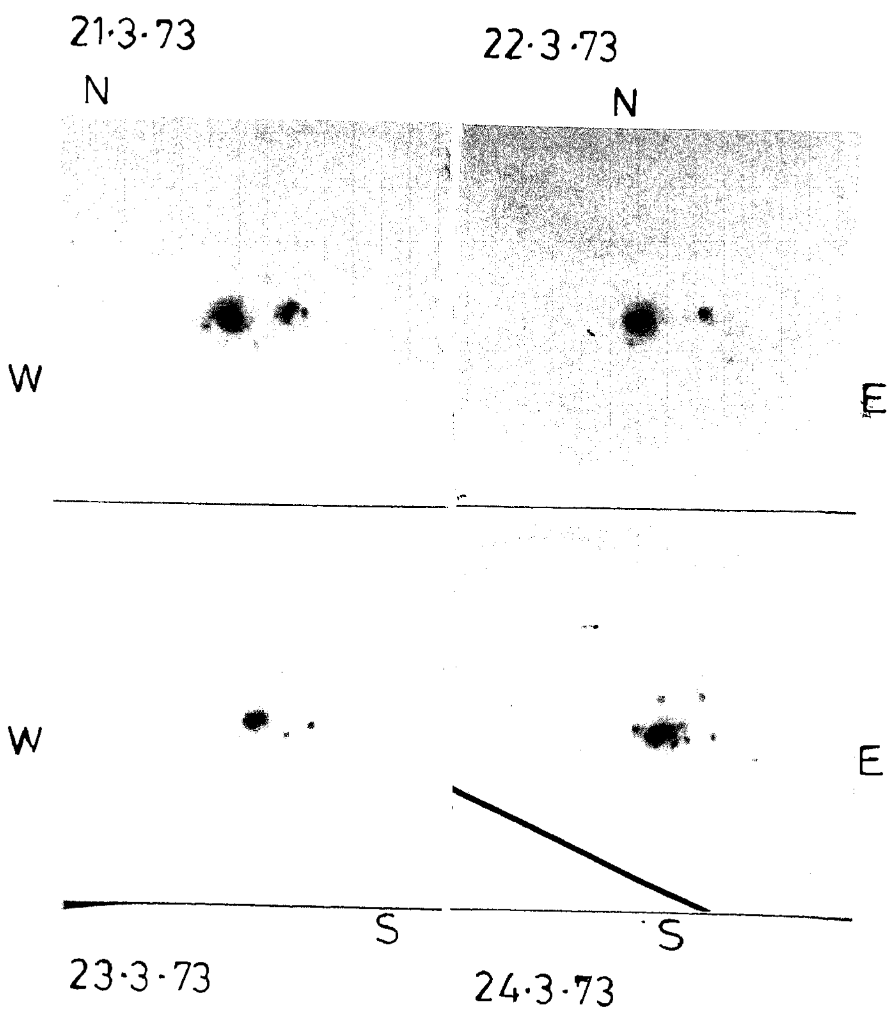


Fig. 4·1 b Fr 111



**(c) 1B Flare on 24 March, 1973** In Figure 4.1b, Frame iii, a spot group from 21 to 24 March, 1973 is shown. The following spot in the group starts decaying from 22 March, 1973. It splits into tiny pores appearing close to the leading spot on 23 March, 1973. A change in the orientation of the spot group is observed on 24 March, 1973 with a shear angle of $21^{o}$. The splitting of the following spot into pores and its rotation lead to a 1B flare at the location 17 N 23 W, a region close to the pores.

**d) Homologous flares** Figure 4.1c shows the evolution of two bipolar spot group S1 and S2 from 10 to 17 March, 1973. The size of the spot group S1 has slightly grown from 10 to 12 March, 1973 with pores emerging between the main sunspots of the group S1 on 12 March, 1973. A rotation of $6^{o}$ is observed on 12 March, 1973 due to change in the orientation of the following spot in the group S1. The emergence of pores coupled with the rotation of the sunspots in the active region lead to a sub flare SF at 07 S 22 E in a region close to the following spot of S1 on 12 March, 1973. The pores in between the main spots in S1 have developed on 13 March, 1973. The size of the following spot of the group S1 has changed and also the pores started decaying on 14 March, 1973. There is a change in the umbral orientation of the following spot S1 on 14 March, 1973 and a over all rotation of $7^{o}$ developed in the main spots of the group S1 compared to the previous day. These changes are responsible for bringing in shear to onset the flare again in the same region of S1 at the location 08 S 09 W on 14 March, 1973. The spot S1 starts splitting from 15 March, 1973 onwards and no appreciable rotation or flare is observed from then onwards.

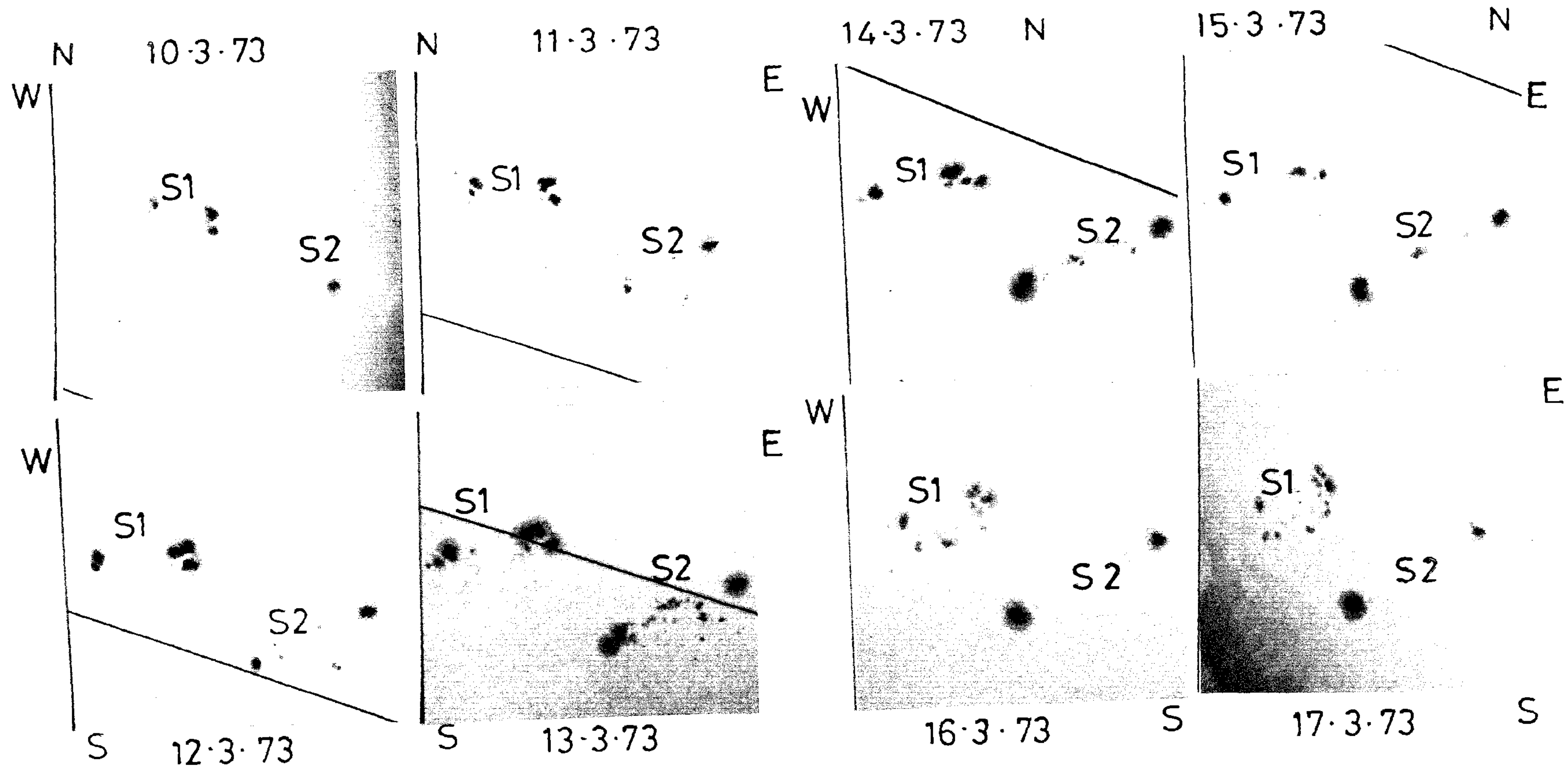



Fig.4.1c. White light photoheliograms from 10 to 17 March, 1973 showing the rotation of sunspots umbrae in spot groups S1 and S2 leading to repetitive flares.

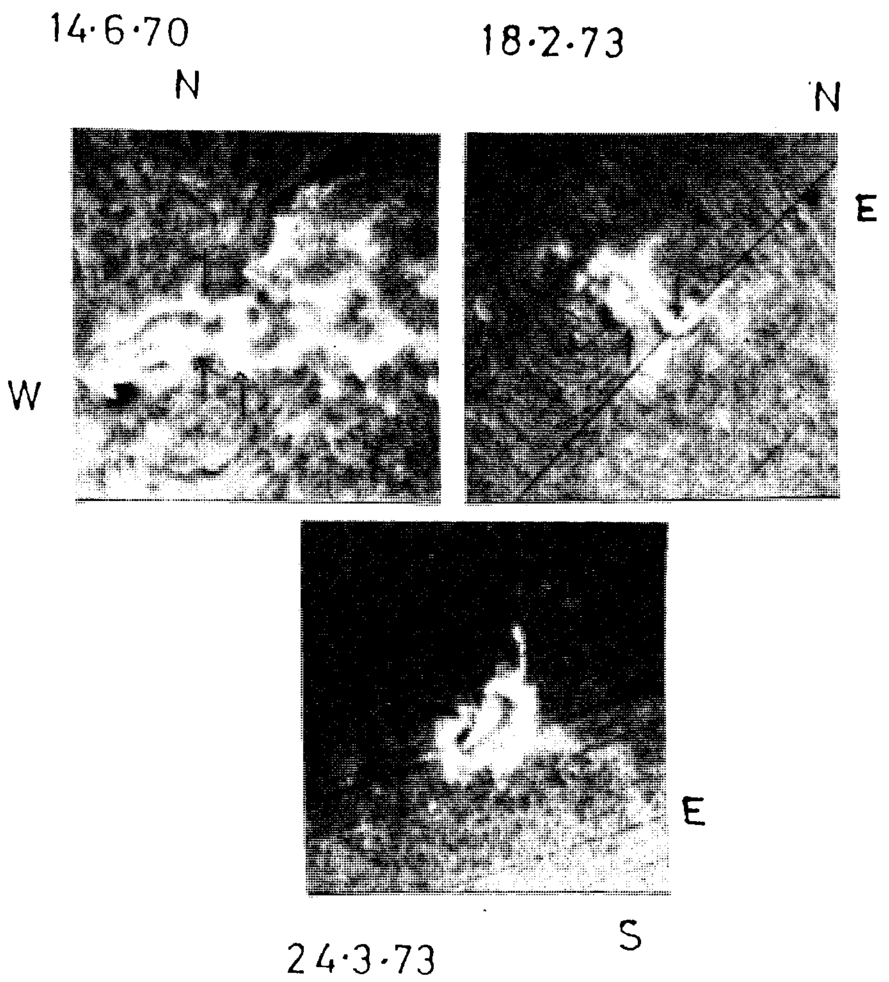



Fig.4.1d. Hα spectroheliograms showing the flares in the regions corresponding to the days in Figure 4.1b. The flare regions are indicated by the arrow marks.

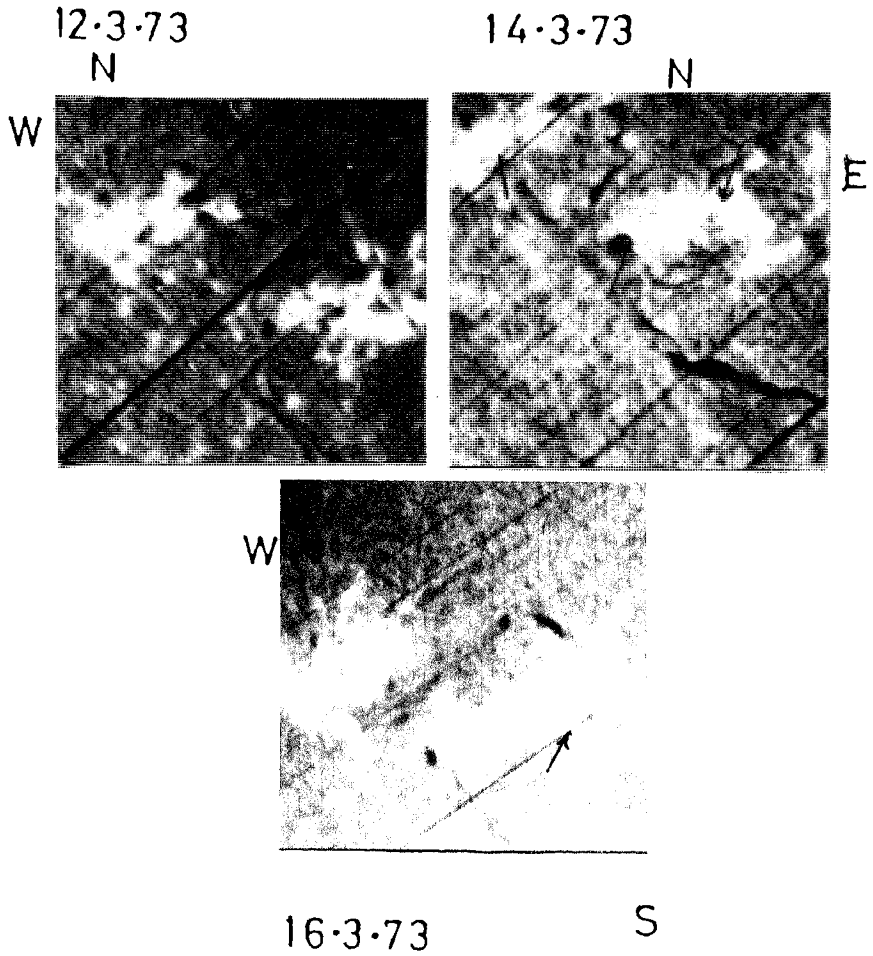



Fig. 4.1e. Hα spectroheliograms showing homologous flares in the region corresponding to the days in Figure 4.1c. The arrow marks indicate the flare region.

The bipolar spot group S2 slowly developed from 11 March, 1973 onwards and has leading and following main spots with pores present in between on 12 March, 1973. The main sunspots of the group S2 have grown on 13 March, 1973. The configuration of the main sunspots of S2 have changed with many pores developed in between on 14 March, 1973 compared to the previous day and also a twist or shear angle of $5^{0}$ is observed in the main spots of the group S2 on 14 March, 1973. The effect of the reorientation of the spot S2 along with its growth triggered a sub flare SB at the location 12 S 05 E in the region linking both the polarities. The number of pores present between the main spots of S2 started reducing from 15 March, 1973 onwards. A rotation of $6^{0}$ is seen in the main spots of S2 on 16 March, 1973. We feel that the disappearance of pores coupled with the rotation of the spots of the group S2 on 16 March, 1973 yielded a flare SN again in the same region between the main spots of S2 at the location 14 S 23 W. There is no marked change or rotation observed on 17 March, 1973 in this spot group S2.

