CHAPTER 1: PREFLARE ACTIVITY

1.1 INTRODUCTION

The Preflare Activity Team at the Solar Maximum Mission Workshops was split into three groups. The first group, concerned with Magnetohydrodynamic Stability (see §1.2), was led by E.R. Priest. Its members were A. Aydemir, F. Brunel, P. Cargill, T. Forbes, A. Hood, J. Melville, B. Schmieder, R. Steinolfson, and G. Van Hoven. The second group discussed Preflare Magnetic and Velocity Fields (see §1.3). It was led by M. Hagyard and included G. Chapman, A. de Loach, F. Drago, A. Gary, B. Haisch, W. Henze, V. Gaizauskas, H. Jones, J. Karpen, M. Martres, J. Porter, E. Reichmann, B. Schmieder, G. Simon, J. Smith, Jr., and J. Toomre. The third group considered Coronal Manifestations of Preflare Activity (see §1.4) under the leadership of E. Schmahl and D. Webb. Its members were R. Bentley, F. Drago, S. Enome, V. Gaizauskas, R. Harrison, G. Hurford, B. Jackson, T. Kosugi, M. Kundu, K. Lang, A. Magun, P. Martens, G. Pneuman, E. Reichmann, A. Schadee, J. Schrijver, B. Schmieder, G. Simon, J. Smith, Jr., K. Strong, P. Waggett and B. Woodgate.

This long list of participants with very diverse interests underscores the subtleties in the ways the Sun prepares for a major flare. Nevertheless, they worked constructively together and have all learnt a great deal about the complexities of preflare solar activity. The authors of this chapter are extremely grateful to their group members for helping in its construction.

The main features of preflare activity such as soft X-ray heating and filament activation are well-known, but we are nowhere near understanding them fully. We do not know the necessary and sufficient conditions for a flare and still cannot predict them with much confidence. Yet this must be our aim — just what is it that gives rise to this bewildering event? Great progress has certainly been made recently. For example, ten years ago it was felt that a flare was due to a magnetic instability of some vague kind and that a current concentration such as a current sheet was needed to release the energy fast enough, since the diffusion and tearing times characteristic of an active region as a whole are years and days, respectively. Now, however, the detailed stability of a loop and an arcade have been calculated (§1.2.6) and the ways that magnetic fields reconnect at current sheets have been studied analytically and numerically (§1.2.1). Much has been learned empirically about the role of velocity fields which stress the lower solar atmosphere during the birth and growth of active regions (§1.3). Measurements made with the vector magnetograph now permit the calculation of electric currents in the stressed areas (§1.3). Preflare changes in magnetic fields at coronal heights are directly observable as polarization changes in spatially resolved microwave structures (§1.4). The precise location in the corona of the initial flare outbursts can now be determined from VLA microwave maps and from HXIS maps in hard X-rays. And during flare onset, there are indications of preflare energy released by non-thermal as well as by thermal processes (§1.4).

1.1.1 The Preflare State — a Review of Previous Results

A comprehensive summary of our earlier understanding of the preflare state was given by Van Hoven et al. (1980) at the Skylab Workshops [see also Svestka (1976) and Priest (1981)]. The basic philosophy in preflare studies presumes that free energy is stored in stressed magnetic fields, although the electric currents can be extrapolated from photospheric measurements of the magnetic field rather than being directly observable. The energy released during a flare was assumed to be by magnetic reconnection of the coronal fields in narrow current sheets; with Skylab, the coronal loops and arcades were seen for the first time. It was well-known that flares occur usually near a polarity inversion line when an active region is changing rapidly. The flare start was defined as the beginning of the flash phase (the rapidly rising or impulsive part of the event). Theoretical studies had concentrated on the storage of energy in the chromosphere and corona in a twisted loop or a sheared arcade in response to the slow passive evolution of footpoints. The cause of the preflare heating was unknown, as was the means of destabilising the magnetic configuration, although it had been suggested that instability might occur when the shear reaches a critical value. The necessity to demonstrate that the marginal state is meta-stable and the instability explosive was appreciated. In a parallel development to the Skylab studies, the Emerging Flux Model (Heyvaerts, Priest and Rust, 1977) had been proposed to explain a class of flare-related erupting filaments. It suggested that energy for large flares was stored in a sheared arcade and that its release was triggered by emerging flux.

Ground-based observations had long ago given evidence for preflare magnetic changes. Evolving magnetic features (emerging flux or satellite sunspots) were often seen near a polarity inversion line. Photospheric velocity measurements showed that flares occur near reversals in the line-of-sight velocity and sometimes near vortex patterns. Also, the presence of strong shear (which tends to promote filament formation) and of large spot motions were common elements in the preparation for a large flare. Another precursor was the expansion of arches as seen at 5303 Å. The eruption of an active region filament was recognized as an important fea-
ture of a two-ribbon flare. First, there is an increase in absorption in the wings and centre of Hα, with the filament crest rising at a few km s\(^{-1}\). Then Hα changes from absorption to emission. The filament splits into fragments and (partially) disappears, with plasma falling down along its legs. Filament activation can begin as much as 3 hours before or as short as 15 minutes before flare start; filament acceleration is largest between 0 and 10 minutes before Hα onset.

Spacecraft observations had revealed a preflare soft X-ray rise in 80% of flares for a few minutes before flare onset accompanying a filament activation, although in 30% of cases the soft X-rays were thought to begin after Hα. A preflare EUV enhancement had been found 30 minutes before flare start from a small point near some emerging flux, while soft X-rays were emitted along the whole length of a filament.

At the Skylab Workshops Van Hoven et al. considered various flare precursors. Coronal transients had forerunners containing 10-20% of its mass which could be traced back to an origin before any possibly associated flare. Also type III radio bursts were twice as common as normal in the last few hours before flare onset. Fluctuating UV bright knots seen by the astronomers were thought to be loop footpoints. In one example a flare occurred after flux emergence below a pre-existing EUV loop, while in another a flare took place in a pre-existing X-ray loop. Sometimes EUV bright points were present. Events with no preflare X-ray rise were often small and there was little evidence for a preflare rise in subflares. Both X-rays and EUV showed preflare brightenings for 2-20 minutes before flare start in two out of three cases, although often displaced from the flare site. Thus a preflare coronal enhancement was common although not always in the later dominant loop. However, it was not possible to relate the character of the slow X-ray rise (its duration or magnitude) to that of the subsequent flare.

Van Hoven et al. studied the flare of 5 September 1973 in particular detail. Several satellite spots emerged over a few days around the main sunspot, producing a series of small flares. Before the biggest flare of the series, the spot rotated with a speed of 20-100 ms\(^{-1}\), producing a possible energy increase of \(2 \times 10^{31}\) erg. A small filament developed at the flare site. It darkened an hour before the flare and ascended with a speed of up to 14 km s\(^{-1}\). Downflow was seen in its legs and a soft X-ray enhancement at its crest. In Hα and Ca II a faint arc propagated away perhaps representing the projection on the disc of a coronal transient. In EUV some compact bright knots smaller than 5 arc sec appeared and disappeared on time scales of minutes. The flare began in an EUV loop which became visible in X-rays and was subsequently replaced by a loop that was higher and less inclined to the arcade axis.

The theorists in Van Hoven’s team studied non-linear force-free solutions for coronal arcades and found that there are no nonlinear static solutions (equilibrium states) when a parameter \(\lambda\) (related to the axial magnetic field) exceeds a critical value. They also set up models for the thermal and magnetic structure of coronal loops. These exhibit nonequilibrium or magnetic instability when the loop is twisted too much.

There have been many advances in our preflare knowledge since Skylab days. In MHD stability much work has been done on the theory of ideal (non-resistive) and resistive modes. In X-rays the HXIS and XRP instruments, by virtue of spatial and spectral resolution, have revolutionised our understanding of the flare. At radio wavelengths we have seen active regions resolved in great detail with the VLA. In the transition region the details of the UV flows have been studied and magnetic fields (of strength 1000 Gauss) have been measured for the first time with UVSP. For filaments, detailed velocity maps have been constructed and associated EUV arcades have been seen a few hours preflare. Also, the preflare heating of filaments, and vector magnetic field have been measured. At the photosphere and chromosphere the importance of velocity and magnetic shears and of emerging flux has been underlined.

1.1.2 Some Questions

During the present workshop series many questions have been raised, and some are at least partially answered in the rest of this chapter. They include the following:

MHD instability Is the preflare equilibrium structure a loop or an arcade? What changes in physical conditions lead to instability? Is the basic instability ideal or resistive? What is the threshold? Can preflare changes occur such that repeated "tries" are needed to exceed the threshold? What is the best way to model photospheric line tying? Is the filament just a tracer of magnetic field lines or crucial to the instability? How do we model an active region when linear force-free fields are inappropriate?

Soft X-rays What causes the preflare rise in soft X-rays? Is it due to a thermal instability, joule heating, magnetic reconnection, or a response to a non-thermal mechanism? Does one type of process first energize the corona with another responsible for the flare phenomenon? Is the preflare gradual phase energized in the same way as the postflare phase?

Radio What are the preflare signatures? How are they related to those of other wavelengths? Are there preflare nonthermal bursts? What are the coronal magnetic fields and what are their relevant preflare changes? What is the \(\beta\) of the coronal plasma? How does the corona respond to emerging flux?

Ultra-violet What are the properties of the brightness fluctuations and mass flows? What causes them? How are they related to changes in Hα, emerging flux, and/or footpoint motions of filaments or loops?

Filaments How do they form? What is their magnetic structure? What drives the observed flows? What happens
during a filament activation? What are the causes of filament eruption? What is the nature of the coronal environment around the eruptive filament? Is there a difference between filaments — those activated in the presence of new magnetic flux and those which are not? Are there two distinct classes of precursor — with and without active filaments?

**Velocity and Magnetic Shear** How are they related to each other and to flare productivity? What is the role of the resulting electric currents? Is there a critical value of shear for eruptive instability? What are the preflare characteristics of the velocity field and how do they evolve?

**Emerging Flux** What are the necessary and sufficient conditions for it to trigger a large flare? What is different in the numerous flux emergences which produce no large flares? What are typical velocities, magnetic field strengths and rates of growth? Are they related to particle acceleration?

### 1.2 MAGNETOHYDRODYNAMIC INSTABILITY

E.R. Priest, P. Cargill, T.G. Forbes, A.W. Hood and R.S. Steinolfson

#### 1.2.1 Magnetic Reconnection

Our basic understanding of magnetic reconnection has changed recently due to the beginning of detailed numerical experiments on various aspects of the process (Priest 1984a and 1984b). These have linked the two previous strands of reconnection theory, namely tearing mode instability and Petschek-Sonnerup reconnection (as described below), and have presented us with new surprises (§1.2.2, 1.2.3).

**1.2.1.1 Linear Tearing Modes**

A current sheet of width d is spontaneously unstable to the linear tearing mode (Furth et al., 1963), which creates long thin magnetic islands on reconnection on a time-scale

$$T_d = d^2/\eta$$

where $\tau_d = d^2/\eta$ is the resistive diffusion time and $\tau_A = d/v_A$ is the Alfvén time in terms of the Alfvén speed ($v_A$). For the active-region corona with global length-scales (d) of typically $10^3$-$10^4$ km, the tearing mode growth-time (1.2.1) is days to weeks and is therefore much too long to explain a flare although it may well be important for normal coronal heating, (Heyvaerts and Priest 1985; Parker 1984).

Tearing may also take place in a sheared magnetic field such as a flux tube. However, in solar coronal applications it is important to incorporate the stabilising effect of photospheric line tying, since the footpoints of coronal magnetic field lines are anchored in the dense photosphere. This has led to suggestions that the resistive modes be completely stable in a loop (Mok and Van Hoven 1982) or in an arcade (Hood 1984a, Migliuolo and Cargill 1983) unless there is a reversal in the axial (loop) or azimuthal (arcade) field component.

An important new development is the discovery of a much faster radiative tearing mode (Van Hoven et al., 1982, Steinolfson 1983, 1984a, 1984b). Steinolfson and Van Hoven have solved the normal incompressible resistive MHD equations but they have allowed the magnetic diffusivity to depend on temperature ($\eta = \eta_0 T^{-3/2}$), which introduces a coupling to the energy equation

$$\frac{n_k}{\gamma-1} \frac{dT}{dt} = \nabla \cdot (xB + vT) - R_p T^{-\alpha} + \mu_0\eta(T)J^2,$$

and produces resistive field changes on energy-transport time scales.

The predicted growth rate of linearly unstable modes is shown in Figure 1.2.1. At coronal values of the magnetic Reynolds number $S$ (typically $S = 10^{10.6}$ for $T = 10^6$ K, $n = 10^{17}$ m$^{-3}$, $B = 100$ G, $a = 100$ km) there are two distinct modes, namely the tearing mode and the radiative mode, which is typically a hundred times faster. However, both modes are modified significantly. Local cooling at the X-points increases the magnetic diffusivity and so enhances the reconnection for the tearing mode. In the radiative mode a considerable amount of reconnection is present (Figure 1.2.2): the island width is typically 30% of that produced by the tearing mode and the perturbed magnetic energy is typically five times the perturbed thermal energy.

![Figure 1.2.1 Growth rate(\omega) for radiative tearing instability in units of the Alfvén travel time ($\tau_A = a/v_A$) as a function of the magnetic Reynolds number ($S = \tau_d/\tau_\eta$), where $\tau_d = a^2/\eta$ is the diffusion time. Here the dimensionless wavenumber (ka) is 0.1, corresponding to a wavelength of 10\tau times the shear length (a), (From Steinolfson and Van Hoven 1984).](image-url)
The inclusion of compressibility is found to be unimportant for solar coronal conditions. It inverts the tearing temperature at very long wavelengths and increases the radiative rate by typically a factor of five at very short wavelengths. Steinolfson (1984) includes perpendicular thermal conduction which introduces spatial temperature oscillations normal to the tearing surface and on a scale comparable with the width of the resistive tearing layer. Such thermal ripples create velocity oscillations but don’t affect the magnetic field. Steinolfson (1983) derives analytical expressions for the growth-rates in the constant-$\psi$ and long-wavelength approximations. He finds that for $S$ smaller than about $10^6$ the modes are generally stabilised. Also, he discusses the Joule heating instability which is present in the absence of radiation.

**1.2.1.2 Petschek-Sonnerup Reconnection**

The second main theme of reconnection theory has been the fast nonlinear mode of steady Petschek-Sonnerup reconnection (Petschek 1964, Sonnerup 1970), which has been reviewed many times (e.g., Priest 1984b, Vasylulis 1975). In this fast nonlinear state the current sheet bifurcates into two pairs of slow shock waves, which exist because the inflow plasma speed exceeds the slow magnetoacoustic wave speed. The shocks are standing in the flow and, as the plasma and magnetic field lines pass through them, they have the effect of transferring inflowing magnetic energy into the heat and kinetic energy of hot fast jets.

In general one would expect the external boundary conditions at the sources of the inflowing plasma to produce a hybrid Petschek-Sonnerup regime. Particular forms of those boundary conditions (namely fixed or free corner conditions) may, however, produce the pure Petschek or Sonnerup extremes, respectively (Vasylulis 1975). The difference between the two extremes is as follows. The Petschek mode has a pure fast magnetoacoustic expansion in the inflow regions upstream of the slow shocks, such that the flow converges and the magnetic field strength decreases as the central diffusion region is approached. By contrast, the inflow region for the Sonnerup mode consists of a slow mode expansion with the flow diverging and the field strength increasing. Although in Sonnerup’s original analysis the slow mode expansion fan was very thin and generated at a single point in the inflow, Sonnerup reconnection here refers also to the more general situation with a wide fan and generation across a substantial part of the inflow region.
When the reconnection develops locally from the tearing of a sheared magnetic field, such as in the simulation of the Kopp-Pneuman model for main phase reconnection (§1.2.5), the nonlinear steady state is expected to be Petschek-like (Figure 1.2.9). When the reconnection is driven from outside, as in a simulation of emerging flux (§1.2.4), the nonlinear state can be closer to the Sonnerup regime (Figure 1.2.7).

Recent numerical experiments by Forbes and Biskamp have produced two main surprises. They have demonstrated that the tearing mode can develop in its nonlinear phase into the fast Petschek-Sonnerup mode (§1.2.2). They have also revealed some new regimes of fast nonlinear unsteady reconnection when the Petschek-Sonnerup mode breaks down or goes unstable (§1.2.3).

### 1.2.2 Nonlinear Tearing

The nonlinear development of the tearing mode is far from simple and not yet completely understood. Several pathways along which the instability may develop appear to be possible, depending on the geometry and the parameter regime, as outlined below.

#### 1.2.2.1 Saturation

The first possibility is that the mode may saturate at an extremely low amplitude, when the island width has only grown equal to the resistive layer width (Rutherford 1973). This benign outcome with an extremely small energy release has been the most commonly expected development in laboratory devices. However, some recent calculations have been performed by Steinolfson and Van Hoven at large values of $S_{\parallel} = 10^6$ and at long wavelengths, conditions much more appropriate to solar applications than previous attempts (Steinolfson and Van Hoven 1983). At a wavelength of only twice the shear length $\lambda$ the reconnection is indeed found to slow down drastically, as in the Rutherford regime. But at wavelengths of 20a the nonlinear reconnection rate is ten times faster and the island grows enormously up to a width of 2a (see also §1.2.3.2).

#### 1.2.2.2 Mode Coupling

In a magnetic flux tube, surfaces at different radii are unstable to modes with different values of $m$. $m = 1$ represents a simple kinking of the tube near the surface, with the cross-section remaining circular. For higher $m$ values the cross-section becomes distorted: for instance, $m = 2$ perturbs the tube to a double-helix shape and $m = 3$ to a triple helix. Normally, one expects several such modes to be present and, when they grow to a large enough amplitude, modes on neighbouring surfaces may couple to one another (Waddell et al., 1978).

Aydemir and Barnes (1984) have performed some numerical studies for a reversed field pinch which may be of relevance to coronal structures. Such a toroidal laboratory device possesses a toroidal field component $B_{\phi}$ and a toroidal current $I_{\phi}$ which produces a poloidal field component $B_\theta$ of the same order of magnitude.

Experimentally, an initially turbulent state leads to a spontaneous reversal of the field near the axis followed by a long quiescent phase. In this state the magnetic field is near to a constant-$\alpha$ force-free field which, according to Taylor's hypothesis (1974), minimises the magnetic energy subject to toroidal-flux and magnetic-helicity conservation. Heyvaerts and Priest (1984) have generalised the hypothesis and applied it to the corona in order to deduce the coronal heating and mini-flarings that are produced by tearing turbulence.