#### 4.1.4. Discussions

Shear in the corona and complexity in the magnetic fields are considered to be necessary conditions for flare production deduced from many observations. It is also well established that the presence of twisted or sheared magnetic loops initiate the flare process (Martens and Kuin 1989). The presence of a prominence indicates the high shear in the corona (Priest 1991). In the absence of a prominence, spot motions and flux interactions are good indicators for the process of pre flare energy storage in excess of potential. The formation of flare related shear is observationally associated with sunspot motions, flux

# TABLE 5

i) Changes in the orientation (shear angle) of sunspots umbrae on various days leading to flares.

| Date | Orientation angle in degrees | Shear angle in degrees (Magnitude of change in orientation angle) |
|---|---|---|
| 12 June, 1970 | 55 | — |
| 13 June, 1970 | 53 | 2 |
| 14 June, 1970 | 66 | 13 Flare |
| | | |
| 15 Feb. 1973 | 80 | — |
| 16 Feb. 1973 | 82 | 2 |
| 17 Feb. 1973 | 85 | 3 |
| 18 Feb. 1973 | 77 | 8 |
| 19 Feb. 1973 | 75 | 2 |
| | | |
| 21 Mar. 1973 | 88 | — |
| 22 Mar. 1973 | 85 | 3 |
| 23 Mar. 1973 | 83 | 2 |
| 24 Mar. 1973 | 62 | 21 Flare |

ii) Changes in the orientation (shear angle) of sunspots umbrae in the spot groups S1 and S2 on various days leading to repetitive flares.

| Date | Orientation angle in degrees for S1 | Shear angle (magnitude of change in orentation angle for S1 | Orientation angle in degrees for S2 | Shear angle (Magnitude of change in orientation angle for S2 |
|---|---|---|---|---|
| 11 Mar. 1973 | 93 | — | 74 | — |
| 12 Mar. 1973 | 87 | 6 Flare | 72 | 2 |
| 13 Mar. 1973 | 85 | 2 | 71 | 1 |
| 14 Mar. 1973 | 78 | 7 Flare | 66 | 5 Flare |
| 15 Mar. 1973 | 76 | 2 | 68 | 2 |
| 16 Mar. 1973 | 75 | 1 | 62 | 6 Flare |
| 17 Mar. 1973 | | | 61 | 1 |

emergence, flux submergence, flux cancellation and vortical motions in emerging flux regions. Two dimensional models of the interaction between neighboring flux system have been presented by Priest and Raadu (1975) and by Tur and Priest (1976) for unequal bipoles and also for the emergence of a bipole into an overlying field. We have attempted here an alternate method to find out the twist or shear developed in a bipolar spot group from the changes observed in the orientation of sunspots with the help of photoheliogram and spectroheliogram data. The shear derived in this manner is completely different from the magnetic shear measured from the vector magnetograms but the role of spot motions or rotations as seen for instance in the relative motion of these spot groups is also a good indicator of the shear developed in the active region. It is felt that the factors like spot growth/decay, pore emergence deform the magnetic structures by changing their orientation. Also it is observed that once the change in the sunspot orientation crosses a threshold value of $5^{0}$, flares are triggered. It is also shown in section 4.1.3(d) that even after relaxation, once the shear crosses the critical value, flares are driven in the same active region. Since the change in the orientation of the sunspots on a specific day play an important role on the evolution of a flare, table 5 gives only the magnitude of angular change over one day. A large shear coupled with complexity of the magnetic structures in the photospheric level may probably place the upper limit for the flare. Finding shear with this method may become difficult when the complexity of the sunspot group increases, but still the rapid rotation that could be observed in the nucleus of the spots may forecast a flare. These observations demonstrate that there exists a correlation between flares and large changes in the orientation angle of sunspots. Simultaneous high resolution observations of photoheliograms and filtergrams may exhibit the changes in penumbral filaments or H$\alpha$

fibril alignments that might corroborate the presence of shear deduced from sunspot motions. Thus it is concluded that small perturbation in the form of shear motion of sunspots may give rise to instability and lead to field line reconnection and rapid relaxation of stressed magnetic field with release of part or most part of the available energy.

**Part - II**

### 4.2. Quiet region flares without filament activation

#### 4.2.1. Introduction

A small percentage of flares also occur in quiet regions with small or no spots (Dodson, and Hedeman 1970). Švestka (1976) proposed the propagation of a slow mode wave from another active region as the cause for triggering a spotless flare. Generally quiet region flares follow the activation and disappearance of dark H$\alpha$ filaments (Moore et al 1979, Moore, and LaBonte 1980). The appearance of a newly emerging flux in the adjoining region is reported as the cause for setting this instability in disrupting the filament (Bruzek 1959, Rust, Nakagawa, and Neupert 1975). Rausaria, Aleem, and Sundara Raman (1992) showed that the plage rotation creates the instability by changing the orientation of the H$\alpha$ filament and subsequently disrupting it in the case of a spotless flare. The quiet region flares without filament activation are rare and exceptional events. In such cases, it would be appropriate to look for the changes in the magnetic field structures at the chromospheric level that may indicate the plasma motions which set the instability to trigger a flare. The changes in the orientation of the plages are discussed here as a measure of shear in the case of few spotless flares that are not associated with any filament eruptions.

**4.2.2. Data reduction**

The plasma motions in the solar atmosphere contribute to an enhancement of magnetic energy over that contained in a potential field. These plasma motions can be inferred from the change observed in the orientations of magnetic field structures in the solar atmosphere. In the solar active regions evolutionary changes take place many hours or even days prior to the flare onset. These changes induce shear. In the case of quiet region flares, the enhanced motion in the active region filament is considered to be outlining the shear that is responsible for flare triggering (Sundara Raman, Gupta and Selvendran 1993). As the spotless flares reported here do not have any filament activity, the development of magnetic shear is inferred from the changes observed in the orientation of the active region plages.

To identify the plasma motions in the solar atmosphere which produce non-potential character to the field lines, the photospheric and chromospheric features are sketched on a sun chart. The sun chart is a rectangular plot of heliographic coordinates with corrections for $B_0$ (solar latitude of disk centre). The photoheliogram and its spectroheliogram mates are enlarged to the same size and the positions of sunspots, calcium K-line plages and $H\alpha$ filaments are sketched on the same sun chart by carefully noting the pole markings. In this way daily synoptic charts are prepared at Kodaikanal which show the daily solar activity. These charts are used in this study to look for the dynamics of active regions. Quiet region flares are usually connected with adjoining plages. It is felt that the changes in the orientation of the neighbouring plages from one day to the next exhibit the relative motion of the

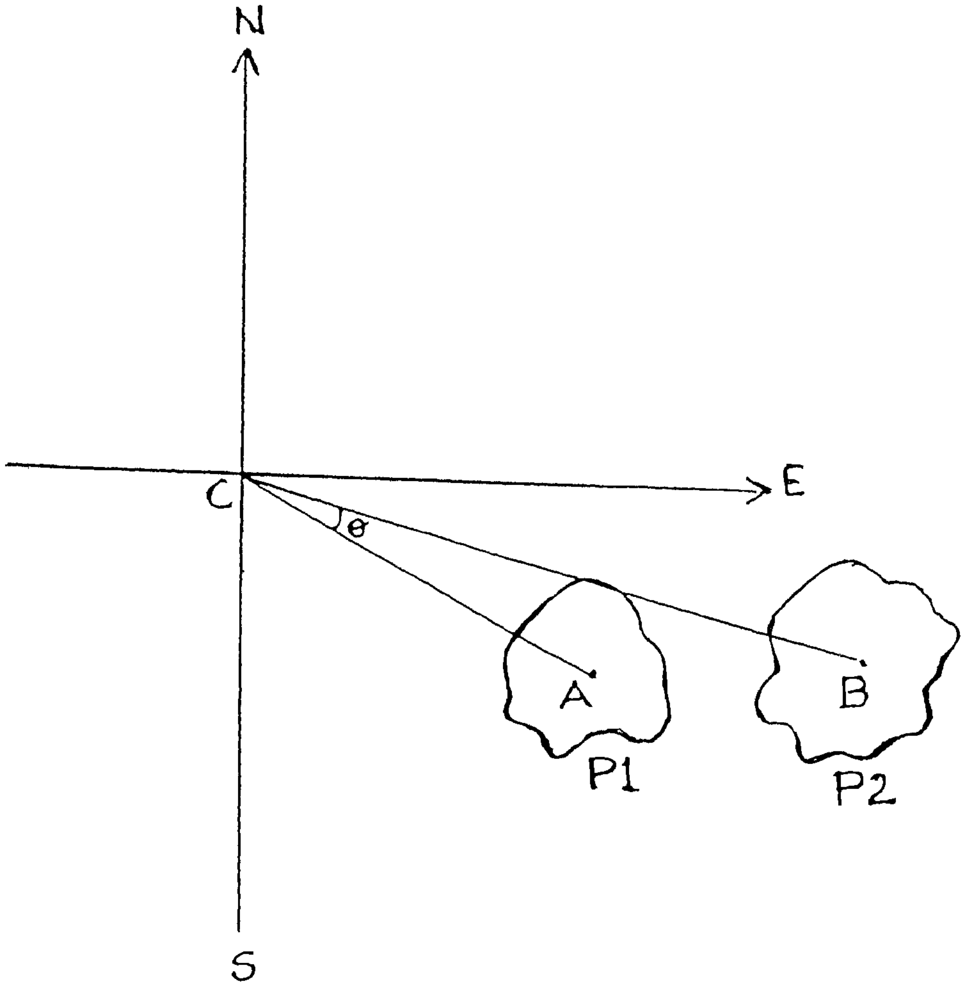



Figure 4.2a.--- Angle 'θ 'gives the direction of the plages P1 and P2 involved in the flare activity with respect to the centre of the sun. Any variation in this angle represents the twist or shear developed in the active region. The line NS represents the solar rotation axis.

plages and can be given as a representative of shear. The rotation axis of the sun is taken as a reference for measurement of angles, as there is no filament present in between the plages which are involved in the flare activity. The following method is adopted to identify the rotation or relative motion of the plages. Figure 4.2a shows the direction of the plages with respect to the centre of the sun. AC and BC are the lines drawn on the sun chart connecting the centres of gravity A and B of the plages P1 and P2 with the centre of the sun C on its rotation axis NS. It is fairly easy to locate the centres of gravity of the plages that are chosen. The direction of the plages P1 and P2 with respect to the centre of the sun on a particular day of observation is given by angle ' $\theta$ ' measured from north towards east direction after applying corrections for foreshortening effects. Any variation in this angle' $\theta$ 'on the next day represents the rotation or relative motion of the plages and indicates the twist or shear developed in the plages P1 and P2. In this way the shear developed due to the changes in orientation of adjoining plages is calculated directly from the sun charts of successive days and the values thus obtained are listed in table 6. The observations show a considerable variation in the shear angle prior to the flare onset. Since too many sun charts are involved in this study, the sequences of photospheric and chromospheric events that are responsible for the flare development are sketched from respective days of the sun charts and are outlined from Figures 4.2b, 4.2c, and 4.2d. Flare regions are marked by arrows in these figures. These sketches provide simultaneous view of the conditions prevailing at different atmospheric levels of the sun prior to flare. Figure 4.2e shows the H$\alpha$ pictures of the flares. Four cases of quiet region flares observed at Kodaikanal are morphologically studied and the details are narrated below.

#### 4.2.3. Results

**a) 1N flare observed on 19 February, 1973** Figure 4,2b shows the activity from 14 to 24 February, 1973. Two pores S1 which appear on 14 February, 1973 evolves as a single spot with multiple nuclei on 16 February, 1973. It has decayed into two pores on 17 February, 1973 and finally disappeared on 18 February, 1973. The plage P1 is covering this spot during its evolution. A 1N flare has resulted on 19 February, 1973 one day after the disappearance of S1. On 19 February, 1973 the plage P1 splits, the sizes of P1 and P2 have changed, and in addition a rotation of $9^0$ is seen in P1 and P2 between 18 to 19 February, 1973. The rotation of the plages P1 and P2 sets the instability resulting a flare in the region covered by the plage P1. The flare region is well above the location of the filament. The plage P3 does not have any resolvable size from 16 to 18 February, 1973 and reappeared along with a group of small plages P4 on 19 February, 1973. The emergence of P3 on 19 February, 1973 has caused a change in the direction of the filament F2 pointing towards the plages P2 and P3.

**b) 1N flare observed on 24 February, 1973** A group of pores S2 appeared on 20 February, 1973 in the region covered by the plage P3 as shown in Figure 4.2b and starts disintegrating during 21 to 24 February, 1973. The plage groups P1 and P2 disappear on 23 February, 1973 and a pore S3 has emerged in the region close to the plage P4 on 24 February, 1973. There is no photoheliogram observation on 23 February, 1973. A rotation of $8^0$ observed in the plages P3 and P4 between 23 and 24 March, 1973 is responsible for triggering a 1N flare in the plage region P4. It is interesting to note that the flare region does not have any filament activity.

Fig. 4.2b

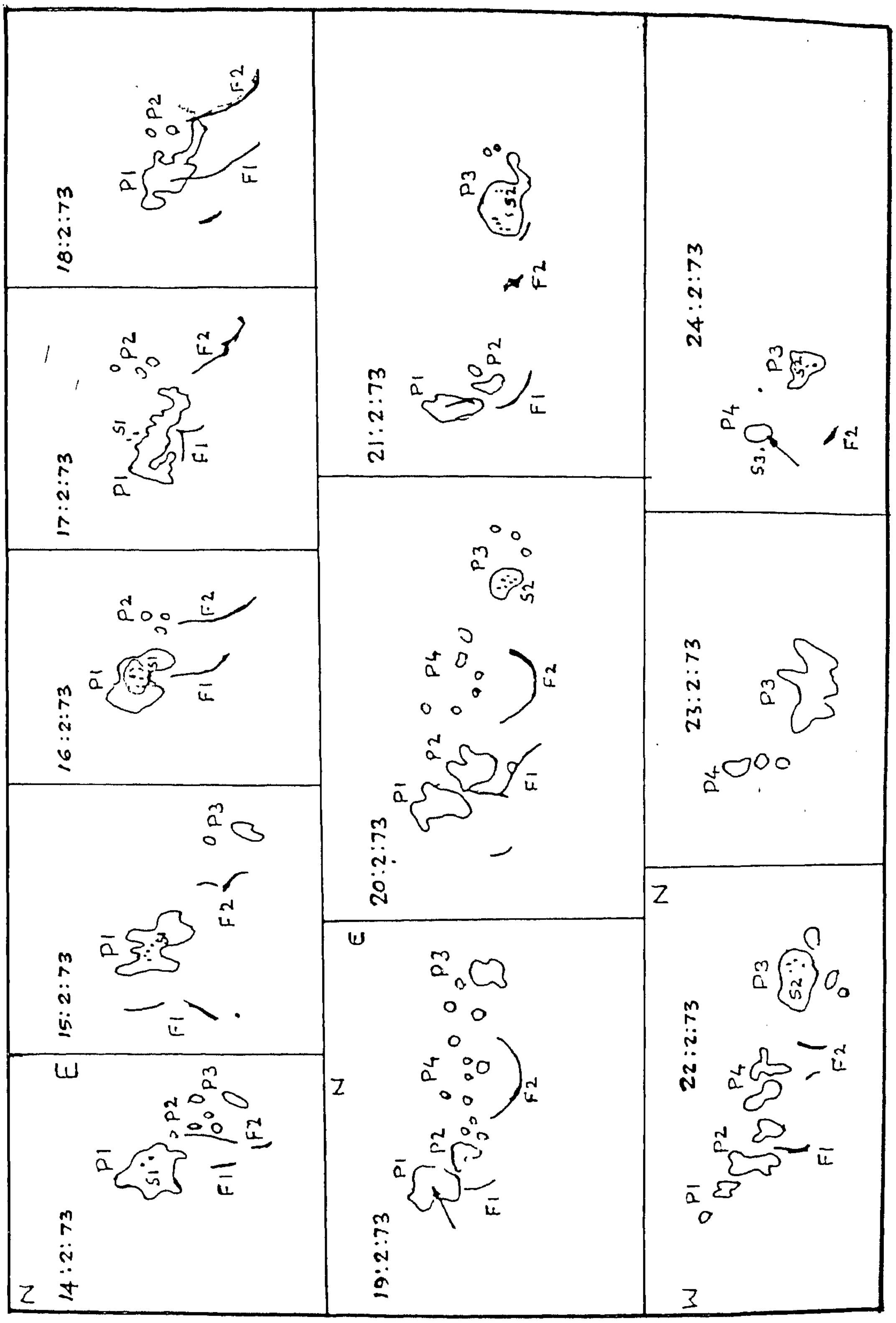



Figure 4.2b to 4.2d. --- Sketches made from the sun charts showing the sequences of events leading to quiet region flares. The positions of sunspots, plages, and Hα filaments are drawn from the respective photoheliograms and spectroheliograms over the sun charts.