Aydemir has studied the relaxation and sustenance of the quiescent state using an incompressible 3D MHD code, with $S = 5 \times 10^1$. The torus is approximated by a periodic cylinder of length $2\pi R_0$, and so the variables are Fourier expanded in the axial and azimuthal directions.

Starting from an unstable equilibrium the nonlinear evolution is followed, with the dominant modes having $m = 1$ and $n = 2$ and 3. The system is driven in the sense that the toroidal current is maintained against resistive diffusion by an external source. For a 2D single helicity calculation, in which only those modes with a given ratio $m/n$ are retained, a steady helical magnetic field is maintained in a laminar manner. For a 3D multiple helicity calculation, when two modes such as $m/n = 1/2$ and $1/3$ are perturbed, many other modes are generated by nonlinear coupling. Below a critical current (such that $\alpha a = 3$) the field evolves to a steady state, and above that value a quasi-steady state is reached with fluctuations about a mean value maintained by a turbulent dynamo for at least 1000 $\tau_A$. Also, for some currents a bifurcation or frequency doubling is observed. Another important effect is that the magnetic flux surfaces break up and the field lines become stochastic, which produces a rapid increase in heat transport across the magnetic field.

#### 1.2.2.3 Coalescence

In the linear regime the fastest growing tearing mode has a very long wavelength ($\approx S^{1/4}$), and so in many cases only one magnetic island will form. Sometimes, however, the structure may be long enough for several islands to grow, and then, in the nonlinear regime, neighbouring islands may be attracted towards one another by an ideal mode known as the coalescence instability (Finn and Kaw, 1977, Pritchett and Wu, 1979). Being an ideal instability, unlike the tearing mode, this mode grows extremely rapidly on Alfvénic times.

The results of numerical simulation by Bhattacharjee, Brunel and Tajima (1983) are shown in Figure 1.2.3b for a plasma $\beta$ of 0.02 and a magnetic Reynolds number of $10^3$. They begin with two magnetic islands in equilibrium, which are assumed to have been created by tearing (first frame).
Figure 1.2.3 A numerical simulation of the coalescence instability showing (a) magnetic field lines at several times (b) plasma density contours. (From Bhattacharjee et al., 1983).
The two islands rapidly approach one another and create an intense current sheet at the interface between them as the coalescence instability saturates (second frame). Then the two islands reconnect (third frame) and coalesce to form a single island (fourth frame), which oscillates in response to its violent birth. Plasma density contours at the beginning of the reconnecting phase (Figure 1.2.3b) at $t = 1.6L/v_A$, where $L = 128$ is the length of the system, suggest the presence of two pairs of slow shocks propagating from the ends of the central current sheet. Also, the large length of the central current sheet and the high speed of approach of the two islands suggest that this may represent a flux pile-up regime (§1.2.3.1).

1.2.2.4 Petschek-Sonnerup Reconnection

When the outflow boundary conditions are free enough and the inhibiting effect of the large tokamak axial field is absent, it is possible for the tearing mode to evolve nonlinearly into the fast steady state of Petschek-Sonnerup reconnection (Forbes and Priest, 1982, 1983a), as described in Section 1.2.1.2. A new discovery by Forbes is that fast-mode shocks may be present in the outflowing hot jets (Forbes and Priest, 1983a, 1983b). These have the effect of degrading the kinetic energy into heat and may be much more efficient at accelerating fast particles than the much thicker slow shocks. The steady Petschek-Sonnerup mode is possible when the inflow speed ($v$) of plasma at large distances is less than a maximum value, $v < v_{\text{max}}$, which depends on the magnetic Reynolds number and also on the external boundary conditions. For pure Petschek reconnection it is typically 0.01 $v_A$, but for pure Sonnerup reconnection it is roughly the Alfvén speed ($v_A$).

1.2.3 Nonlinear Reconnection Experiments

1.2.3.1 New Regimes of Fast Reconnection

Recent numerical experiments at high magnetic Reynolds number by Forbes (Forbes and Priest, 1982, 1983a, 1983b) and by Biskamp (1982a, 1982b, 1982c) have revealed two new regimes of fast unsteady reconnection when the Petschek-Sonnerup mode breaks down (Figure 1.2.4).

The flux pile-up regime occurs when the inflow of plasma is so fast that ($v > v_{\text{max}}$) is violated, as for instance when reconnection is driven by an ideal instability such as coalescence or kinking. In this case the flux cannot reconnect as fast as it is brought in and so it piles up outside the central diffusion region and causes it to grow in length.

The impulsive bursty regime occurs when the length ($L$) of the central diffusion region in either the Petschek-Sonnerup or flux pile-up regime becomes too great (1.2.3)

In this case the central sheet goes unstable to secondary tearing (on the tearing mode time-scale) and coalescence (on the

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure124.png}
\caption{Regimes of Fast Reconnection: (a) Petschek-Sonnerup, (b) Flux Pile-up, (c) Impulsive Burst. (From Priest, 1984).}
\end{figure}
Alfvén time-scale). The result is a more rapid energy release in a series of bursts as the islands coalesce. This could be extremely important for particle acceleration and the impulsive energy release that is often seen in flares.

1.2.3.2 Nonlinear Tearing at High $S$

Steinolfson and Van Hoven (1984b) have investigated numerically the nonlinear evolution of the tearing mode at values of Lundquist number ($S$), (normally equal to the magnetic Reynolds number) between $10^2$ and $10^6$ and dimensionless wavenumber ($\alpha = k\lambda$) between 0.042 and 0.5. They find that the growth slows considerably from the linear rate, and at least 80% of the stored magnetic energy is converted into thermal energy for the long wavelength modes with $ka < 0.5$. Also the maximum electric fields are about three orders of magnitude smaller than the Dreicer field. However, other features depend on the $k$-$S$ parameter regime, as follows.

The incompressible resistive MHD equations are solved with temperature ($T$) and magnetic diffusivity ($\eta$) assumed constant. The initial state is taken to be one isolated wavelength of a linear oscillatory mode extending from the centre ($x=0$) of one island to the adjacent X-point ($x_{\text{max}}$) and from the tearing surface ($y=0$) to a large distance ($y_{\text{max}}$) such that the perturbation is negligible and is decaying exponentially with $y$. Symmetry boundary conditions are applied at $x = 0$, $x = x_{\text{max}}$, $y = 0$, and a non-uniform grid is used in the $y$-direction with a concentration of grid-points near $y = 0$ in order to resolve the resistive layer.

Figure 1.2.5 plots the reduction $\Delta E_{\text{m}} = E_{\text{m,0}} - E_{\text{m}}(t)$ in the magnetic energy $E_{\text{m}}(t)$ stored in the shear layer, where $E_{\text{m,0}} = E_{\text{m}}(0)$. Except for the constant $\psi$ solution, the energy that has been released by the end of the computation is between 8% and 27%. It can also be seen that the longer the wavelength ($\lambda = 2\pi a/\alpha$), the more magnetic energy is ultimately converted, even though the conversion rate is slower at first.

Figure 1.2.6 shows the formation near the X-point of the secondary flow vortex in the opposite sense to the initial linear vortex. When $S$ and the wavelength are large enough the secondary flow can create a second magnetic island near the original X-point. Also, one finds intense current filaments and electric fields near the X-points. At the same time for long wavelengths ($\alpha = k\lambda = 0.05$) the width of the magnetic island grows to more than twice the initial shear layer width ($a$) by the end of the computation, even though nonlinear saturation has not yet occurred.

1.2.4 Emerging Flux and Moving Satellite Sunspots

1.2.4.1 Their Two Roles

Small regions of emerging flux and small satellite sunspots are often observed before flares. They signify the interaction of separate magnetic flux systems, in the first case by means of a vertical motion and in the second case via a horizontal motion, but in either case the effect is similar, namely the pressing of one flux system against another and the creation of a current sheet at the interface at some height $h$. The first role of such flux evolution is to create small flares when the current sheet reaches a critical height such...
that the current density exceeds the threshold for the onset of microturbulence. This has been estimated by solving the energy balance equation within the sheet and so deducing the resistivity from the temperature (Heyvaerts, Priest and Rust 1977, Milne and Priest 1981).

The second role of emerging flux and moving satellites is thought of as a trigger of large flares by initiating energy release in a much more extensive overlying field. In particular, emerging flux may push up against a magnetic arcade containing an active-region filament until it goes magnetically unstable of its own accord (§1.2.6). Alternatively, it may tear away some of the overlying field lines that are helping to stabilise the arcade, or it may cause a large-scale reconnection by creating a small region of enhanced resistivity.

### 1.2.4.2 Numerical Experiment

Forbes (Forbes and Priest, 1984 submitted) has recently conducted the first numerical experiment of emerging magnetic flux by solving the resistive MHD equations with a code that is especially designed to treat shock waves well. The initial state consists of a uniform horizontal magnetic field
in a numerical box with free-floating conditions on the top and sides. New oppositely directed flux is forced in through the base rather rapidly at a speed of $v_A/8$, and the magnetic Reynolds number is 2000. The resulting magnetic and flow patterns are shown in Figure 1.2.7. In the first three panels the flux emerges and reconnects, with internal energy being converted to the kinetic energy of fast jets of plasma. At $t=4$ the emergence of new flux through the base is halted, but the flux continues to rise and enters a highly dynamic stage as it loses quasi-equilibrium. The magnetic field lines pinch off near the base and form a plasmoid, which ultimately disappears as the field reduces to a potential state.

Figure 1.2.8a presents a time-development of the mass density contours, showing the dense emerging flux region and, especially at $t = 3.29$, the two regions compressed by the shock pairs extending from the central current sheet. This sheet is longer than expected for steady Petschek-Sonnerup reconnection, indicating that reconnection is taking place at this time in a flux pile-up regime (§1.2.3.1). The top panel of Figure 1.2.8b gives the heights of the neutral lines as functions of time, with continuous and dashed curves referring to X- and O-points, respectively. It can be seen that at $t=4$ a pair of such points is created and at $t=14$ a pair is annihilated. The lower panel indicates the electric field as a function of time at the X-points. Just before $t=4$ it shows the onset of an impulsive bursty regime (§1.2.3.1), with the electric field having impulsive spikes in excess of the steady Petschek value.

Since the electric field at the X-line is a direct measure of the reconnection rate (i.e. the rate at which closed flux in the emerging region is converted into open flux), the variation of $E_0$ in Figure 1.2.8b gives an indication of the rate at which magnetic energy is converted into kinetic and thermal energy. During the impulsive bursty regime from $t =$
Figure 1.2.8  (a) Mass density contours. (b) Height and electric field of the neutral lines. (From Forbes and Priest, 1984).
3.7 to 4.5 there is a rapid release of magnetic energy over a period of about an Alfvén scale-time, while before and after this period there is a slower release on the order of the tearing-mode time-scale. That this sequence is suggestive of the flare cycle of pre-flare, impulsive, and main phases is possibly not a coincidence. Instead it seems more likely that structures which incorporate both ideal MHD and resistive instabilities (or, alternatively, non-equilibrium states) will show fluctuations in the reconnection rate on both Alfvén and tearing-mode time scales.

1.2.4.3 Current-Driven Instabilities

At the workshop, J. Karpen presented an investigation of the potential role of current-driven instabilities in producing brightenings and general preheating of the plasma in the preflare coronal loops (Karpen and Boris, 1985, submitted). This analytical work calculates the temporal evolution of the ambient plasma characteristics in an emerging, expanding flux tube with an axial magnetic field and electric current. In lieu of focusing on a specific current-driven instability (CDI), they constructed a "generic" CDI with a typical on/off cycle and associated heating. The magnetic-field configuration of an emerging flux tube is simulated by moving two point sources of magnetic flux away from a common origin with constant velocity. The density evolution is derived by considering the mass influx required, but not necessarily attained, for equilibrium in the expanding loop; thus, a range of mass flow rates into the tube is allowed, the zero mass flow yielding complete mass conservation. The temperature evolution is determined by the energy equation, which includes the effects of volumetric heating, intermittent heating due to the CDI, radiation, thermal conduction, and adiabatic cooling. The threshold criterion for the onset of the CDI heating depends solely on the characteristics of the beam current and ambient plasma, and operates under the assumption of marginal stability (e.g., Manheimer and Boris, 1977). Calculations were performed with fast and slow footpoint-separation rates, and with high, intermediate, and low mass-flow rates. The results show a variety of temperature behaviors: in particular, some cases include a single episode of excess CDI heating, lasting for tens of seconds, while others manifest temperature oscillations throughout a large fraction of the simulation period. These types of activity are reminiscent of the patterns of preflare brightenings often observed in the EUV, soft X-ray, and microwave regimes before flare onset (§1.3). The authors plan to use the NRL Dynamic Flux Tube Model (cf. Mariska et al., 1982) to obtain more detailed calculations of the effects of the CDI on the dynamics and energetics in the expanding loop.

1.2.5 Main Phase Reconnection in Two-ribbon Flares

The overall magnetic behaviour during a large two-ribbon event is believed to be as follows. Throughout the preflare phase a large flux tube (containing an active-region filament) and its overlying magnetic arcade rise slowly. The rise may be caused by an ideal eruptive instability when the twist in the flux tube or its height become too great (Hood and Priest, 1980, Hood 1984a). Alternatively, it may be due to magnetic nonequilibrium when the equilibrium of a curved tube ceases to exist (Parker 1979, Browning and Priest 1975, §1.2.6.1) or it may be triggered by emerging flux.

The onset of the flare itself coincides with the start of the much more rapid eruption of the filament. It probably occurs because the magnetic field lines of the stretched out arcade start to reconnect below the filament (Priest 1981a, 1981b). The linear tearing of the field lines leads on to the fast Petschek and impulsive bursty regimes of reconnection, as described below (Figure 1.2.9). During the main phase

![Figure 1.2.9 Magnetic field lines and flow velocity vectors at a quarter of the grid points during the Petschek phase of quasi-steady line-tied reconnection. (Forbes and Priest, 1984).](image-url)
the reconnection is thought to continue and create hot 'post'-flare loops with Hα ribbons at their footpoints as the field closes down. The source of the immense mass of plasma that is subsequently seen to be falling down along cool 'post'-flare loops below the hot loops is an upflow of plasma from the chromosphere along the open field lines before they reconnect (Kopp and Pneuman 1976). The cause of the upflow may well be evaporation driven by thermal conduction or by fast particles that are accelerated at the shocks associated with the reconnection process. Furthermore, it has now been shown that these slow magnetoacoustic shocks can heat the upflowing plasma to the temperatures observed in the hot loops of up to twenty million degrees (Cargill and Priest 1982).

A numerical experiment on the line-tied reconnection that takes place below the erupting filament has been undertaken by Forbes (1982, 1983a, 1983b). He starts with open, stretched out and oppositely directed magnetic field lines in equilibrium and solves the 2D resistive MHD equations for the subsequent development of the right-hand half of the structure. The base of the numerical box is line-tied. Its left-hand edge is an axis of symmetry, and free-floating conditions are imposed on the other two sides.

First of all, the sheet tears near the base and the magnetic field lines start to close down with the X-type neutral point rising and a plasmoid being ejected from the top of the box. In the nonlinear development, reconnection enters a quasi-steady Petschek regime, which is shown in detail in Figure 1.2.9. The decrease of magnetic field strength and convergence of the flow vectors as the reconnection point is approached are characteristic of a fast-mode expansion associated with a Petschek-type of regime (§1.2.1.2). Also, the fast shock in the downflowing jet may be important for particle acceleration. In the subsequent development the sheet thins and the Petschek mode goes unstable, with the reconnection entering an impulsive bursty regime. Secondary tearing creates a new pair of O and X points, and reconnection at the upper X dominates so that the O is moved down and coalesces with the lower X. Meanwhile, a new pair appears and the process of creation and annihilation of neutral point pairs is repeated. The energy release in this process is faster than the steady Petschek rate, and it occurs in the impulsive manner that is observed in many flares.

### 1.2.6 Magnetic Instability Responsible for Filament Eruption in Two-Ribbon Flares

#### 1.2.6.1 Loop Configuration

Many people have modelled the preflare magnetic configuration by a single loop and have investigated its stability, with applications to both small simple-loop flares and large two-ribbon flares in mind. Many such stability analyses have been undertaken neglecting for simplicity the curvature of the loop and regarding it as a straight cylinder (e.g., Raadu 1972, Hood and Priest 1979, Einaudi and Van Hoven 1981). Line tying of the ends of the loop in the dense photosphere is an important stabilising effect which makes the perturbation (ε) vanish there. It keeps the loop stable until the amount of twist in the loop exceeds a critical value, typically 2π or more, depending on the particular equilibrium. The most complete analyses of this type have so far been carried out by Hood and Priest (1981) and Einaudi and Van Hoven (1983). The perturbed equation of motion is solved numerically to give the threshold twist for instability.

The effect of curvature on the equilibrium of an isolated slender coronal loop has also been considered in a simple model (Parker 1979, Browning and Priest 1985) which balances tension and buoyancy. One finds that the variation of the height $H$ of the loop summit with the footpoint separation $W$ is given by

$$\tan^2 \frac{W}{2A} = e^{H/A} - 1,$$

where $A$ is the gravitational scale height. Thus, as the footpoints move apart ($W$ increases) the summit rises ($H$ increases) until, as $W$ approaches $\pi A$, the loop summit floats up indefinitely. For large footpoint separations there is no equilibrium at all. Including an external magnetic field lowers the buoyancy force and therefore the summit height, but it doesn’t change the critical footpoint separation. Including a twist in the loop lowers the magnetic tension and so increases the summit height. It also lowers the critical width and changes its nature to a nonequilibrium point.

#### 1.2.6.2 Arcade Configuration

For two-ribbon flares the preflare magnetic configuration has been modelled more accurately by a coronal arcade. In particular, the effect of line tying has been included in models of force-free arcades (Migliuolo and Cargill 1983, Hood and Priest 1980, Birn and Schindler 1981, Ray and Van Hoven 1982, Hood 1983a, Cargill et al., 1984). The original analysis (Hood and Priest 1981) considered various classes of ideal perturbations and found that a simple arcade with its magnetic axis below the photosphere is always stable to those classes. It also appears to be stable to resistive modes usually (Hood 1984, Migliuolo and Cargill 1983). However, arcades with their magnetic axis a distance d above the photosphere are more interesting, since they are more likely to represent configurations within which an active-region (or plage) filament can form (Hood and Priest 1979). Such filaments are quite different from the large quiescent filaments and form along flux tubes. They are indicators of a highly sheared field and very often erupt before two-ribbon flares, slowly at first and then much more rapidly at flare onset. This type of coronal arcade (whose cross-section contains a magnetic island) is found to become unstable when either the height of the magnetic axis (and therefore of the filament),
or the amount of twist become too great (Hood and Priest 1981). This suggests that the eruption of the arcade may be caused by a spontaneous eruptive instability when the filament height or the magnetic shear become too great.