**Table 6**

Change in the orientation of the plages as a measure of shear.

| Event | Date | Plage direction in degrees | Magnitude of shear angle in degrees |
|---|---|---|---|
| 1 | 14 Feb. 1973 | 4 | — |
| | 15 Feb. 1973 | — | — |
| | 16 Feb. 1973 | 9 | — |
| | 17 Feb. 1973 | 10 | 1 |
| | 18 Feb. 1973 | 10 | 0 |
| | 19 Feb. 1973 | 19 | 9 |
| 2 | 22 Feb. 1973 | 12 | — |
| | 23 Feb. 1973 | 9 | 3 |
| | 24 Feb. 1973 | 17 | 8 |
| 3 | 14 Feb. 1981 (03:24:44) | 16 | — |
| | 14 Feb. 1981 (08:40:50) | 2 | 14 |
| 4 | 2 Mar. 1983 | 25 | — |
| | 3 Mar. 1983 | 23 | 2 |
| | 4 Mar. 1983 | 5 | 18 |
| | 5 Mar. 1983 | 7 | 2 |

**c) 1B flare observed on 14 February 1981** The activities from 10 to 14 February, 1981 are shown in Figure 4.2c. No spot activity is observed in the plage region P1. A group of pores S appears on 10 February, 1981 and decays into a single pore on 14 February, 1981 in the location of plage P2. A filament F is formed between the plages on 10 February, 1981. The filament structure and position has changed from 10 to 14 February, 1981 due to the interaction of the active regions at P1 and P2. The plage P1 is split at 03:24:44 hours on 14 February, 1981. A rotation of 14° is observed in the split plages of P1 between 03:24:44 hours and 08:40:50 hours on 14 February, 1981 but there is no apprecia-

Fig. 4.2c

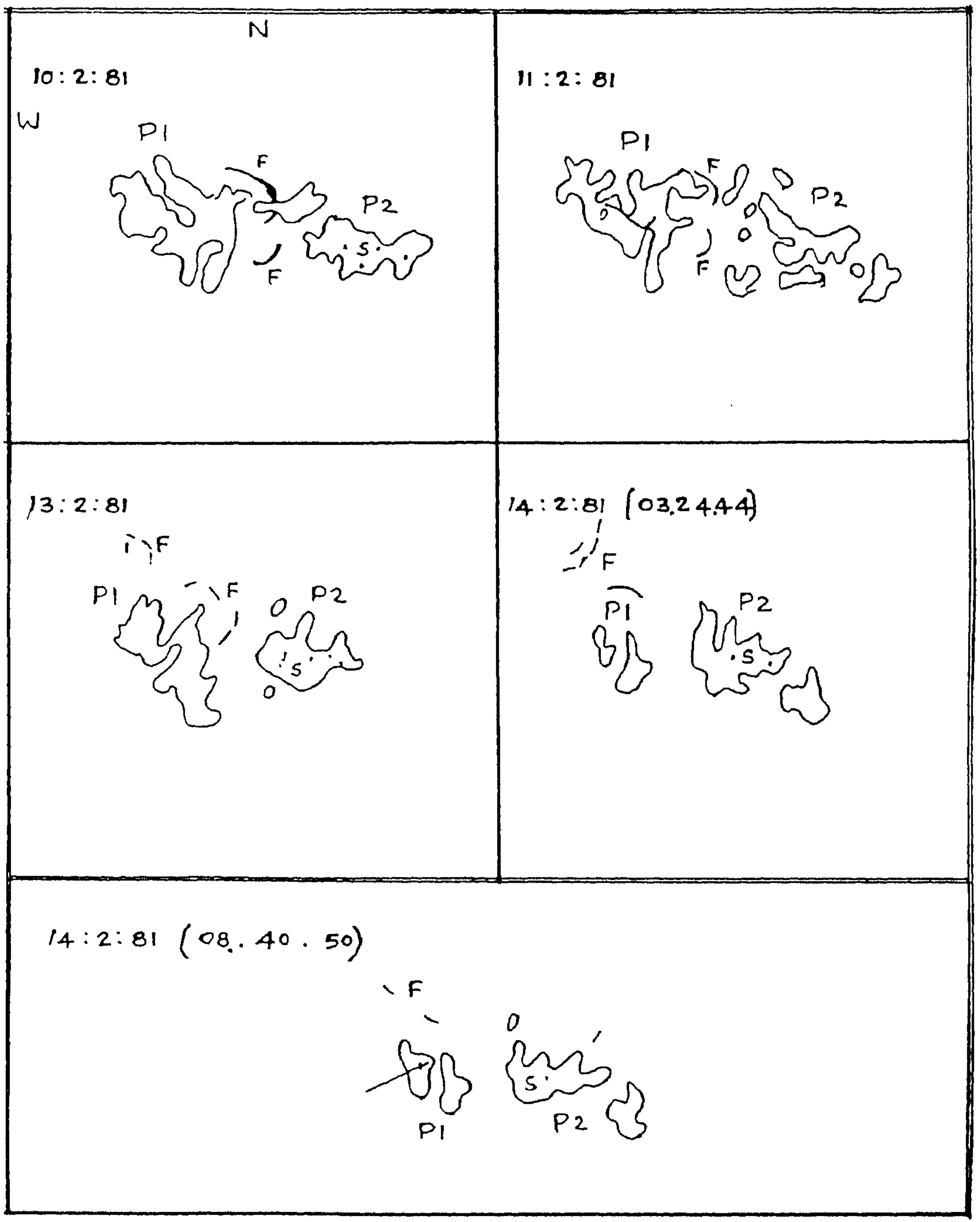
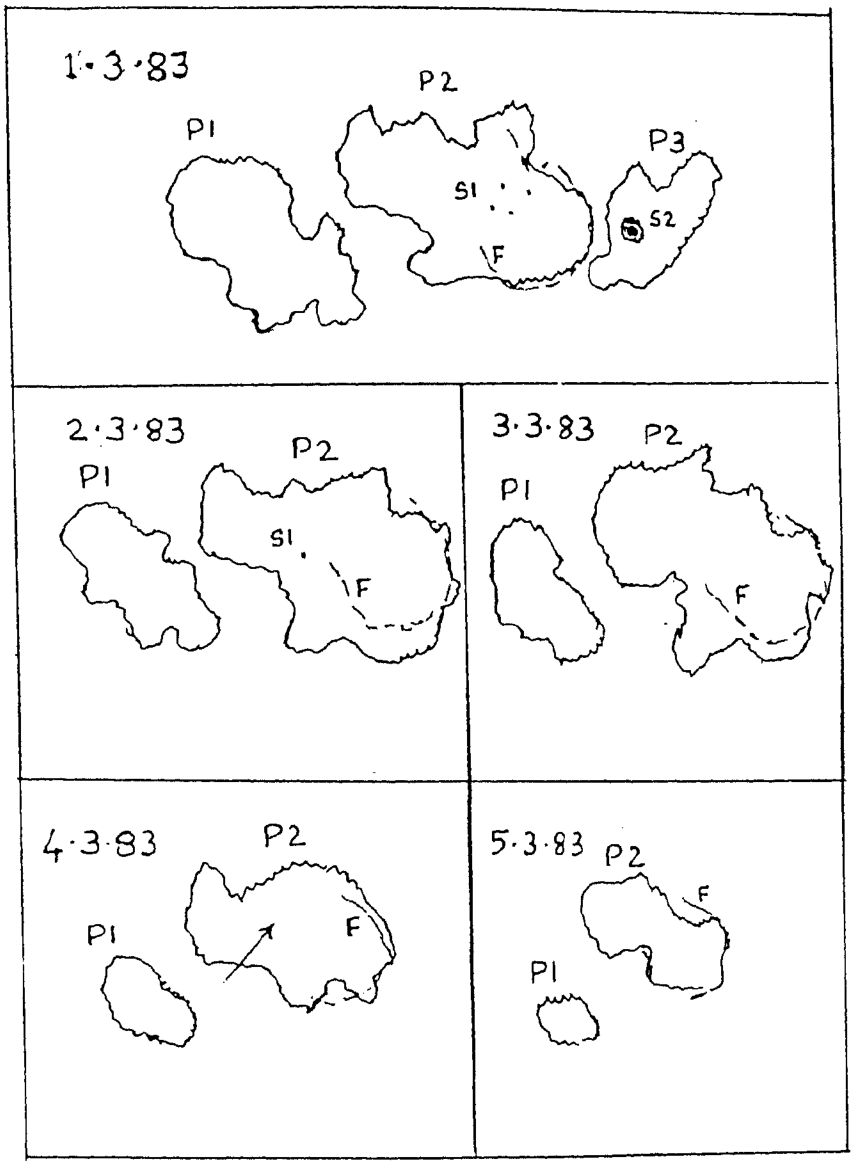

N
W
10:2:81
P1
F
P2
S
F
11:2:81
P1
F
P2
F
13:2:81
F
P1
F
P2
S
14:2:81 (03.24.44)
F
P1
P2
S
14:2:81 (08.40.50)
F
S
P1
P2

Fig. 4.2d


1·3·83
P1
P2
P3
S1
S2
F
2·3·83
P1
P2
S1
F
3·3·83
P1
P2
F
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P1
P2
F

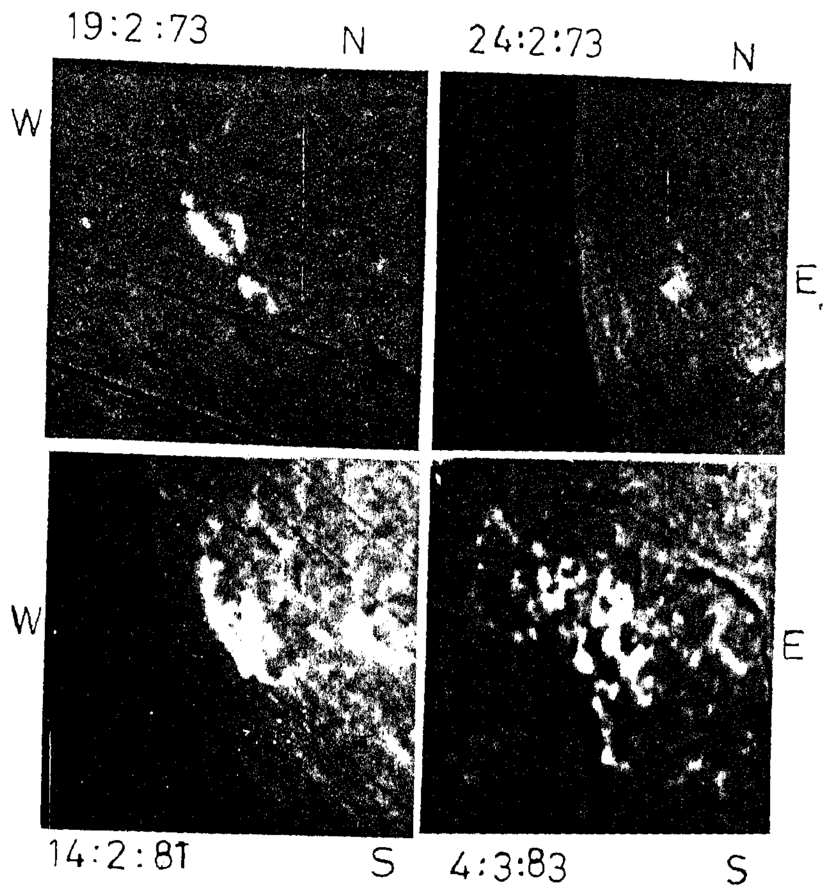



Figure 4.2e. --- Hα pictures of the quiet region flares.

ble rotation between the plages P1 and P2. A 1B flare results in the spotless region on the leading part of the plage P1 at 08:40:50 hours on 14 February, 1981 and is shown by the arrow mark. It is felt that splitting of the plage P1 and its rotation has caused the flare. Figure 4.2e gives the flare in Hα and there is no filament activity seen in the flaring region.

**d) 1B flare observed on 4 March, 1983** The activities from 1 to 5 March, 1983 are shown in Figure 4.2d. A new group of pores S1 has emerged on 1 March, 1983 in the region covered by the plage P2. An Hα filament F is present in the region between the sunspots S1 and S2. Since the flare activity takes place in between the plages P1 and P2, the following plage P3 covering the spot S2 is not shown from 2 March, 1983 onwards in Figure 4.2d. A slight variation in the filament direction from 1 to 5 March, 1983 is due to the interaction of the active regions P2 and P3. The spot S1 is reduced to a single pore on 2 March, 1983 and subsequently disappeared on the next day 3 March, 1983. There is no appreciable rotation of the plages P1 and P2 from 1 to 3 March, 1983 but a change in the orientation of $18^{o}$ is observed in the plages P1 and P2 between 3 and 4 March, 1983. We feel that the large shear developed on 4 March, 1983 is responsible for triggering a 1B flare. The flare is in the spotless region covered by the plage P2 and is shown by the arrow mark in Figure 4.2d. The position of the filament present is away from the flare region and it is not involved in the flare activity.

### 4.2.4. Summary

The cases of quiet region flares associated with plages have been discussed in the part - II of this chapter. The plage corridors or dark lanes which delineate the magnetic neutral line show the opposite polarity plages (Gibson 1973). The flare cases reported here do not have any Hα filament present in the region between the opposite polarity plages, where interaction is taking place. The flare is in a spot free region on 19 February, 1973 and also on 4 March, 1983 but pores were present one day earlier in the same locations, whereas the flare on 14 February, 1981 is evolved totally in a spotless region. The changes in the orientation of the adjoining plages play an important role for the development of magnetic shear, and storage of energy. Hence, the relative motion between the plages are calculated here as a measure of shear. It can be seen from table 6 and also from Figures 4.2b to 4.2d that the same active regions have no flares when the shear value is minimum. Once the shear attains a sufficient value, the instability sets in for the release of stored energy as a flare. For example a $2^{\circ}$ shear on 3 March, 1983 has not yielded a flare whereas a shear of $18^{\circ}$ observed on the next day 4 March, 1983 has resulted a flare. Since the changes in the orientation of the plages on a particular day is responsible for triggering these spotless flares, table 6 gives only the magnitude of the shear angle. It suggests that two oppositely directed fields in the form of plages are pushed together in a steady motion, as a result the lines of force reconnect in a neutral plane and the flare is triggered. We conclude that it is possible to predict the flare occurrences by continuously monitoring the changes that are taking place in the active regions. In the cases reported here, perturbations due to the relative motion of neighbouring plages in an active region play a crucial role in triggering these quiet region flares.

# CHAPTER 5

# EFFECTS OF MAGNETIC SHEAR ON PROMINENCE EVOLUTION

## 5.1. Introduction

Prominences are the exotic objects in the corona. The details of their formation, magnetic structure and support still are not clearly understood (Priest 1989). Recently it has been shown observationally that the prominences posses fine structures and consists of a large number of threads (Zirker 1989). Various attempts have been made in the past to understand prominence characteristics (Tandberg-Hanssen 1974, Priest 1989, Hirayama 1985, Zirker and Koutchmy 1990). In the present analysis, the problem of thread formation in the prominences, involving plage and sunspot rotations as the cause for the same is addressed.

Prominences are H$\alpha$ filaments in projection. However, there is no one to one correlation between H$\alpha$ filaments and the subsequent formation of prominences observed. Using Kodaikanal Observatory H$\alpha$, Ca II K spectroheliograms and white light photoheliogram data for two events from 12 to 19 February, 1992 and 6 to 17 March, 1992, an attempt is made to find out the cause which results in the twisting of H$\alpha$ filament to acquire its inverted U-shape. The analyses of the data show that that rotations of plage and spots bring in non-potentiality in the magnetic structure of the filament. This in turn develops a shear and kink in the filament at a point where rotation of the plage is significant. This shear/kink keeps developing with the evolution of the plage and spot thereby imparting a curved structure to the filament. When the twist or shear reaches a critical stage it becomes untenable, and makes a quiescent prominence active and the fine structure threads in the filament becomes more easily observable. The Hα thread linking the main filament to spot probably works as a channel for the supply of materials to the prominence.

The Hα and Ca II K spectroheliograms showing the development of filament and plage orientations on various days for the event 12 to 19 February, 1992 are given in Figures 5.1a and 5.1b, respectively, whereas the photoheliograms for the same event are given in Figure 5.1c. The details of the Hα, Ca II K spectroheliograms and white light photoheliograms for the event 6 to 17 March, 1992 are given in Figures 5.2a, 5.2b, and 5.2c, respectively.