Recently, attention has been focussed on magnetohydrostatic arcades with a force balance between the Lorentz force, a pressure gradient and gravity. For a two-dimensional isothermal arcade in which the variables are independent of the direction z along the arcade, the magnetic field components can be found, especially in the limit as H approaches infinity such that the gravitational force is negligible (Low 1979, Heyvaerts et al., 1982, Priest and Milne 1980, Zweibel and Hundhausen 1982, Melville et al., 1983, 1984).

Having obtained the equilibria for magnetostatic arcades, it is important to analyse their stability, since an arcade must be stable if it is to store magnetic energy prior to flares. On the other hand, it is also necessary that this energy can be released by an instability when some critical threshold is reached. The stability of arcades can be studied either by the energy method or by solving the equations of motion. Using the energy method Schindler et al. (1983) and Hood (1984a, 1984b) independently obtained a sufficient condition for stability. For free-flow boundary conditions (see below) this condition also becomes necessary when there is no axial field ($B_z = 0$).

The strong stabilising influence of the dense photosphere, known as line-tying, has been modelled in two different ways, either by setting the perturbation ($\xi$) perpendicular to the magnetic field at the photospheric footpoints equal to zero or by making the total perturbation ($\xi + \xi$) vanish there. The physical argument is that the high density (and low temperature) does not allow the photosphere to move in response to disturbances that propagate from the corona. For example, assuming the ratio of photospheric to coronal wave speed to be $10^4$, 99.6% of the energy of a non-resonant MHD wave propagating from the corona should be reflected back and only 0.4% transmitted. It is generally agreed that line tying makes perturbations that are perpendicular to the magnetic field vanish at the photosphere for perfect reflection. However, the condition on perturbations parallel to the magnetic field is more controversial (Cargill et al., 1985 submitted). The two main choices are to regard the ends as being rigid and set $\xi = 0$ (e.g., Hood and Priest 1979) or to allow free flow through the ends ($\nabla \cdot \{\xi e^{-yH}\} = 0$ for an isothermal plasma). Many results in the literature differ because of the choice of this parallel boundary condition as well as the choice of equilibrium.

By solving the equations of motion with free-flow boundary conditions parallel to the magnetic field Migliuolo et al. (1984), have demonstrated that arcades with $B_z = 0$ are unstable to interchange modes with very short wavelength ($\lambda_0$) along the arcade. This instability may be important for the small-scale structure of the corona rather than for the global flare instability. They also showed that, if $B_z$ is non-zero, the arcade becomes unstable when the pressure gradient is large enough, a result which may account for the second stage of a double impulsive flare, in which the second part of the flare occurs after plasma has been evaporated up to the corona by the first part.

More recently, the work has been extended to compare the stability thresholds that result from free-flow and rigid end conditions (Cargill et al., 1985, submitted). For cylindrically symmetric equilibria the presence of a rigid boundary gives rise to substantial differences in the stability thresholds. Equilibria with $B_z = 0$ may be either stable or unstable, depending upon the exact details of the equilibrium and the ratio of the specific heats ($\gamma$). Inclusion of shear ($B_\phi$) is stabilising, and for the equilibria considered a small amount of shear is sufficient to stabilise all the equilibria. Physically, the rigid conditions do not permit incompressible modes, and so there is an increase in the potential energy due to compression of the plasma. Clearly, the difference in the results from two sets of boundary conditions makes it important to understand the real nature of line tying, and to model it adequately (Cargill et al., 1985, submitted).

Hood (1983b) has considered the arcade equilibrium

$$A = A_0 \cos \left( \frac{x \sin Y}{4H} \right)^{1/2} \quad \text{(1.2.5)}$$

where

$$Y = 2\beta H \exp (-1/2 y/H) \quad \text{(1.2.6)}$$

and $\left(2\beta H^2\right)^2$ is the plasma beta. This is a special case of the class considered by Zweibel and Hundhausen (1982), and the field lines are shown in Figure 1.2.10a. As the base pressure (and therefore $\beta$) increases, so the magnetic field lines bow outwards, and eventually for $2\beta H > 1.15$ a magnetic island appears (Figure 1.2.10b). When the pressure is so large that $2\beta H > \pi$ the upper field lines become detached from the photosphere and the configuration ceases to be physically realistic. When the magnetic island is present, Zweibel (1981) has shown that such fields tend to be unstable. Hood (1983b) has extended her analysis to include the effect of magnetic tension, which makes the field stable for small $\beta$.

It should be stressed that stability analyses of the above type may be used to estimate the amount of magnetic energy that may be stored in the corona in the stable state. The equilibria that are considered are certainly not accurate representations of active-region fields (see §1.3), but they do typify their expected properties.

1.2.6.3 Prominence Models

Recently, Malherbe (Malherbe and Priest 1983, Malherbe et al., 1983) set up some new current sheet models for quiescent prominences using complex variable theory. Figure 1.2.11a,b shows two models of the Kippenhahn-Schluter type, while Figures 1.2.11c,d indicate some of the Kuperus-
Raadu type with the magnetic field lines crossing through the prominence in the opposite direction. Leroy, Bommier, and Sahal-Brechot (1984) find observationally that those of Kuperus-Raadu type are, somewhat surprisingly, twice as common. Also, observations of slow steady upflows in prominences when seen on the disc can be explained by a dynamic prominence model in which the magnetic field evolves in response to photospheric motions. The large quiescent prominences are mainly of Kuperus-Raadu type and the footpoint motions would need to be convergent, which suggests that such prominences lie at the boundaries of large-scale giant cells. By comparison, the plage filaments have a Kippenhahn-Schluter field orientation and would need divergent footpoint motions. At present, Malherbe, Forbes and Priest are studying numerically the formation of prominences in current sheets by radiative tearing. They have adopted the previous radiative code of Forbes and Priest (1982, 1983a, 1983b) to include an energy equation with Joule heating, coronal heating and radiative cooling. In particular, the cases when the cooling time is a factor of between 0.1 and 10 times the tearing times are being investigated.

1.2.7 Conclusion

During the Workshop there have been major advances in the theory of magnetic reconnection and of magnetic instability, with important implications for the observations, as follows:

1. Fast and slow magnetic shock waves are produced by the magnetohydrodynamics of reconnection and are potential particle accelerators.
2. The impulsive bursty regime of reconnection gives a rapid release of magnetic energy in a series of bursts.
3. The radiative tearing mode creates cool filamental structures in the reconnection process.

Figure 1.2.11 Current sheet models of prominences.
4. The stability analyses imply that an arcade can become
unstable when either its height or twist or plasma pres-
ture become too great.

1.3 PREFLARE MAGNETIC AND VELOC-
ITY FIELDS

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A description of the structure, dynamics and energetics
of the preflare state depends on our ability to characterize
the magnetic and velocity fields of the preflare active region.
In this SMM Workshop, we fortunately had at our disposal
many sets of coordinated SMM and ground-based observa-
tions of magnetic and velocity fields from the photosphere,
chromosphere, transition region and corona to aid in this
characterization. At the outset we decided that several of
these fields are of special interest to the preflare state:
configurations in the magnetic and velocity fields that seem
peculiar to flaring active regions; the existence of shears (in
both the magnetic and velocity fields); the occurrence of
emerging flux. Some questions naturally arise concerning
these topics. Do flares occur in active regions where the mag-
netic field is force-free (currents are field-aligned), non-force-
free or both? If it is force-free, can it be specified by a
constant-alpha? [Alpha is the ratio between current density
and field strength]. Is magnetic shear correlated with the oc-
currence of flares and, if so, is there a critical value of this
shear? What is the role of the resulting electric currents?
What are the preflare characteristics of the velocity field and
how do they evolve? What is the spatial and physical corre-
lation between sheared velocity and magnetic fields? What
are the conditions necessary for emerging flux to trigger a
flare? What growth rates of flux are significant? How does
the flux emerge into the corona?

Although we did not find answers to all these questions,
we made significant progress in many areas. We found that
the preflare active region is very dynamic, exhibiting recur-
cent mass surges and intermittent heating events at many sites.
In one case, that of an active region not particularly produc-
tive of large flares, the structure of the magnetic field was
best represented by a nonlinear force-free field; for a par-
ticularly flare-productive region, there were indications that,
subject to certain restrictions on the boundary conditions,
the field was non-force-free, exhibiting a measurable Lorentz
force. We also found that both the magnetic and velocity
fields are sheared in flaring regions; the shear of the mag-
netic field attained maximum values at the sites of flare on-
set, whereas the velocity field sometimes exhibited an unusual
vortical structure at these sites. These sheared magnetic fields
produced persistent, large-scale concentrations of electric
currents at the flare sites; numerical values for the magni-
tudes of these currents provided input to models describing
preflare brightenings based on joule heating or current-driven
instabilities. Finally, we found the role of emerging flux in
flares to be ambivalent, providing an obvious triggering of
some classes of flare while having no role in the flare process
in others.

In describing these various results the material has been
arranged as follows. We begin with a characterization of the
preflare magnetic field, using theoretical models of force-
free fields together with observed field structure to deter-
mine the general morphology. We then present direct ob-
servational evidence for sheared magnetic fields. The role
of this magnetic shear in the flare process is considered within
the context of an MHD model that describes the buildup
of magnetic energy, and the concept of a critical value of shear
is explored. The related subject of electric currents in the
preflare state is discussed next, with emphasis on new in-
sights provided by direct calculations of the vertical electric
current density from vector magnetograph data and on the
role of these currents in producing preflare brightenings.
Next we discuss results from our investigations concerning
velocity fields in flaring active regions, describing observa-
tions and analyses of preflare ejecta, sheared velocities, and
vortical motions near flaring sites. This is followed by a criti-
cal review of prevalent concepts concerning the association
of flux emergence with flares.

1.3.1 General Morphology of the Preflare
Magnetic Field

It is generally accepted that magnetic fields are the ulti-
mate source of the energy released in a flare (e.g., Svestka,
1976) and that this energy is stored in an active region prior
to the flare as a result of the stressing of these fields into
non-potential configurations. We have accumulated observa-
tional evidence for such stressed fields, both on large and
small scales, and studied the stressing processes which result
in the eruption of a flare. We first discuss our studies of the
general morphology of the preflare magnetic field.

A. Gary endeavored to classify the non-potential charac-
ter of magnetic fields in active regions assuming that the fields
are force-free, i.e., that the following relation is valid:

$$\nabla \times \vec{B} = \mu_0 \vec{J} = \alpha \vec{B},$$

(1.3.1)

Several active regions observed during SMM were modeled
using the force-free formulation developed by Nakagawa and
Raadu (1972), who assumed that the parameter $\alpha$ is spatially
invariant. One of these regions, AR2684, was of particular
interest since it was observed by instruments on a Lockheed
rocket flight at 20:30 UT on September 23, 1980, as well
as by SMM and ground-based instruments. Although the flare
activity in the region was relatively minor, several C- and
M-class flares occurred on the 23rd and 24th, the largest be-
ing a 1B/M1 event at 07:28 UT on the 24th.
This coordinated observational program produced UVSP, XRP and HXIS data from SMM, Lyman-alpha and 1600 Å spectroheliograms from the rocket experiments, and magnetic field, H-alpha and He 10830 Å data from the ground-based observatories; B. Haisch assembled these data for the workshop. It was hoped that chromospheric and coronal filamentary structure would delineate both footpoints and field lines of the magnetic field of the entire active region. Then, using these inferred structures, the most appropriate value of the parameter alpha could be selected, i.e., the one that matched calculated field lines with the observed ones. A similar method was used extensively in analyses of Skylab data to model the magnetic field of active regions. The basic observational data used in the analyses are shown in Figure 1.3.1a. The bright points observed in the 1600 Å spectroheliograms were assumed to be footpoints of the Lyman-alpha loops and H-alpha fibrils and were thus used as the initial coordinates of the field line calculations for various constant-alpha computations. As expected, Gary found that the field lines calculated for a single value of alpha would not fit all of the observed structures. In Figure 1.3.1b, areas are indicated where field lines calculated for different alphas showed good agreement with the observed fibrilar orientations. Although there are areas of positive, negative and zero alpha, a dominance of positive alpha is indicated. Because the “footpoints” used in the calculations were generally outside the sunspots, this “alpha map” applies only to the weaker field areas.

To investigate the non-potential character of the region’s magnetic field without resorting to an assumption of constant alpha, Gary compared the direction (azimuth) of the observed transverse field in the photosphere with that of a potential field distribution. The use of the azimuth of the transverse field as an indicator of the non-potential character of the field is based on the observation that the projected field lines from the force-free calculations were parallel to the observed azimuthal directions; the only exceptions were the field lines that rose very high into the corona and whose lengths were characteristic of the scale of the magnetogram’s field-of-view. In his analysis, Gary found the deviation of the observed azimuth from a potential orientation at each grid point, and assigned to these points a positive or negative sign depending on the sense of the observed deviation or “twist”; the results are shown in Figure 1.3.1c. Since this “alpha map” only pertains to the regions in and near the sunspots where the transverse field is above 200 G, it is difficult to relate it to the alpha map in Figure 1.3.1b for the areas of the weaker fields. However, where there is some overlap, the two methods give consistent results, and confirm that a constant alpha force-free field cannot characterize the magnetic topology of this active region.

A second region of interest, AR 2372 (very flare-productive on the solar disk in early April 1980), also proved difficult to model, but for another reason. As will be discussed in Section 1.3.2.2, this region exhibited a large degree of shear in its magnetic field in the area of a magnetic δ-configuration (umbrae of opposite polarity within the same penumbra). This extreme shear could not be reproduced with the linear force-free computation of Nakagawa and Raadu because of the limitations on the maximum value of alpha (i.e., twist or shear). In their formulation, alpha must be less than 2π/L, where L is the scale of the magnetogram. However, an analysis by Krall (private communication) produced some evidence that the magnetic field in the area of the δ-configuration was non-force-free. Using transverse field measurements obtained with the MSFC vector magnetograph, he calculated the resultant Lorentz force in the region of the delta from a formulation derived by Molodensky (1974). Krall found this force had a non-zero horizontal component that was consistent with the observed sunspot motions in that area.

These attempts to model the magnetic fields indicate that, for a moderately active region, the structure of its field was fairly well represented by a nonlinear force-free field. On the other hand, calculations based on the observed field of a highly flare-productive region resulted in a non-zero Lorentz force. Until analyses of other regions are available, these results must be regarded as very preliminary.

1.3.2 Magnetic Field Shear

1.3.2.1 Evidence for Sheared Magnetic Fields

Storage of flare energy in stressed magnetic fields arises from the increasing deformation of the magnetic field from a potential configuration. This deformation can occur, for instance, through the shearing of magnetic loops as a result of footpoint translations, or through the twisting of individual loops rooted in sunspots which rotate. Some of our indirect evidence for preflare energy storage in stressed fields comes from the geometry of fibrils and structures within filaments in the vicinity of flares; these fibrils and filamentary structures presumably delineate the chromospheric magnetic field. For example, in a detailed study of the August 1972 flares, Zirin and Tanaka (1973) inferred the presence of strongly-sheared, transverse magnetic fields from the twisted appearance of penumbral filaments. In more recent work using both SMM and ground-based observations, Athay et al. (1984) determined the broad features of the magnetic field geometry from chromospheric and transition region Dopplergrams, assuming that the fluid flow follows magnetic lines of force. H-alpha filament orientation and motion, and the relationship of the filaments to sunspots provided additional information on the field geometry. From these data, they deduced that pronounced magnetic shear was present at transition region heights over the entire length of a prominent segment of the polarity-inversion line. This shear remained relatively steady for periods of several days except for temporary local disruptions due to emerging flux regions (see Section 1.3.4.2).
Figure 1.3.1 Force-free field modeling of AR 2684 for September 23, 1980. (a) The filamentary structures inferred from H-α and Lyman-α spectroheliograms are shown superposed on a plot of the photospheric line-of-sight magnetic field of the region, which was located at N18W22. Also shown are the bright points observed in the 1600 A spectroheliograms. The solid (dashed) magnetic field contours represent positive (negative) field levels of 250 and 500 G; the solid curve separating positive and negative fields is the magnetic neutral line. The field-of-view is 2.5' × 2.5' and the solar orientation is as shown in panel b. (b) Regions are specified where the fibrilar structures of panel a are matched (or not matched) by force-free field lines calculated with positive, negative or zero (potential field) values of the parameter alpha. The symbols are shown in the upper right corner of the panel; cross-hatched areas specify regions where the fibrils and field lines could not be matched to within 45 degrees. The contours shown are identical to those in panel a. (c) Map of the differences between the orientations of the observed transverse field and a potential field, where the potential field fits the boundary conditions imposed by the observed line-of-sight field. Areas of positive, negative and zero deviations or "twist" are shown according to the legend for the parameter alpha since the force-free parameter alpha is also a measure of the twist of the field. Only areas for which the line-of-sight field is greater than 250 G are indicated, except for one region in which the transverse field was above 200 G. The contours shown are again those designated in panel a.
Based on such indirect indications of sheared magnetic fields, much of the previous modeling of preflare magnetic fields during the Skylab series of flare workshops was performed with the assumption that configurations of sheared magnetic fields did indeed exist in preflare active regions. Now, however, direct evidence for sheared magnetic loops comes from measurements of transverse magnetic fields in the photosphere near the magnetic neutral line. At the neutral line, the direction of the transverse component of the field will indicate the orientation of low-lying field loops which connect footpoints on opposite polarity sides. Initial observations of transverse field directions which appeared sheared relative to the neutral line were reported by Smith et al. (1979) using data from the NASA/ Marshall Space Flight Center (MSFC) vector magnetograph (Haygard et al., 1983), which observes in the FeI 5250 A line originating in the photosphere. During SMM, many subsequent examples of sheared magnetic fields in a number of active regions, most of which produced flare activity, were reported by the MSFC group (Krall et al., 1982; Patty and Hagyard, 1984; Smith, 1984 [private communication]).