### 5.2. Event 12 to 19 February, 1992

The dark Hα filament appeared at the location S20 E55 on 11 February, 1992. The filament was well outside the sunspot region. The filament was thick and curved on 12 February, 1992 (Figure 5.1a, Frame i). It became thin and straight on 13 February, 1992. On 15 February, 1992 fibril structures appeared to be connecting the filament with a nearby sunspot region. On 16 February, 1992, fibrils took the form of small Hα threads, and the connecting link between the filament and the sunspot became visible and prominent. The plage regions surrounding the filament underwent rotation producing a noticeable, well developed, inverted U-shape kink in the filament (Figure 5.1a Frame v). The sunspot connected to the filament through a small thread also underwent rotation (Figure 5.1c, Frames iii and iv). On 17 February, 1992 the plage and spot orientations changed further and the curved shape became much more prominent. The

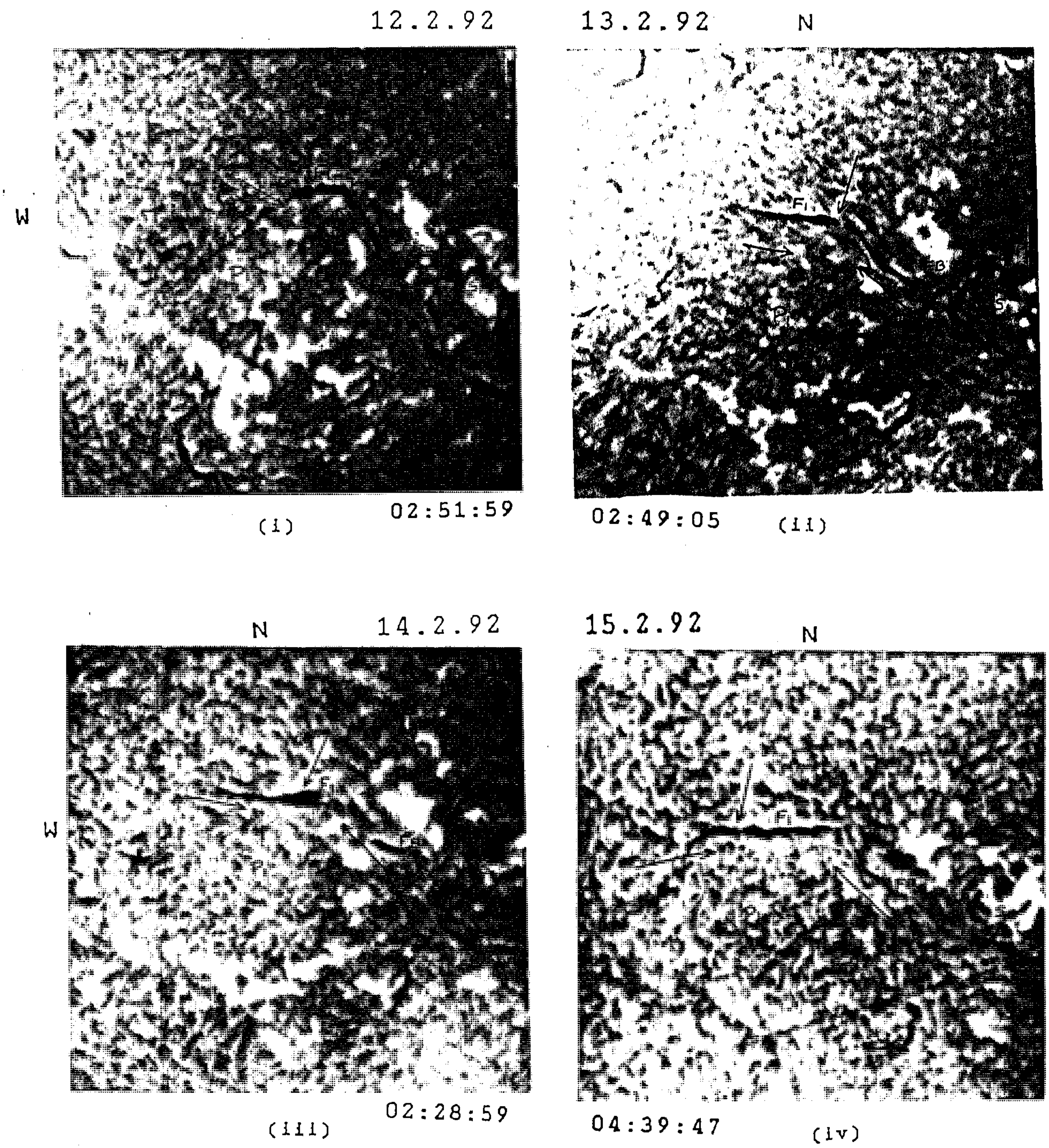
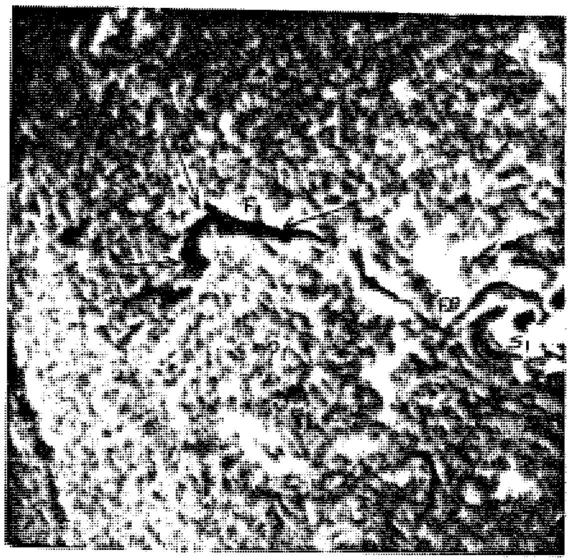



Fig.5.1a. Hα spectroheliograms from 12 to 19 February, 1992 showing the variations in the orientations of the filament and associated plage region marked by arrows. The evolution of the fibril structure indicated by FB can also be seen.

16.2.92 N

W




02:21:05 (v)

17.2.92 N


02:32:22 (vi)

18.2.92 N

W


02:49:27 (vii)

19.2.92 N

03:01:00 (viii)

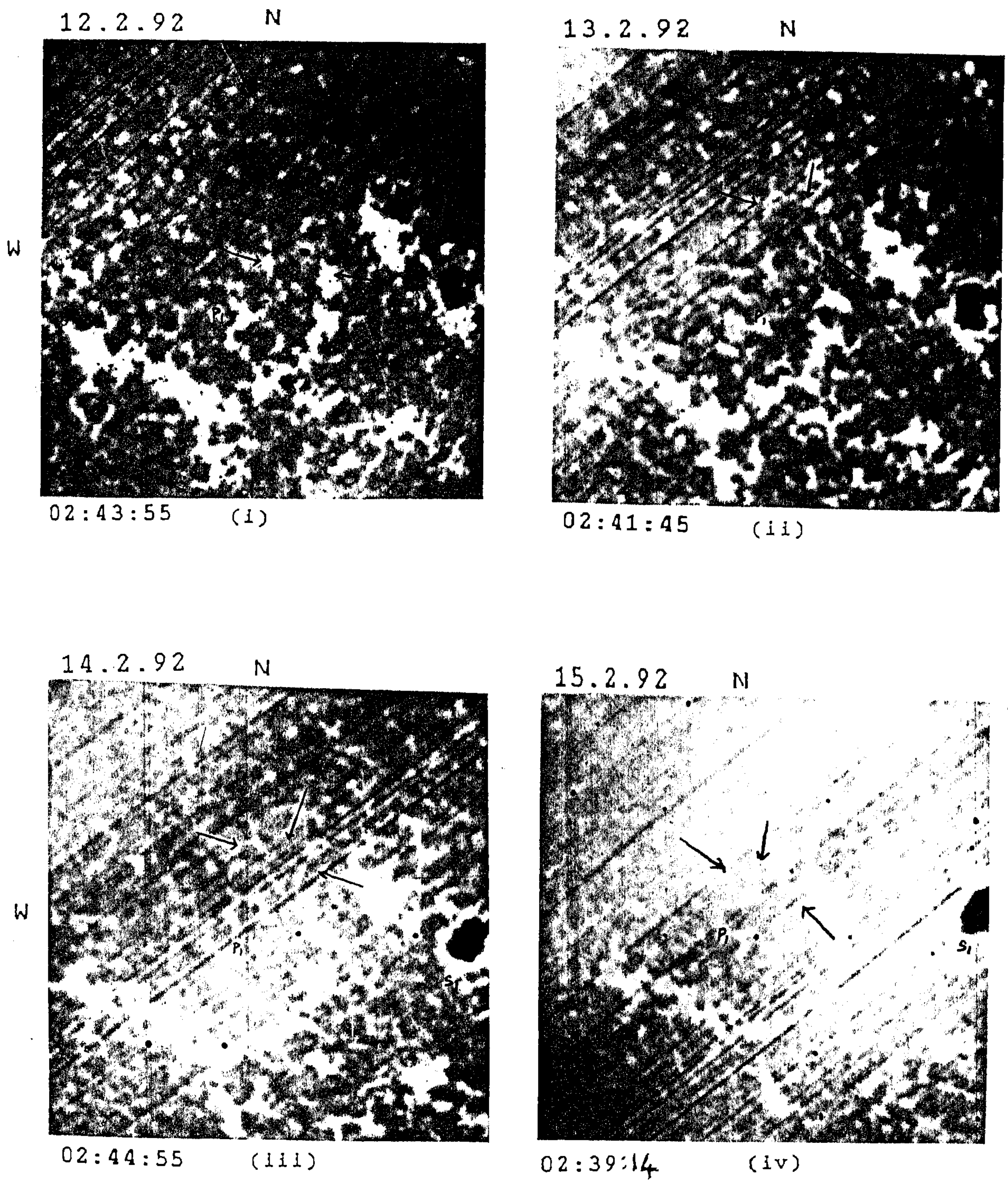


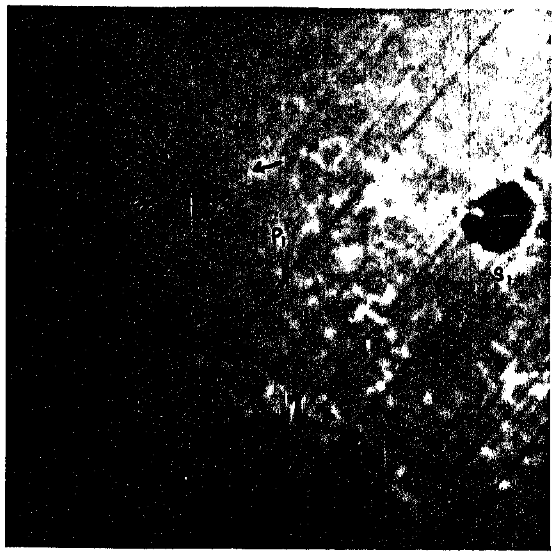

Fig.5·1 b. Ca II K spectroheliograms corresponding to the days in Figure 5·1(a). The main plage is marked by P1 whereas the portion of the plage undergoing change is marked by an arrow.

16.2.92 N

W

02:39:07 (v)

17.2.92 N



02:51:47 (vi)

18.2.92 N

W

04:04:00 (vii)

19.2.92 N

03:15:00 (viii)

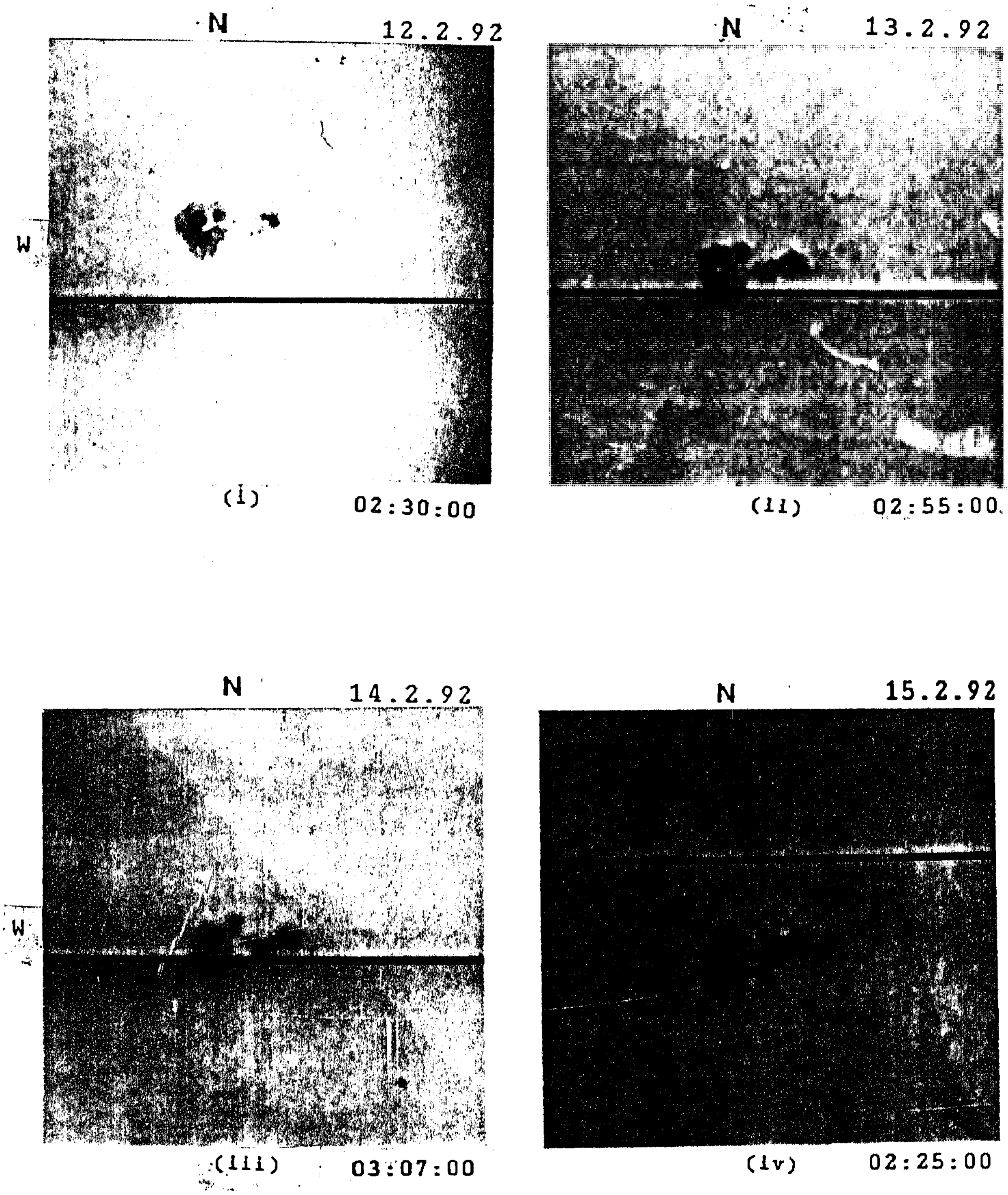
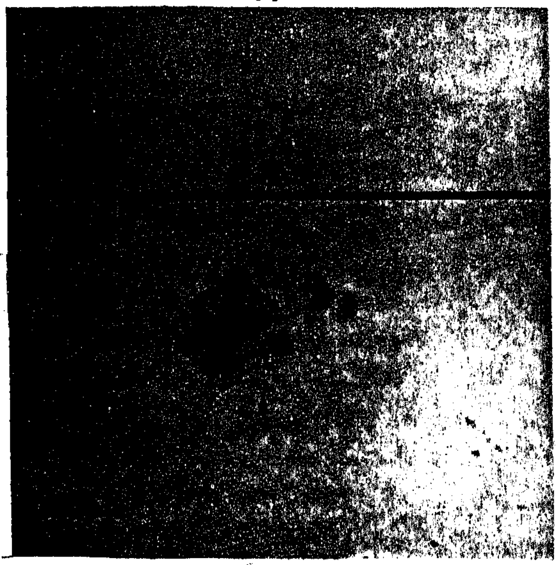



Figure 5·1c. White-light photoheliograms showing the changes in the rotation of the sunspots umbrae corresponding to the days in Figure 5·1(a).

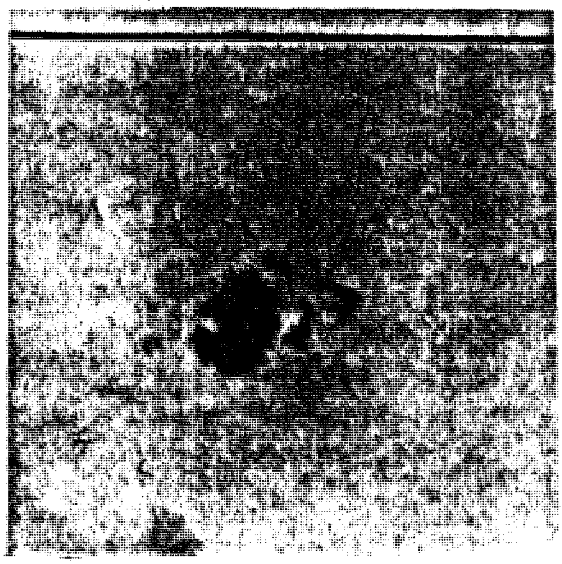
16.2.92 N

W



02:35:00 (v)

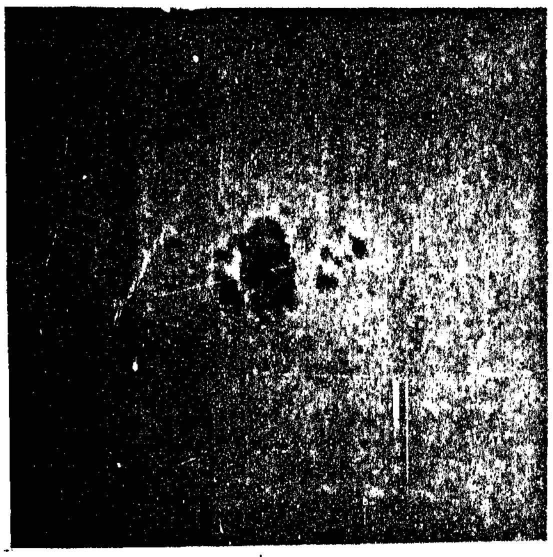
17.2.92 N



02:35:00 (vi)

18.2.92 N

W



02:45:00 (vii)

19.2.92 N

02:25:00 (viii)

front position of the filament became very thick in appearance with a further change in the orientation of the plage on 18 February, 1992, and the inverted U-shape nature became much more discernible. At the same time the thick portion started breaking into strands (Figure 5.1a, frame vii) and on 19 February, 1992 the prominence appearance is visible on the disk.

### 5.3. Event 6 to 17 March, 1992

The dark Hα filament first appeared on 6 March, 1992 at location N05 E75. On 6 March, 1992 the filament was broken into parts. However, the parts were connected with fibrils (Figure 5 2a, Frame i). The plage intensity associated with the filament was very feeble. On 8 March, 1992 the filament became thick and all the parts of the filament seemed interconnected (Figure 5.2a, Frame iii). The plage area grew, and the intensity of the plage also increased. On 10 March, 1992 a portion of the filament became more compressed and almost straight with 2-3 small kinks. The connected plage area grew further and broke into smaller parts. The filament also appeared to be linked to a nearby spot with fibrils. On 11 March, 1992 the connection of the filament with the spot became more pronounced and the fibril structures took the form of the Hα thread (Figure 5.2a, Frame vi). The elongation underwent significant change in the orientation (Figure 5.2b, Frame vii marked by arrow). This produced a kink in the Hα filament away from the position of the kinks already present (Figure 5.2a, Frame vii marked by a double arrow). On 13 and 14 March, 1992 the plage and spot underwent further rotation, as a result the kink became more pronounced, resembling an inverted U-shape on 14 March, 1992 (Figure 5.2a, Frame ix). With further increase in the rotation of plage on 15 and 16 March, 1992, the prominence appearance became more pronounced and visible. On 15 March, 1992 the

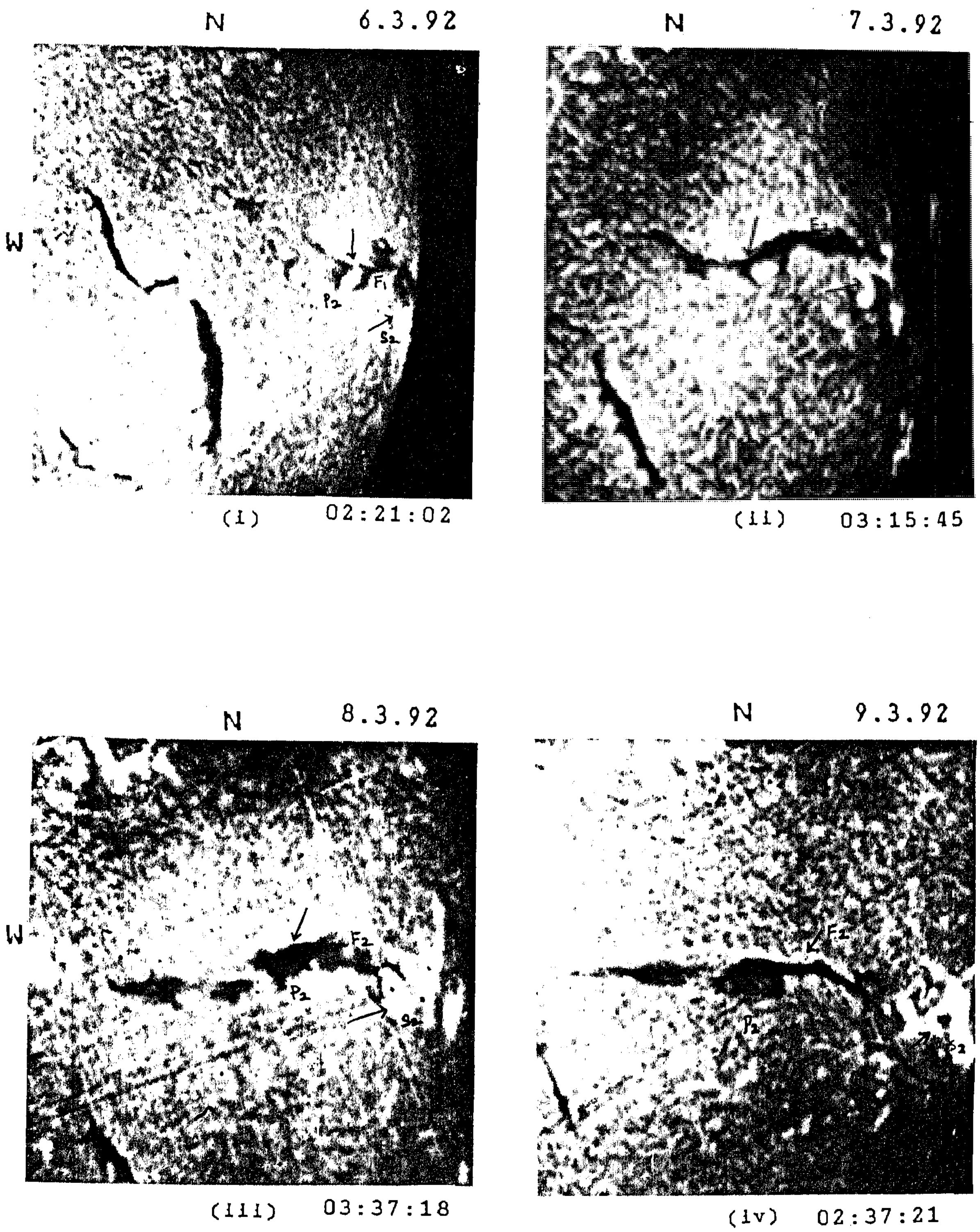



Fig. 5.2a. Hα spectroheliograms from 6 to 17 March, 1992 showing the variations in the orientations of the filament and associated plage region marked by arrows. The evolution of the fibril structure indicated by FB2 can also be seen.

10.3.92 N

W


04:34:41 (v)

N 11.3.92


(vi) 02:31:45

12.3.92 N

W

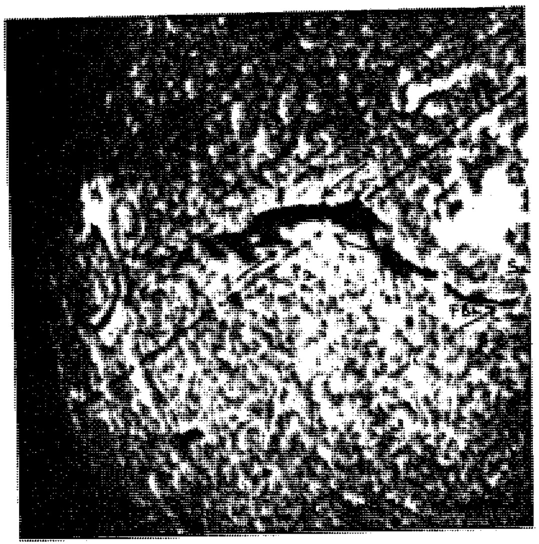
02:22:37 (vii)

N 13.3.92


(viii) 02:32:10

14.3.92 N

W




02:20:32 (ix)

15.3.92 N


02:03:13 (x)

16.3.92 N

W


03:34:34 (xi)

17.3.92 N


03:50:52 (xii)

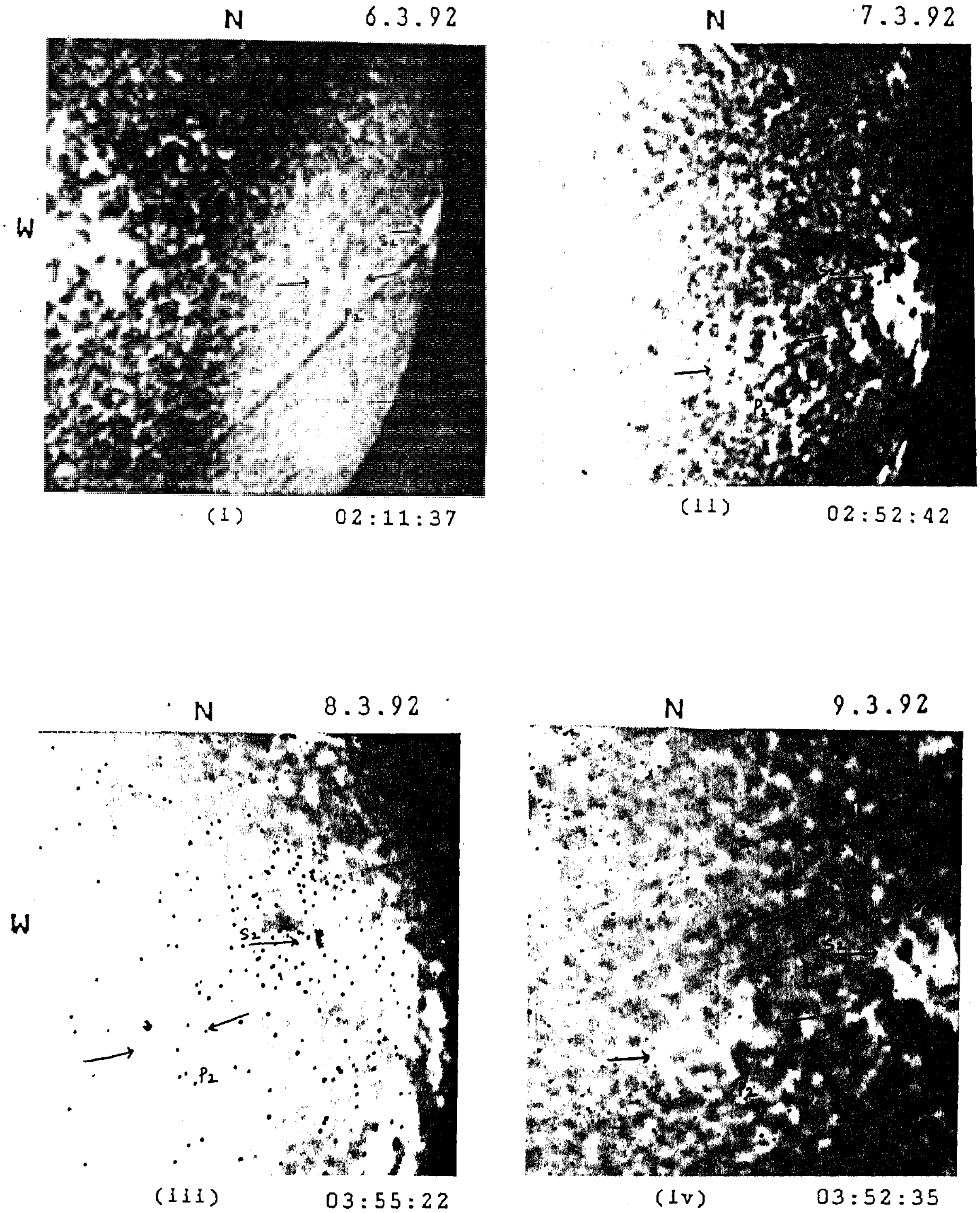
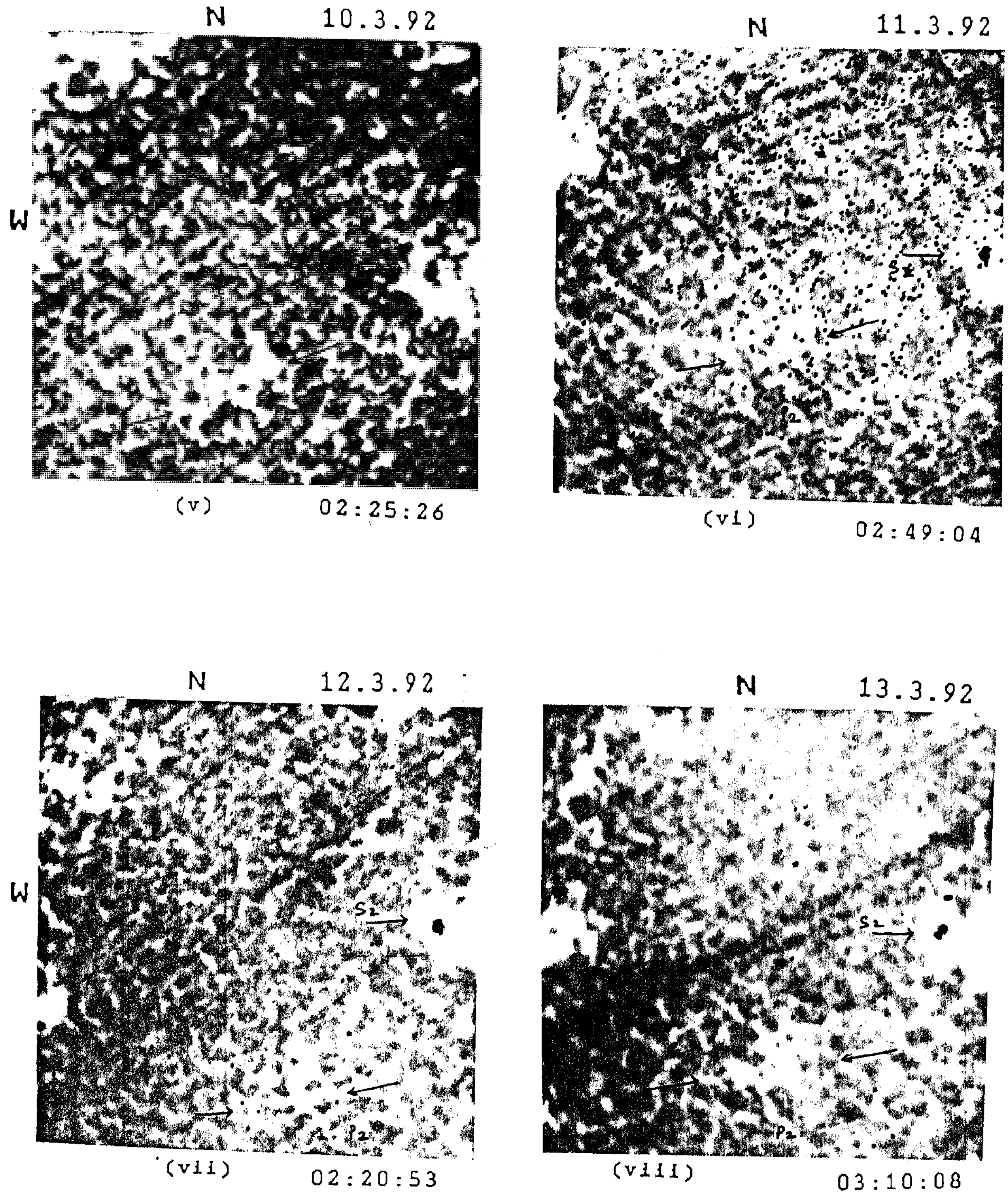
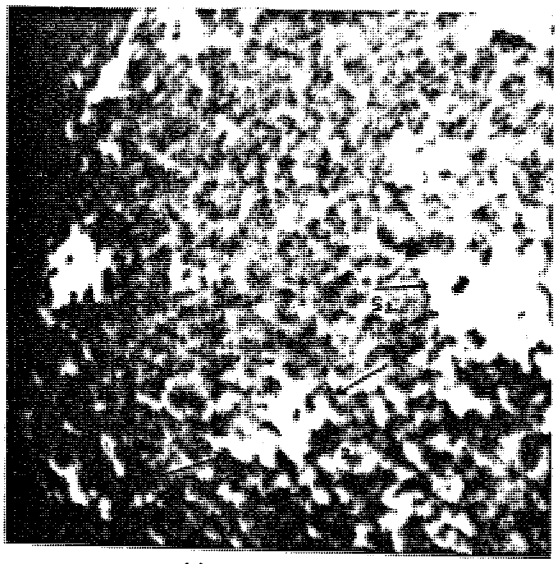



Fig.5·2 b. Ca II K spectroheliograms corresponding to the days in Figure 5·2(a). The main plage is marked as P2 whereas the portion of the plage undergoing change is marked by arrow.