1.3.2.2 Correlation with Flare Activity

These direct measurements of magnetic shear provide compelling evidence for linking magnetic shear with the incidence of flares. For example, in a statistical study J.B. Smith, Jr. (private communication) found a distinct preference for high flare productivity and major flares in areas with significant magnetic shear. In evolving regions, an increase in shear clearly accompanies an increase in flare frequency and magnitude, while decreasing shear is commonly accompanied by a decrease in flare production. To evaluate the magnetic shear, Smith used the vector MSFC magnetograms which depict the transverse fields at the photosphere as line segments. Their length and orientation give the strength and direction of the transverse field at each point in the field-of-view. The “angle of shear” along the neutral line can be determined by comparing the directions of the line segments to the orientation of the neutral line. This interpretation of shear assumes that line segments of a potential field cross the neutral line orthogonally.

Smith qualitatively evaluated several regions for correlation between this “angle of shear” and flare production. In two cases, a pair of regions were simultaneously visible, one with measurable shear and the other with fields that appeared more potential. In both cases, the region with observable shear produced flares while the other was essentially quiet. Perhaps the most notable example occurred in April 1980 when AR 2370, a large region promising significant activity but producing little of note, rotated onto the visible disk a few days before the birth nearby of AR 2372 early on the 4th of April. Following rapid development of the main spots of AR 2372, pronounced photospheric shearing motions were observed between the 5th and 7th of April for the sunspots of opposite polarities inside this region. During this epoch of spot motions, the transverse field directions indicated the presence of strong shear along the neutral line in relatively strong magnetic fields; flares, some major, were frequent (Krall et al., 1982). A decrease in the shear of AR 2372 after the 7th was followed by a sharp decrease in flare production. Several other regions were analyzed with similar results: those with strongly sheared fields were flare productive while those with essentially potential fields (or weakly sheared fields) had only minor activity.

Smith also studied the development and evolution of shear within AR 2776, during November 1980 during SMM. The evolution of its vector magnetic field over the period November 2-5 is shown in Figure 1.3.2. On November 2nd (Figure 1.3.2a), some magnetic complexity was evident in the presence of a Δ configuration, although the surrounding magnetic gradients were moderate, the fields only moderately strong, and the field alignments generally appeared to be potential. This situation held also on the 3rd and 4th (Figures 1.3.2b,c) but with some complexity added by the building of the positive fields to the north. Still, the observed shear was not extensive. However, the changes between the 4th and 5th were striking, particularly in the pronounced shear seen in the near alignment of the transverse field with the entire length of the neutral line in the area of the delta on the 5th (Figures 1.3.2d,e). In addition, field strengths and gradients increased markedly from the 4th to the 5th. Smith examined the X-ray flares that occurred during the period November 1-12. He found that energetic soft X-ray flares (class M1 or greater) were infrequent until the 5th, when both frequency and magnitude rapidly increased and several major flares followed. Again, the correspondence of increased shear with increased flare activity is borne out by this study.

Smith also analyzed the magnetic shear in other active regions: AR 2522 (June 1980), AR 2544 (June/July 1980) and AR 2725 (October 1980). In Figure 1.3.3, the line-of-sight (B_z) and transverse (B_p) components of the magnetic fields of these three regions are shown along with the calculated vertical electric current densities, J_x. Varying degrees of magnetic complexity were reflected in the level of flare activity for two of the three regions; the third region was somewhat of an anomaly. AR 2725 (columns c and d in Figure 1.3.3) was the most magnetically complex and also the most flare productive. Examination of the transverse magnetic field data revealed significant shear and moderate field strengths along that portion of the neutral line to the left of center in the magnetograms where the flare of October 11 at 17:41 UT (classified as 1B/C7) occurred, as determined from SMM soft X-ray data. Although significant flares were infrequent, a few class M X-ray flares were observed and a major flare (3B/X3) occurred on October 14. AR 2522 (column a in Figure 1.3.3) has the complexity of a convoluted neutral line and an isolated island of positive polarity, but

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Figure 1.3.2 Magnetic evolution of AR 2776 over the period November 2-5, 1980. The field-of-view in all panels is approximately 2.1′ × 2.1′. In all line-of-sight magnetic field maps (B_L), solid (dashed) contours represent positive (negative) fields of 100, 250, 500, 1000, 1500, 2000 and 2500 G. In overlaid transverse field plots (AZ), the transverse field strength and direction are indicated by the length and orientation of the line segments. (a) Overlay of the transverse magnetic field (AZ) on contours of B_L from observations on November 2. A magnetic delta configuration is formed by the intrusion of the negative-polarity sunspot into the positive-polarity field just to the east of the large positive-polarity spot. Analysis of the line segments representing the transverse field that are overlaid on the contours of B_L reveals a generally potential-appearing field, aligned more or less directly from the positive center to the negative portion of the delta. (b) Overlay of AZ on contours of B_L from observations on November 3. Note the growth of the positive fields to the north of the delta. (c) AZ/B overlays for November 4. Growth of the fields continues, but the field orientation remains generally potential in appearance. (d) B_L field on November 5. (e) Overlay of AZ and B_L for November 5. Only the high B_L field contours from panel d have been depicted in order to make more visible the highly-sheared transverse field along the neutral line. The increase in field strengths and gradients can be seen from comparisons of panels d with panels a, b and c, where the contour levels are all the same. (f) Contours of the vertical component of the electric current density (J_z) for November 5 (see Section 1.3.3.1.). Positive (negative) J_z values of 150, 200 and 250 × 10^{-4} A m^{-2} are depicted by solid (dashed) curves. The neutral lines of panel d have been superposed to aid in orientation.
Figure 1.3.3 Vector magnetic fields and electric currents for active regions selected for study by the Preflare Group. The panels in the top row depict the longitudinal magnetic field $B_L$ wherein positive (negative) fields are represented by solid (dashed) contours; contour levels are 100, 250, 500, 1000, 1500 and 2000 G. Panels in the center row show the transverse field $B_T$ depicted as line segments whose length and direction represent the strength and orientation of the transverse component; the magnetic neutral lines are superposed. The bottom row depicts the corresponding vertical electric current densities with the neutral line overlaid in bold lines; contour levels are 150, 200, and $250 \times 10^{-4}$ A m$^{-2}$. (a) Data for AR 2522 on June 25, 1980. Only weak shear is seen along the convoluted neutral line in the area of the southern boundary of the large intruding peninsula of positive polarity near the center of the field-of-view ($2.1' \times 2.1'$). (b) Data for AR 2544 on July 1, 1980. This region was born near central meridian on June 28, but it developed only minor magnetic complexity in the area of the isolated positive spot to the south of the leading negative spot. Field-of-view is $2.1' \times 2.1'$. (c) Preflare data for AR 2725 on October 11, 1980. Significant magnetic shear is seen along the neutral line that lies to the left of the center of the magnetogram, with additional, weaker shear found along the neutral line lying above and to the right of center. The field-of-view is $2.5' \times 2.5'$. (d) Postflare data for AR 2725 on October 11, 1980. The IB/C7 flare, which occurred about midway in time between the two magnetograms (c and d), coincided with the area of most significant shear. At 17:42 UT, near frame maximum, the X-ray loops appeared centered over the north-south portion of the neutral line to the left of center. The field-of-view is the same as in c.
examination of the transverse field reveals only weak shear along the convoluted neutral line. The region produced numerous minor flares, with a few class M events during its disk passage.

But the third region AR 2544 (column b) proved to be anomalous. It produced only a few flares, but there was a rash of activity on June 30th, including an M1, and a major flare (X2) on July 1st, the day of the illustrated magnetogram. From the magnetic data, there appears to be only the minor complexity of the isolated positive spot intruding into the southern portion of the leading negative polarity, and there is clearly no evidence of strong or extensive shear.

In another anomalous example, the active region complex composed of NOAA active regions 2516, 2517 and 2519 produced very little flare activity along the segments of the magnetic neutral line which showed the most evidence of shear in the transition region (Athay et al., 1984). The flares that did occur were mainly associated with emerging flux regions. The magnetic shear was either "rather stable" or did not generate sufficient free energy to fuel a flare.

However, an important factor may be the overall configuration of the magnetic field from the photosphere through the transition region. For the relatively inactive June complex, Athay et al. (1984) inferred the configuration of the magnetic field from observations of fluid flows in the transition region. They found that the extreme velocity shears in the transition region diminished greatly at the photosphere. If the fluid flow follows magnetic lines of force, this result seems to indicate that the magnetic shear also decreased from the transition region into the photosphere (see Section 1.3.4.2). Such a configuration appears to be exactly opposite to that reported by Krall et al. (1982) for a flare-productive active region where the flares occurred at the sites of greatest shear (Hagyard et al., 1984a) as deduced from photospheric observations with the MSFC vector magnetograph. Investigating the field configuration at higher levels, Krall et al. found that the short fibrils seen in Hα aligned with the sheared photospheric field, whereas the orientation of the longer, and presumably higher, fibrils was more or less normal to the magnetic neutral line, a configuration indicative of less shear. Thus, the overall structure of the magnetic field in this more active region was one of decreasing shear in going from the photosphere up into the lower corona.