N
10.3.92
W
(v)
02:25:26
N
11.3.92
S2
P2
(vi)
02:49:04
N
12.3.92
W
S2
P2
(vii)
02:20:53
N
13.3.92
S2
P2
(viii)
03:10:08

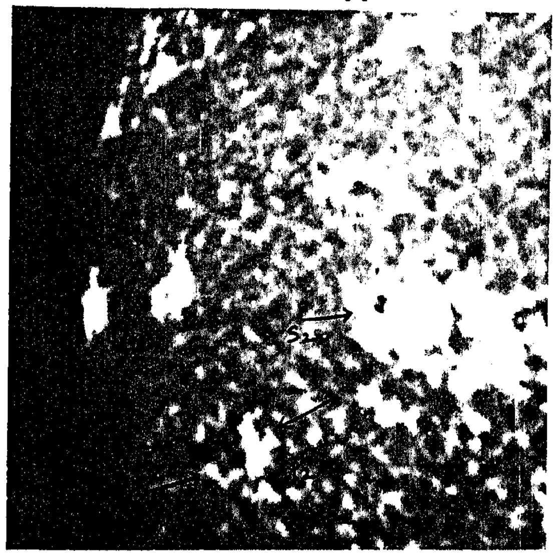
14.3.92 N

W



(ix) 02:11:48

15.3.92 N



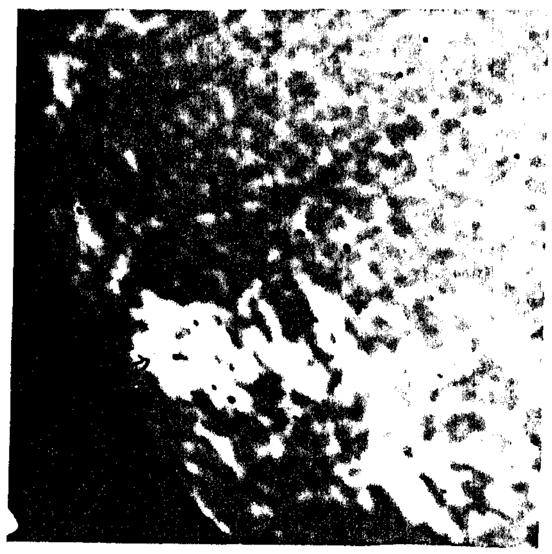
(x) 02:07:15

16.3.92 N

W

(xi) 02:50:51

17.3.92 N



(xii) 04:11:13

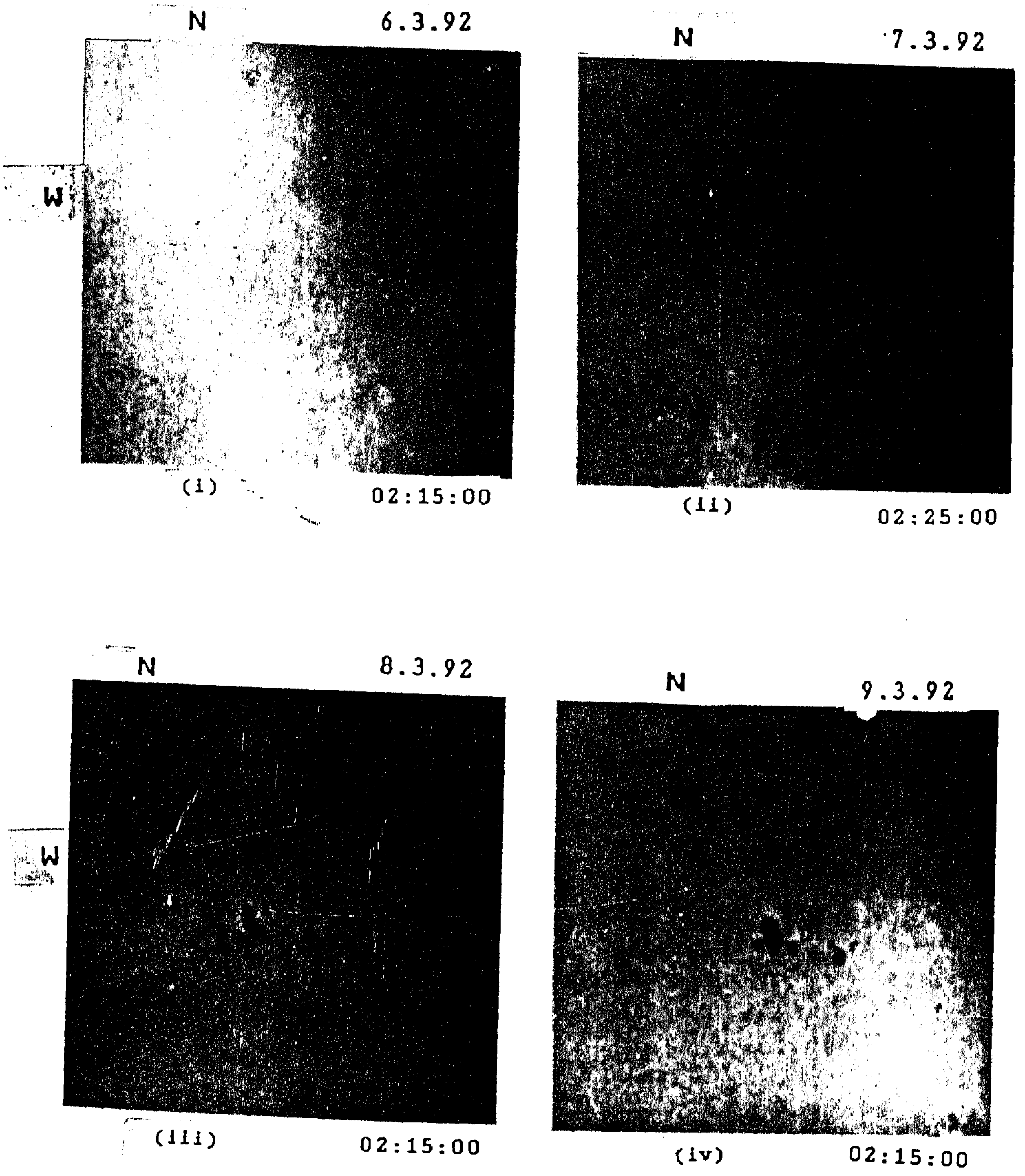
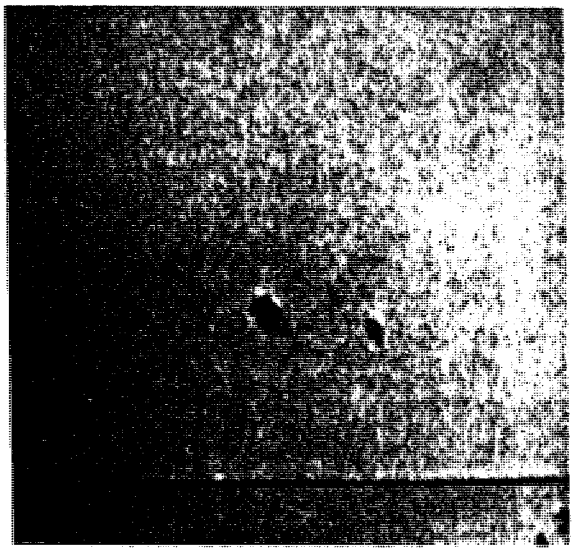



Fig.5·2 c. White-light photoheliograms showing the changes in the rotation of the sunspots umbrae corresponding to the days in Figure 5·2(a).

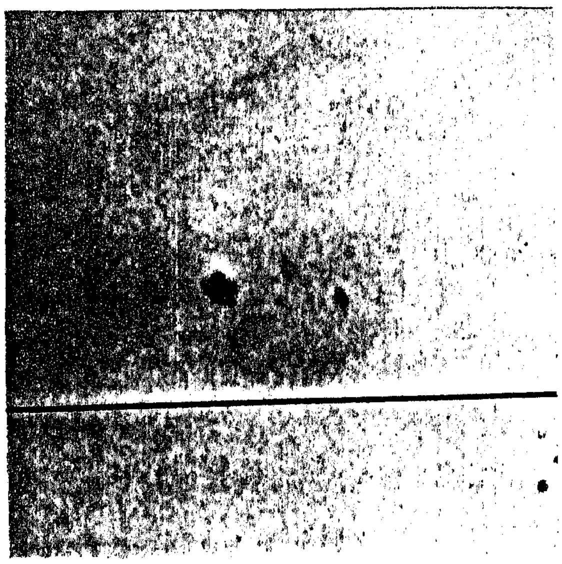
N 10.3.92

W



(v) 02:15:00

N 11.3.92



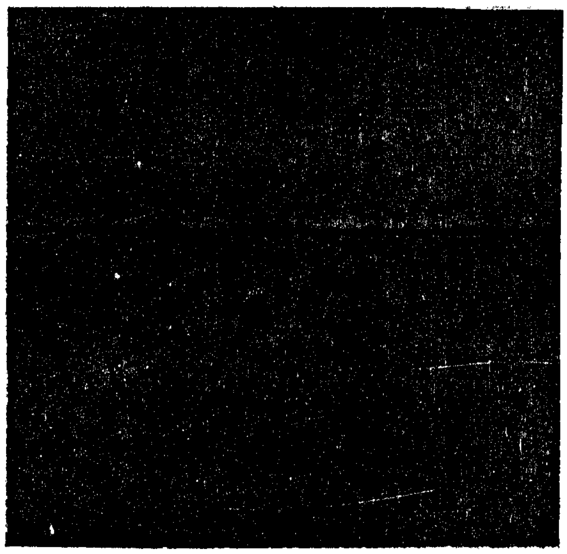
(vi) 02:28:00

N 12.3.92

W

(vii) 02:32:00

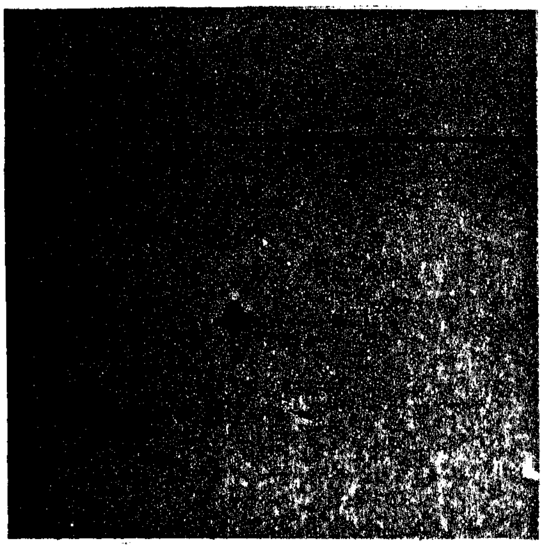
N 13.3.92



(viii) 02:25:00

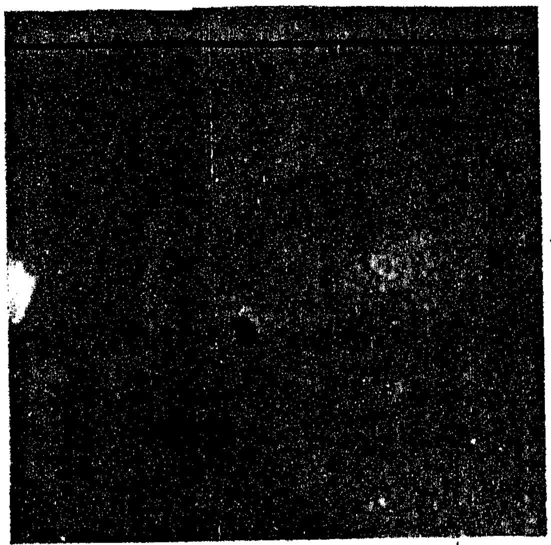
14.3.92 N

W



(ix) 02:15:00

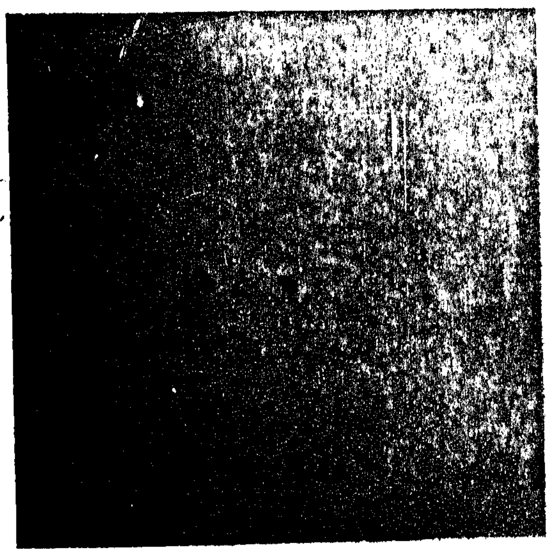
15.3.92 N



(x) 02:10:00

16.3.92 N

W



(xi) 02:10:00

17.3.92 N

(xii) 02:00:00

## TABLE 7

Changes in the orientations (shear angle) of the Ha filament on various days leading to prominence appearance

| Event I | | | | Event II | | | |
|---|---|---|---|---|---|---|---|
| **S.No.** | **Date** | **Value of the shear angle** | **Change in the shear angle** | **S. No.** | **Date** | **Value of the shear angle** | **Change in the shear angle** |
| 1 | 12 Feb. 1992 | $40^0$ | Initial value of the shear angle | 1 | 6 March. 1992 | Filament at the limb | |
| 2 | 13 Feb. 1992 | $30^0$ | $5^0$ | 2 | 7 March. 1992 | $40^0$ | Initial value of the shear angle |
| 3 | 14 Feb. 1992 | $35^0$ | $5^0$ | 3 | 8 March. 1992 | $45^0$ | 5o |
| 4 | 15 Feb. 1992 | $20^0$ | $15^0$ | 4 | 9 March. 1992 | $40^0$ | 5o |
| 5 | 16 Feb. 1992 | $10^0$ in opposite direction | $30^0$ | 5 | 10 March. 1992 | $35^0$ | 5o |
| 6 | 17 Feb. 1992 | $2^0$ in opposite direction | $8^0$ [a] | 6 | 11 March. 1992 | $42^0$ | 7o |
| 7 | 18 Feb. 1992 | $20^0$ in opposite direction | $18^0$ | 7 | 12 March. 1992 | $50^0$ | 8o |
| 8 | 19 Feb. 1992 | Appearance of the prominence | | 8 | 13 March. 1992 | $42^0$ | 8o |
| | | | | 9 | 14 March. 1992 | $15^0$ | 27o |
| | | | | 10 | 15 March. 1992 | $30^0$ | 15o |
| | | | | 11 | 16 March. 1992 | $40^0$ in opposite direction | 70o |
| | | | | 12 | 17 March. 1992 | Filament at the limb and the prominence appearance | |

[a] The change in the shear angle looks small after reaching the maximum change, but the variations are in the opposite direction.

orientation of the filament had undergone significant change. This change in the orientation of the filament brings in non-potentiality in the field lines, which in turn develops shear and activates the filament.

## 5.4. SUMMARY

To quantify the role of shear, we have evaluated it on various days for the two events. It is argued that the value of shear can be derived from using dark Hα filaments as a proxy for the magnetic neutral line. The filaments are situated well outside the spot regions and anchored between two opposite polarity plages (Figures 5.1a and 5.2a). In the absence of magnetogram data, following Gibson (1973, p.51), the opposite polarity plage regions are taken as the reference point and the variation of shear angle using dark Hα filaments, from one day to the next with respect to the centre of gravity of the plage regions, is calculated. The values of shear angle derived in this way on various days for the two events are given in table 7.

A look at table 7 shows that initially the change in the orientations of the two filaments are small. However, they keep increasing regularly and become very significant on the day when the curved structure of the filament becomes pronounced. In the first event this happened on 15 and 16 February, 1992 (Figure 5.1a, Frames iv and v) and the corresponding changes in the shear angles are $15^{\circ}$ and $30^{\circ}$ , respectively, while in the second event, the variations in shear angles became pronounced on 14 and 16 March, 1992 (Figure 5.2a, Frames ix and xi) having the values $27^{\circ}$ and $70^{\circ}$. The change in the shear angle for the second event on 16 March, 1992 is very high ($70^{\circ}$ ). However, the filament is on the limb and even after applying the secant correction, the value still remains large. The total changes in the shear angles for the two events, from the day of their appearance close to the eastern limb and between their passage to the western limb, are $80^{\circ}$ and $60^{\circ}$, respectively. Thus it can be concluded that a cumulative change in the filament orientation coupled with the variations in spot and plage rotations on specific days play an important role on the evolution of a filament as a prominence. The shear angle, after reaching the critical value, makes the appearance of the fine structure in the filament more discernible (Figure 5.1a, Frame vii marked TH and Figure 5.2a, Frame xi). Working with some more events may evoke a better insight and probably confirm this result. More detailed studies concerning quiet and active prominences and the role of shear is in progress and will be reported elsewhere.

# CHAPTER 6

# EVERSHED VELOCITY IN BIPOLAR SUNSPOTS

## 6.1. Introduction

### 6.1.1. Observations of sunspots

Sunspots, the active regions observed on the face of the Sun are due to the manifestation of solar magnetism. They posses magnetic fine structures of scales beyond the present available resolution. Sunspot phenomenon is the most striking structure on the solar disk from the beginning of telescope observations. It attracted attention first time in 1611 and it does so till today to understand the physical processes that are taking place in sunspots. It was the discovery of the large scale magnetic field by Hale (1908) that started the astrophysical investigations of sunspots. From that time onwards the scientific significance of the observations was mainly determined by instrumental improvements and in many cases by the seeing conditions during the observations. So it is time and again that efforts are made to determine the parameters like temperature, magnetic field, velocity field in sunspots in addition to its fine structure. Different observing methods are employed and each of them yields information concerning to a particular problem related to the sunspot phenomenon. Some of them are very simple and others very sophisticated but careful interpretation of the observations obtained under better conditions by selecting appropriate sites and bigger telescopes will help us to understand what sunspots are all about.

### 6.1.2. Evershed effect in sunspots

Evershed (1909) at the Solar Physics Observatory, Kodaikanal discovered the existence of a systematic outward radial flow of matter in sunspots which is termed in the literature as "Evershed Effect". Till 1960, very detailed and thorough studies on Evershed effect have not been possible because of limitations like image size, spectroscopic resolutions, and also due to the limitations of earth's atmosphere. Development of powerful solar telescopes along with high resolution spectrographs, filtergraphs, magnetographs with facilities to operate in velocity mode set the stage now for the detailed spatial analysis of Evershed effect in spots of different characteristics. Also theory in the form of rapidly growing subject of hydrodynamics, has given considerable impetus in the inter relationship of plasma dynamics and magnetic fields, and as a sunspot is the seat of extremely large magnetic fields, the measurements of 'Evershed effect' would be an observational evidence of the complex hydrodynamic interactions taking place in sunspots.

Evershed while studying the sunspot spectra for determining pressure in spots observed that the spectral lines in the region of penumbra got a shift and this was opposite on the two sides of the umbra and was maximum when the slit was parallel to the solar radius. These line shifts were permanent, affect most of the Fraunhofer lines, and were greatest in the penumbra. Spots situated within 10 degrees of the centre of the disk showed no displacements, whatever the direction of the slit may be. Outside this limit, the displacements increased with the distance from the centre. Quite near the limb, the penumbra often being hidden by the facule, and always very much foreshortened in the direction of the centre of the disk, the measurements have not become possible and also due to the photospehric scattered light in the penumbra, the displacements were gradually reduced. The motion must be essentially horizontal or parallel to the Sun's surface as it was shown by the total disappearance of the line shifts near the disk centre. But this hypothesis of the radial movement was entirely out of harmony with the splendid discovery of Zeeman effect in sunspots made by Professor Hale which demands a vortex or at any rate a circular motion in sunspots. Evershed obtained the value of velocity of matter accelerated from the umbra of sunspots as 2 km per second near the edge of the penumbra.

### 6.1.3. Chromospheric Evershed flow

Considering the rate of energy for the outflow as the interior regions below the photosphere, Evershed (1910) had attempted to discover the vertical motion in the umbra but rather found a motion of descent of 0.4 km/sec in general and concluded that the source of supply must be from the higher chromosphere. Therefore, Evershed continued the observations in H and K regions of the spot spectrum and found the central absorptions of H and K lines were slightly inclined in the direction opposite to that of other absorption lines indicating an in draught of calcium vapour from the higher chromosphere.

St. John (1913) verified Evershed's findings and substantially confirmed Evershed's hypothesis. Since the shifts are proportional to the wavelength, this phenomena is a true Doppler effect caused by the flow of reversing layer material from the interior and the centre of the spot and simultaneous flow of chromospheric material towards the centre and interior of the sunspot. The outward velocities increase in proportion to the distance below a mean level where the velocity is zero and the inward velocities increase with altitude above this mean level which may be called as velocity reversal level.

### 6.2. Spectral line asymmetry in Evershed effect

In the penumbral Evershed effect, in addition to the core shift, the spectral line develops a strong asymmetry, wherein the centre of gravity of the line gets displaced (Evershed 1910, Bumba 1960, Schröter 1962, Bhatnagar 1964). Beckers and Schröter (1969) obtain Evershed effect in terms of line asymmetry instead of the real shift of the entire line. When observed along the penumbral filaments, line asymmetry of the Evershed effect shows up a distinct line kink (Bumba 1960, Holmes 1961, Schröter 1965a) which Maltby (1964) considers to be the characteristic of the Evershed effect. The line kink observed in the spectral line is interpretted as a shifted satellite component superposed on an almost unshifted main component both originating from the unresolved penumbral fine structures (Bumba 1960, Stellmacher and Wiehr 1971, Wiehr 1995). According to the siphon flow model (Meyer and Schmidt 1968, Thomas 1984, 1988, Montesinos and Thomas 1989, 1993, Degenhardt 1989, 1991, Thomas and Montesinos 1990, 1991, 1993), the core shift and asymmetry of the spectral lines observed in the penumbra is produced by the stationary mass flow driven by pressure difference between foot points of an arched magnetic flux tube. The interpretation of both line asymmetry and shift in terms of an outward gas flow with a height gradient yields conflicting results. The line asymmetry requires an exponential velocity decrease whereas the core shifts of the lines from different heights indicate a linear decrease with height (Stellmacher and

Wiehr 1980). Hofmann et al (1994) reports that the line asymmetry is related to the height variation of the magnetic field inclination.

### 6.3. Evershed flow related to magnetic fields

#### 6.3.1. Velocity components and magnetic field

Sunspots are the most highly organised phenomena observed on the Sun. They are characterised by intense concentrations of magnetic field that is yet to receive a convincing physical explanation. Due to the presence of strong magnetic fields, the electrical conductivity of the solar plasma must be very high and any material motion has to follow the magnetic field lines in sunspots. Observations of highly spatial resolution demonstrate the existence of radially elongated structures in the penumbra. The Evershed effect that is associated with the sunspot is certainly the result of magnetic field organisation. All the observations on Evershed effect give only the horizontal flow pattern in sunspots. The Evershed flow vectors should provide a map of the magnetic field vectors at the three atmospheric levels. Large scale variations in Hα velocities reported by Haugen (1969) may be due to the existence of unresolved structures with different velocities. According to Dere et al (1990) the Hα flow pattern follows a spiral path outlined by the fibrils. Dialetis et al (1985) have shown that the velocity maximum occurs in regions where the magnetic field is almost horizontal in both photosphere and in chromosphere.

Additional information can be derived from the vertical component of the velocity vector. The spiral pattern seen Hα should be evident in the vertical and tangential components of the velocity. A small vertical component can be measured for a spot positioned close to the disk centre (Evershed 1910, St. John

1913). The vertical and tangential components computed from the observed radial velocity are very small and probably less than the errors of measurements (Kinman 1952, Holmes 1961, Servajean 1961, Bhatnagar 1964). Except Abetti (1932) no one is able to get any appreciable tangential component and the values obtained by him may be due to instrumental errors. Photospheric velocity field is dominated by granular and oscillatory noise and a high resolution data is needed to detect small vertical components amidst this noise background. Maltby (1975) demonstrated that the flow is concentrated into channels with typical widths of 1000 km. By selecting spectral lines of different geometrical heights, it is now confirmed that the sunspot penumbra consist of flow tubes with low and high velocity streams adjacent to each other (Schröter 1965a, Stellmacher and Wiehr 1980, Wiehr and Stellmacher 1989, Lites et al 1990, Börner and Kneer 1992). The recent high resolution observations of sunspots establish the earlier findings that the material flow in penumbra is confined to channels where the magnetic field is nearly horizontal (Title et al 1992, Degenhardt and Lites 1994). However, the length, shape and maximum elevation of loop structures that carry Evershed effect are not yet well determined by observations.

### 6.3.2. Evershed flow and penumbral fine structures

Although the fine structures seen in white light and in H$\alpha$ pictures are known for centuries, the relations of Evershed flow and the magnetic field of the penumbral fine structures are still under constant debate (Schröter 1965 a,b, Beckers 1968). It was uncertain whether the flow predominantly occurs in the bright or dark lanes and how the magnetic field fluctuations correlate with these structures. Because of the high electrical conductivity of the solar plasma, any material motion in a sunspot penumbra has to follow magnetic field lines even if the material is confined to field free penumbral intrusions, since the neighbourhood is magnetic (Degenhardt and Wiehr 1994). It will be also interesting to know the inclination of magnetic structures in the penumbra to understand the radial flow of matter in sunspots.

In the traditional picture of a sunspot, the inclination of the magnetic field to the local vertical varies with distance from the spot centre (Hale and Nicholson 1938, Bray and Loughhead 1964). Title et al (1992) showed that the inclination of magnetic field varies with azimuth and according to the recent picture of 'deep penumbra' it consists of highly inclined (with respect to the surface) flux sheets interlaced with nearly horizontal fields (Title et al 1992, Jahn 1992, Thomas and Weiss 1992). The magnetic field of the bright filament is found to be strongly inclined to the surface, whereas that of the dark filament is nearly horizontal (Beckers and Schröter 1969, Wiehr et al 1984) but the magnetic field strengths show very little variation between dark and bright filaments (Rimmele 1995). Such a picture is close to the theoretical model which suggests that the associated differences in observed field strength and corrugations of the visible surface in bright and dark penumbral filaments will be very small and the magnetic field in the outer penumbra will be almost horizontal (Schmidt et al 1986).

Observations to check whether material motion in penumbra is aligned with the magnetic field show that Evershed flow is confined to dark fibrils (Beckers and Schroter 1969, Abdussamatov and Krat 1970, Stellmacher and Wiehr 1971, 1980). Spectroscopic data of Johannesson (1993), Degenhardt and Lites (1994) and filtergrams by Title et al (1993) show a certain tendency for velocity patterns to line up with dark penumbral fibrils. However, spectroscopic observations of Wiehr and Stellmacher (1989), Lites et al (1990) do not show this correlation. High spatial observations by using filtergrams Shine et al (1991), Rimmele (1993) show that discrete dark cloud like features move outward in the penumbra. Most of the high resolution observations indicate that Evershed flow is confined to dark filaments where the field is nearly horizontal (Beckers 1981, Wiehr et al 1984, Küveler and Wiehr 1985, Bones and Maltby 1978) and the controversy over the location of magnetic field and Evershed effect within the penumbral structures may be due to the effects of instrumental errors.

The question of whether the asymmetries and the shifts of the spectral lines observed in the penumbra are related to their filamentary structure (Schröter 1965a) can be resolved only by correlating Evershed effect with the continuum intensity. Observations of spatial resolution of about 1" show that the outward motion is mainly concentrated in the dark filaments and asymmetry in the bright filaments (Wiehr et al 1984) and Wiehr and Degenhardt (1994) conclude that better resolution is needed to confirm penumbral fine structure and asymmetry relation.

### 6.4. Evershed effect beyond penumbral boundary

Another point of interest and controversial discussion is the extension of the Evershed effect beyond the white light penumbral boundary. The question on the geometrical distance over which the penumbral magnetic and velocity field (Evershed effect) disappear at the sunspot border is important for the understanding of the topology of both the fields. Very highly resolved white light pictures of sunspots show an extremely sharp outer edge where granulation abruptly replaces the penumbral filaments. The fact that radial flow of matter disappears near the sunspot border (Evershed 1910, St. John 1913, Abetti 1932, Maltby 1964, Beckers 1968) gives an impression that Evershed effect is exclusively a sunspot phenomena.. However, spectroscopic observations yield conflicting results on the Evershed flow sticking to the sunspots alone. Some of the results show the Evershed flow stopping at the penumbral boundary (Brekke and Maltby 1963, Kawakami 1983, Wiehr et al 1986, Wiehr and Degenhardt 1992) whereas the flow beyond the sunspot penumbra are also obtained (Kinman 1952, Küveler and Wiehr 1985, Börner and Kneer 1992, Solanki et al 1994). Beckers and Schröter (1969), Wiehr and Balthasar (1989) show both magnetic and velocity fields in sunspots extend the outer sunspot border and Sheeley (1972) correlates the extra penumbral velocity to superpenumbral borders. Filtergrams which have better resolution show the flow beyond the penumbral boundary (Dialetis et al 1985, Alissandrakis et al 1988, Dere et al 1990, Muller 1992). However Title et al (1993) find a sudden drop of Evershed shift at the visible penumbral boundary from spectral and spatial resolution filtergrams. Rimmele (1995) from high quality velocity maps and Ichimoto (1987) show the evidence for foot points and elevated flow channels within the penumbra where the Evershed flow is confined to dark elevated filaments. However, Rimmele's (1994) earlier observations show Evershed velocities extending beyond the penumbral boundary, but it is not clear how far in the adjoining regions the Evershed arches reach. Conflicting results on Evershed flow stopping at the penumbral border is a hindrance for better understanding of the correlation that may exist between magnetic and velocity field in sunspots.

### 6.5. Evershed flow - a wave phenomena ?

The penumbral filamentation and its association with the dynamical Evershed phenomena is not yet fully resolved. Danielson (1961) suggests that the filamentary appearance of the penumbra is due to convection in rolls which are directed along the magnetic field lines. This model does not include Evershed effect as a cause or effect. Galloway (1975) proposes a homogeneous model for the whole sunspot and allows convection in rolls to interact with the magnetic field to produce an inhomogeneous penumbra. Due to this convection, magnetic flux is concentrated in the dark filaments, driving the Evershed motion outwards in this region ; the subsequent superficial Evershed motion shear the magnetic field and causes it to appear flatter in the dark filaments. This situation must be time dependent and so the Evershed flow will be in the form of pulses to avoid rapid destruction of the whole spot. The scenario has suggested for observations to detect the existence of any osicllations in the flow of material in sunspots.

Bhatnagar (1970) while studying the oscillatory nature of Evershed flow finds a fluctuating velocity with an amplitude of 50 to 70 m per second having a period of 180 to 260 seconds and comes to a conclusion that the presence of magnetic field may inhibit the oscillatory velocity field. Discrete periods of oscillations both longer and shorter than the 5 minutes within the boundaries of a unipolar spot and in addition 3 minutes umbral oscillations are detected (Rice and Gaizauskas, 1972). Becker and Shultz (1972) interprets these oscillations in terms of gravity or acoustic waves travelling along the magnetic field lines. This observational evidence regarding the suppression of the oscillatory fields inside sunspots has an important bearing on understanding both the transfer of energy from sunspots to their surroundings and mechanisms that support the oscillations.

Moore (1981) and Thomas (1981) gives a model in which dark filaments are elevated with respect to photosphere explaining Evershed effect as a flow of material along the filaments. However, in the siphon flow model (Meyer and Schmidt 1968, Thomas and Montesinos 1991), the core shift along with the strong asymmetry of the spectral lines observed in the penumbra is thought to be produced by a stationary wave driven by a difference in the internal gas pressure between the foot points of an arched magnetic flux tube.

According to Maltby and Eriksen (1967) the observational signature of the Evershed effect may be explained in terms of an accoustic wave propagating parallel to the solar surface. Rimmele (1994) observes some velocity packets with a period of 15 minutes travelling into the photosphere and predicts it as a wave propagating along a magnetic arch. Evershed effect is also termed as the spectral signature of magneto acoustic-gravity surface waves (MAGS - waves) existing at the interface between lower boundary of the magnetic field of the sunspot penumbra and non magnetic gas below (Bünte et al 1993).

Therefore, it is even uncertain whether the line shift and line asymmetry associated with the Evershed effect are due to a material flow or whether due to some form of a wave.

## 6.6. Evershed flow in bipolar sunspots

### 6.6.1. Observation

We have taken simple cases of opposite polarity sunspots for measurements of Evershed velocity in the present study. Spectra of the bipolar sunspots were obtained at the solar tower telescope-spectrograph. A precise determination of the velocity field in sunspots is greatly faciliated if the influence of the Zeeman effect is eliminated. A symmetrically broadened line by the normal Zeeman effect may not affect the velocity measures. But due to instrumental polarization, a partial suppression of one the $\sigma$ -components can occur. When number of aluminized mirrors are used at different angles, the instrumental polarization certainly exists. To avoid completely the influence of the magnetic field, the line $\lambda$ 4912 Ni I which is insensitive to the Zeeman effect ($g = 0$) is chosen for velocity measurements. This line is also free from the effects of blending. The formation level of the spectral line core $\lambda$ 4912 Å is 300 km in the photosphere above sunspots and for the line wing, the height is 150 km calculated from the contribution function to the line depression (Degenhardt and Wiehr 1994). The spectra were observed in the fifth order where the dispersion at $\lambda$ 4912 Å is 8.1 mm per Å. Kodak 103 aE high resolution astronomical emulsion was used to record the spectra. The slit width corresponded to 0.55 arcsec and the exposure time was of the order of 2-3 seconds. Spectra were obtained at the best seeing conditions of the order of 1-2 arcsec. The sunspots located at the heliocentric angles between $\theta = 30^\circ$ to $\theta = 50^\circ$ on the observing days were only chosen.

It is also important to know precisely the coordinates of the points where the displacements were measured on the spectra. To achieve this, the orientation of the slit and the disk position of the spot was precisely determined. A thin wire of about 0.2 mm thickness, was stretched over the slit jaws. This wire casts shadows on the spectrum and serves as the fiducial marks on the emulsion. The spot spectra was taken after bringing the desired portion of the spot below this wire. A recording of the position of the wire, the slit position and the spot was made immediately on the termination of the exposure. These sunspot maps with the wires, and the slit position marked, were later used during the measurement of the spectra. The coordinates of the points where velocity measures are made, can be determined by using these sunspot maps and white light photoheliogram taken at Kodaikanal around the time of the spot exposures. The films were developed in Kodak D19 developer for 5 minutes at $20^{\circ}$ C.

### 6.6.2. Data reduction

The analysis of the spectra were carried out using a computerised positional densitometer system (PDS). Software programs were written to deduce the Doppler shifts, from which the line of sight velocity values were measured. Smoothing of the spectrum is needed as a compromise between resolution and stability and a 5 point equally weighted average is done for the all the scans. On a high dispersion solar spectrum of the kind used in this study, it is very difficult to measure precisely the small Doppler displacements. Since the Fraunhofer lines become very broad and diffuse under high dispersion, some precise method like photographic subtraction has to be employed for measuring smaller displacements which is not needed for the present study.

Michrophotometry was done with a sampling interval corresponding to $50\mu$ (0.275 arcsec) along the direction of the slit (x-direction). Several micro-

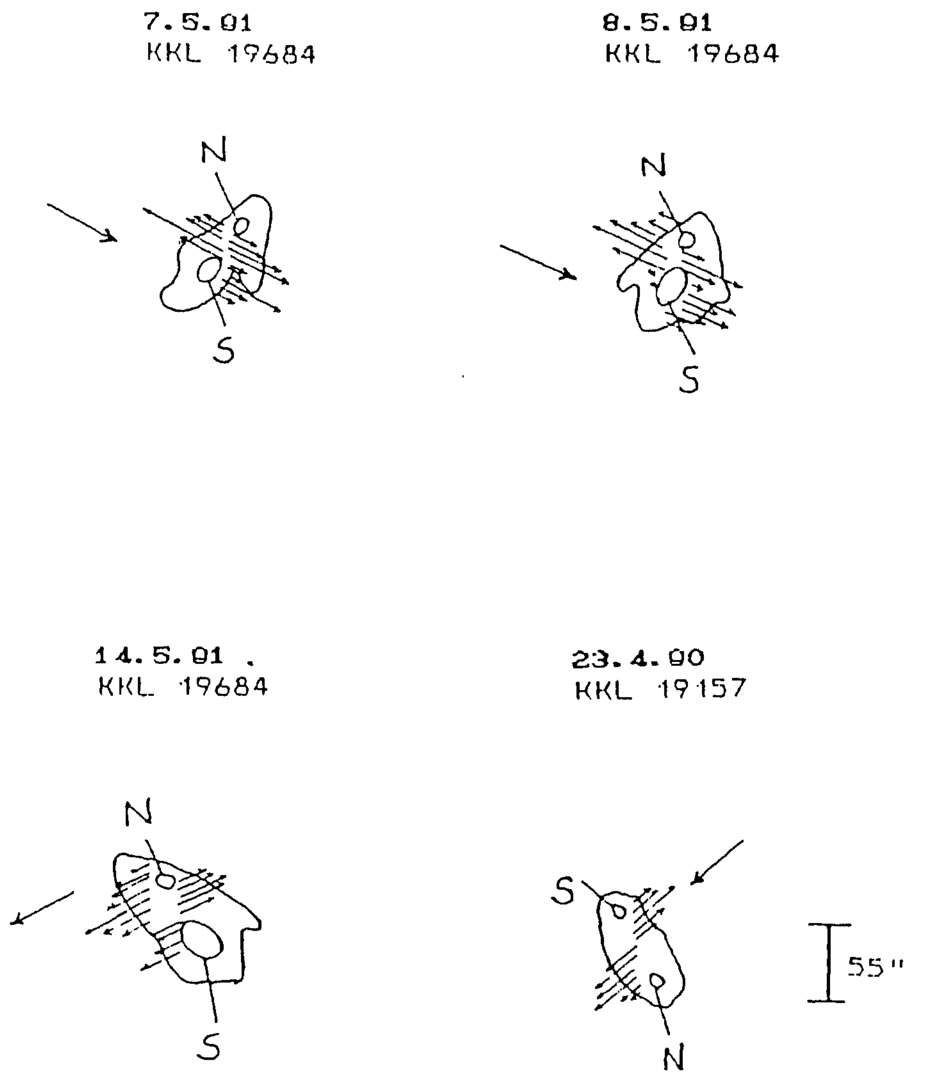



Figure 6.1. Evershed velocity in the neutral regions of bipolar sunspots having common penumbra. The bold arrow shows the direction of the disk centre.

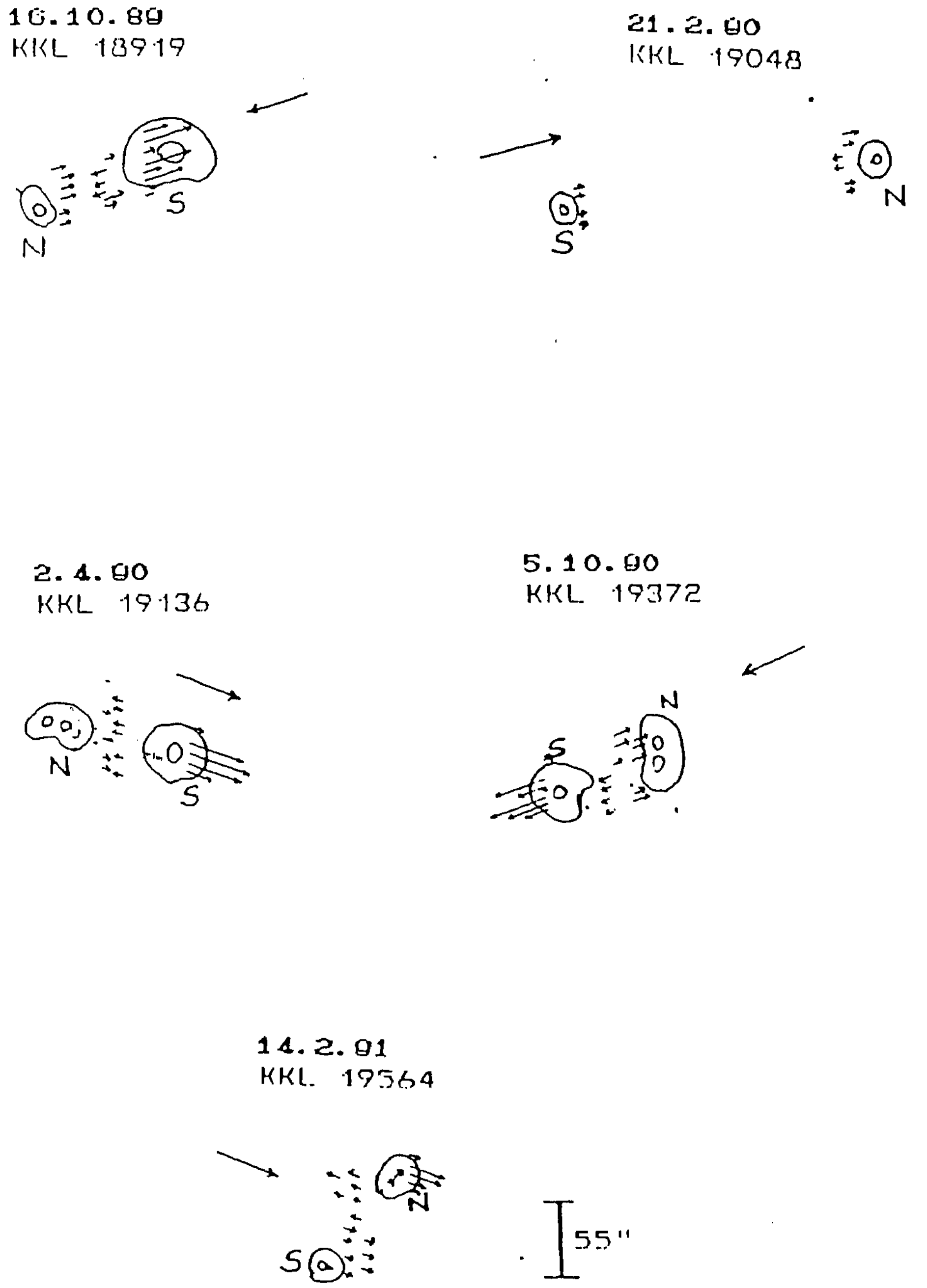



Figure 6.2. Evershed velocities in the neutral regions of the bipolar sunspots.

photometer scans over the spots at intervals of 0.2 mm (1.1 arcsec) parallel to the dispersion (y-direction) were obtained. For the dispersion of 8.1 mm per Å at λ 4912 Å in the fifth order, the Doppler shift corresponding to one pixel difference is 0.006 Å or a velocity of 377 m per second. The error bar in the calculation of velocity is also one pixel and hence with this method it is not possible to obtain any velocity less than 0.377 m per second. The scattered light contribution from the instruments and other seeing effects are not corrected which are essential only in the studies of velocity fluctuations. The idea here is to find out the quantitative measure of the velocities, if any, in the neutral regions of the bipolar sunspots and so these corrections, which may turn out to be very less, are neglected. The bipolar sunspots that were studied are shown in the Figures 6.1 and 6.2 with the image scale marked. The day of observation and the Kodaikanal sunspot number are marked above these spots in the figures. A single arrow in the region away from the spot shows the direction of the disk centre. The cluster of arrows seen within the spot and also close to it show the line of sight velocities. The velocity arrow with minimum length shows the minimum velocity and vice versa. Though the velocities were calculated for various slit positions covering the entire spot region, the figures only show the selected regions like the neutral regions of the bipolar spot configuration and one slit location crossing the spot away from the neutral region. The polarities refer to the umbrae of sunspots and were obtained from the bulletin of Russian Geophysical Data.

### 6.6.3. Results

The spectra have shown no velocities in some of the regions of the penumbra and this may be due to penumbral fine structures. Since the best seeing was 1-2 arcsec, it is not possible to have the direct view of the penumbral fine structure which have sizes less than 0.5 arcsec. The value of the velocities range from 1 to 2.5 km per second in the penumbral regions of the sunspots. According to Harvey and Harvey (1976), the horizontal shearing motion along polarity reversal lines may be an important factor for flare production. Also Keil et al (1993) provide direct quantitative evidence for velocity shear associated with the location of flares. Since flare occurrences are more in $\delta$-type sunspots, it becomes of our interest to look for the velocities in the regions between the opposite polarity in $\delta$-type sunspots and in addition we have given importance to find out velocity, if any, in the cases of bipolar sunspots of leading and following types. The results show velocities of 1 to 2.5 km per second in the regions between opposite polarities umbrae of sunspots with common penumbra (Figure 6.1). In the other category of bipolar sunspots (Figure 6.2), the velocities are very small in the neutral regions. The bipolar sunspot KKL 19048 which appeared on 21 February, 1990 during its passage on the third consecutive solar rotation is separated by a big margin (Figure 6.2a) and in this case, the velocities are conspicuously absent in most of the regions between the two polarities. It is interesting to note that in both the categories of bi-polar sunspots, the velocities are in opposite direction in between the regions of opposite polarity. The observations presented here were not obtained during the flare time and future observations of this type before, during, and after the flare may throw better insight in the range of velocities that may be useful for predicting the flare occurrences. Also it is interesting to note that except in the neutral regions of the spots in Figure 6.2, the photospheric non-spot regions do not show any appreciable velocity. It is difficult to say at present whether the flows are determined by the field structures or whether the flows are driving the flare process.

# CHAPTER 7

# SUMMARY

## 7.1. Summary of the results

Strong magnetic shears near the neutral line at the photosphere are identified as the cause for triggering major solar flares from the measurements of vector magnetograms. However, such strong shears also occur in active regions without resulting a flare. In the absence of vector magnetograph facility at Kodaikanal, it has been realised that it would be appropriate to study the overall development of the entire active region rather than confining to the neutral lines of the photosphere for determining shear. The manifestation of flare phenomena may be due to the complex processes that may take place at different atmospheric levels of the Sun. As the magnetic field of the active regions are deep rooted in the Sun, the disturbances developed in the regions below the photosphere would be transferred to the upper layers in the form of changes in the active regions that are quite often detected all through the solar atmosphere. In view of this, we consider that the studies of the entire morphology of the flare active regions both in photosphere and in chromosphere without restricting the shear analyses only to the photospheric neutral lines are essential for predicting the flares. The need for accurate knowledge regarding predictions of flares drives the search for flare precursors. Study of the precursors may shed light on the whole process like the environment, prehistory, and birth of flares.

It is considered that the variations in the filament directions are the primary change in the magnetic field re- organization and these are caused due to the relative motions of the active regions of both photosphere and chromosphere. The change in the orientation of the Hα filament with respect to the opposite polarity sunspots or plages are discussed in this study as a measure of shear. It has been found that, when the shear calculated in this way attains a critical value, flares are triggered. Therefore, we feel that the dynamic activity of the filament is an important indication of magnetic field change and also a primary and vital step in the flare process. Only few argue against the concept that two ribbon flares result from magnetic shear and reconnection and that the filament eruption is the characteristic symptom of this rearrangement. Routine and automatic observations are feasible and not beyond the reach and hence the filament association remains the top of the precursors in forecasting flares.

However, there are cases of flares which are not associated with filament eruptions or even the presence of a filament in the flaring regions. In these cases, the rotational, relative or translational motion of one sunspot with respect to the other in the bipolar active region is given close attention for detecting magnetic field rearrangement. Thus, the day to day variations observed in these sunspot configuration is considered to be representative of shear in the case of flares without filament activation. In spotless category of these types of flares, the dynamics of the active region plages plays a crucial role in triggering a flare by inducing necessary shear, which is represented from the variation in their orientation. These cases also show a threshold value of shear for flare triggering. Thus the entire geometry of the active regions belonging to the photosphere and chromosphere are studied simultaneously. The shear derived in this manner is entirely different from the magnetic shear arrived from the studies of vector magnetograms. We would like to emphasize here that the dynamics of the active regions and sunspots based on studying the phtoheliogram and spectroheliogram data are still very much useful for flare predictions.

Shear is also considered to be the basic property of the Hα filament to evolve as a prominence. The cases of two dark Hα filaments evolving as prominences during their disk passage are analysed in this thesis. These two filaments were well outside the spot regions. However, they were connected to sunspots by small threads. Outside the sunspot regions, the filaments were also anchored between opposite polarity plages. Both the filaments were almost straight in the beginning. However, they acquired a curved shape (an inverted U-shape) as the spots and plages underwent rotation. It has been shown that the rotation of the plage and spot plays an important role in the evolution of prominences, one serving as the anchor and other imparting necessary shear. Once the shear reaches a critical value, it starts unwinding the filaments, resulting in the fine structure of the two prominences studied.

Though the Evershed effect has been studied elaborately till now, many questions concerning material motion in sunspots are still unresolved. It is even uncertain whether the Evershed effect is due to material motion as e.g. a siphon flow or due to some form of a wave. The physical nature of the penumbral filamentation and this dynamical phenomena is still not known. Our studies show that the resolution needed for correlating the material flow with the fine structures of the penumbra is still out of our reach, though it is not impossible. The flow velocities are in opposite direction in the regions between the bipolar sunspots of δ-type, but in between the regions of bipolar spots of separate structures, the velocities are very less. Except the case of individual sunspots of opposite polarities, the velocity is generally restricted to the penumbral boundary attaining the maximum value near the centre of the penumbra. These observations of material flow in bipolar sunspots are not taken during the flare time and so at this juncture, it is difficult to say anything about the nature of material flow near the neutral line that may give an insight for flare triggering. However, the attempt, which has shown the tendency of the flow in opposite direction near the neutral regions of the bipolar sunspots is a welcome step for further work in this direction.

### 7.2. Scope for further work

The flare problem, at its current stage of evolution, now comprises a close linking of sub-problems involving acquisition and interpretation of data, the analysis of theoretical concepts, and the difficult task of assembling these concepts into a comprehensive model that is theoretically self-consistent and in accord with observational facts. The present situation indicates clearly the need for more detailed and specific observational data. Observations with higher spatial resolution, and sufficiently high temporal resolution, to determine the spatial and temporal relationship of various forms of radiation from flares are necessary to obtain a more detailed picture of the magnetic field structure that precedes a flare and how that structure changes as the result of the flare. The continuous acquisition of high quality optical data will be most valuable, but they should supported by high resolution X-ray images and radio data.

The question of how both magnetic and Evershed velocities as seen in photospheric layer disappear at the outer spot boundary is of high interest for a theoretical understanding of the penumbral filaments. Also the extension of the study of velocity fields in bipolar sunspots during the flare time along with pre and post flare observations may throw light on the velocity shear playing a role in the flare process. We realise that the key for a better understanding of these dynamical phenomena is not exclusively the importance of instrumentation but also the application of well-suited interpretational methods. Modeling and further analysis of the observation will determine whether the dynamical process in the atmosphere are transferring energy into the magnetic fields, which then become unstable and erupt or fields are better driven from below, and in turn controlling the dynamics of the atmosphere. In either case, it appears that measuring atmospheric flows should provide a means of assessing the stability of active regions.

These observational challenges are matched by comparable theoretical challenges. We are faced with the general problems of trying to model possible pre flare plasma-magnetic-field configurations, and then following the evolution of that system, realising that a plasma process in one part of the system is likely to influence a neighbouring region and stimulate a similar or a different process in that region. At present flare theory is lead by observation and the examined experience of forecasters provide useful tools for prediction. Nevertheless theory does provide guidance in the search for significant parameters to observe and interpret. Theoretical results are to be simple and should be in a predictable fashion, rather than trying to explain all the observational details. Although a complete theory to forecast these eruptive phenomena is still out of reach, recent advances provide a coherent framework for planning further effort towards that goal. Perhaps we will be ready for this challenge at the beginning of the 21st century.

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