1.3.2.3 Formation of Magnetic Shear

There is good observational evidence that magnetic shear forms as the result of sunspot motions. Two particularly good examples correlating sunspot motions with the development of photospheric magnetic shear and subsequent flare activity were unveiled in the course of the workshop. The first was the active region of early April 1980, Boulder number 2372. Born on the solar disk early on April 4, it produced many flares during its period of growth and development.

Observations made at the Yunnan Observatory on April 5 from 00:50 to 09:15 UT showed the rapid development of three sunspots through the coalescence of several smaller spots (Hoyng et al., 1982). The motions of the smaller sunspots were grouped into three sectors, with the spots in each sector converging and coalescing into one of the three major sunspots seen on the 6th. Since these motions involved spots of different magnetic polarities, stretching and/or shearing of the inter-connecting fields probably occurred, with energy buildup taking place in the process. Sunspot motions occurred through the 6th, as inferred from MSFC white-light photographs and the magnetic field changes seen in Figure 1.3.4. These motions continued until 19:00 UT on the 7th, whereafter no significant motions were observed. In an extensive study of this active region, Krall et al. (1982) found that these spot motions produced significant shear in the magnetic field with resulting flare activity in the region. This can be seen in Figure 1.3.5 which shows the first large flare on the 5th, and the most intense one, on the 6th, both occurring at the locations of the isolated positive spot and the eastward-moving negative spot. Krall et al. related the formation of magnetic shear to the spot motions using the observed orientations of the transverse fields as shown in Figure 1.3.6. These observations confirm that the transverse magnetic field evolved from a slightly sheared configuration on the 5th (Figure 1.3.6a) into a strongly sheared one on the 6th (Figure 1.3.6b), which then relaxed on the 7th (Figure 1.3.6c) as the sunspot motions ceased. Following this apparent relaxation of the field, the high frequency of flares which occurred through the 7th ceased, and little significant flaring was produced on the 8th and 9th.

The second example was provided by G. Chapman, who presented filtergrams, spectroheliograms and magnetograms showing the buildup of stressed magnetic fields through both rotational and translational motions of a large sunspot in conjunction with a satellite spot of opposite polarity in close proximity to the main spot. Observations of AR 2530 were obtained at the San Fernando Observatory (SFO) for approximately 9½ hours on June 24, 1980.

They showed that during this interval, the leading sunspot of this region rotated and deformed substantially from a round to a U-shape. The satellite spot of opposite polarity was adjacent to one edge of the evolving leader spot; the satellite remained intact until the following day despite the drastic changes of its larger companion. The deformations increased the magnetic gradients in the area of the satellite spot. Major flaring took place while the compression and twisting of the magnetic fields were occurring, rather than after the maximum deformation had been reached. This suggests that the rate of change in the stressing of the magnetic field was more a factor in the flare activity than the sheared topology of the field. In addition, the persistence of the satellite spot following the large flare suggests that magnetic shear between the satellite and main sunspot, rather than the high
field gradient associated with the satellite spot, was the more important factor for the flare.

There are mechanisms other than spot motions that might produce sheared magnetic fields. Newly-emerged flux can produce such complex magnetic configurations as “kinky” neutral lines, satellite spots, and δ-configurations, all recognized as correlating positively with the frequent occurrence of flares. The statistical studies of J.B. Smith, Jr. (private communication) and Patty and Hayward (1984a) show that both kinky neutral lines and δ-spots associated with flare activity are areas of sheared magnetic fields. Sturrock (1983, FBS Study Work Group on magnetic shear, Big Bear Solar Observatory) has suggested that in the process of flux emergence the upflows that bring the field to the surface may shear the emerging field due to the coriolis force. Athay et al. (1984) proposed that the sheared magnetic and velocity configurations they observed in the transition region might be produced by two coherent masses of gas of opposing magnetic polarity converging in the stably stratified layers of the solar atmosphere. This suggestion that shear is produced by two converging eddies is based on analogy with shear in the terrestrial atmosphere. Tang (1983) argues that shear also is produced when originally unconnected sunspots of opposite polarity move past each other. Flux cancellation and submergence probably occurs at the neutral lines in active regions (Rabin et al., 1984), and processes may contribute in the formation of sheared magnetic fields.

1.3.2.4 The Role of Magnetic Shear in the Flare Process

However magnetic shear is produced, its existence and association with flares have been directly demonstrated. Questions then arise as to the exact nature of this association, the role of magnetic shear in the buildup of flare energy, and the triggering and eruption of the flare when a critical value of shear is attained.

In a study of magnetic shear, Wu et al. (1984) used a self-consistent magnetohydrodynamic (MHD) model of shearing magnetic loops to investigate the magnetic energy buildup in AR 2372 the period April 5-7. Wu et al. argued that the evolution of the field observed between the opposing poles of the bipolar region was consistent with a gradual, relative displacement of the bipolar footpoints which occurred during the period April 5-6 (see Figure 1.3.6). The separation of the footpoints of the loops, the maximum footpoint field strength, and the average separation speed of the two spots were all determined from the observational data and used as the initial boundary conditions for an MHD model of an arcade of magnetic loops whose footpoints undergo shearing motions in opposite directions.

Calculations were performed for two different initial configurations of this field: a potential and a force-free field. The photospheric shearing motion of the footpoints of the magnetic arcade was simulated by imposing antiparallel mo-
MAGNETOGRAM (MSFC)  
05:1603 UT

H-ALPHA (SOON)  
06:1423 UT

06:1436 UT  
30 ARC SEC

Figure 1.3.5 Magnetograms and H-alpha images for two flares in AR 2372. The left-hand panels depict the observed line-of-sight magnetic field, using the format of figure 3.4. The right-hand panels show H-alpha images from the SOON system for the flares of April 5th (a IB/M5 at 15:57 UT) and April 6th (a IB/X2 at 14:23). Comparisons of the flare locations with the magnetograms show that both flares occurred in the area of the bipole where significant spot motions were taking place. The fields-of-view are 5' × 5'.
Figure 1.3.6 Evolution of the transverse magnetic field of AR 2372. All panels show the observed line-of-sight magnetic field as solid (positive) and dashed (negative) contours with the transverse field superposed as line segments whose length and direction indicate the strength and orientation of the transverse field. The fields-of-view are 167’ × 167’ and represent blowups of the bipolar region in Figure 3.5. (a) At 14:07 UT on April 5 (shortly before the flare shown in Figure 3.5), the transverse field east of the isolated positive spot was oriented perpendicular to the neutral line. However, to the north and west of this spot, some alignment with the neutral line was seen, implying the presence of shear in the field. (b) By 20:55 UT on the 6th, during the period of spot motion, the strong transverse fields were sheared along most of the neutral line, indicating significant energy storage. (c) Following cessation of spot motion, the shear in the transverse field was less pronounced as observed on the 7th at 19:10 UT.

itions on the footpoints on opposite sides of the neutral line. The magnitude of the velocities varied sinusoidally with distance from the neutral line (axis of the arcade). The self-consistent solutions from this model provided numerical values for the magnetic field, velocity, density, temperature, and pressure as functions of two spatial dimensions and time.

Figure 1.3.7 shows a typical result from this calculation; the different energy modes are shown as functions of time as the photospheric shearing motions proceed for the case of an initial potential magnetic field. The magnetic energy buildup clearly dominates, and its growth rate becomes constant after a short interval, while the interaction among the other modes of energy becomes insignificant. Results obtained for different initial values of the parameters are summarized in Table 1.3.1, which gives the energy growth rates in erg day⁻¹ per km of arcade length. For parameter values typical of the observed conditions, where magnetic energy density dominated the plasma thermal energy density at the photosphere by a factor of 10, i.e., β₀ = 0.1, and where the maximum shearing velocity was 0.1 km s⁻¹, the rates of energy buildup are 2×10³⁰⁻³¹ and 1×10³¹⁻³² erg day⁻¹ for initially potential and force-free fields, respectively, taking arcade lengths of 10⁻⁻³ km. These values are consistent with the observed flare output rates that were estimated by Krall et al. (1982) to be 2×10³¹ erg day⁻¹. Examination of the spatial distributions of magnetic energy showed that the highest concentration of magnetic energy was located near the neutral line, with the concentration being more pronounced in the case of the pre-sheared (force-free) field configuration.

Critical Value of Shear — The preceding studies demonstrate that magnetic energy sufficient to fuel solar flares is accumulated as a result of increased shear in the magnetic field, with the growth rate of magnetic energy roughly proportional to the shearing speed, to the length of the affected neutral line, and approximately inversely proportional to the initial value of the plasma parameter β₀. The next problem, then, is to determine the mechanism by which this free energy is suddenly released in the form of a solar flare. In the context of the smooth buildup of magnetic energy through increasingly greater shear in the field, it is tempting to think in terms of a “critical” value of this shear which,
Figure 1.3.7 Magnetic energy buildup through shearing of magnetic fields: results of an MHD model calculation. The calculation models an arcade of magnetic loops whose footpoints on opposite sides of a magnetic neutral line undergo shearing motions in opposite directions. The excess (above that at time $t = 0$) magnetic, kinetic, thermal, and potential energies are shown as functions of time for an initially unsheared magnetic field configuration. Note that the buildup of magnetic energy dominates and is approximately an order of magnitude greater than the kinetic, thermal and potential energy modes.

When exceeded, triggers the release of energy at these sites of excess shear. Such a concept has been proposed by several theorists (Barnes and Sturrock, 1972; Low, 1977a, 1977b; Birn et al., 1978; Hood and Priest, 1980). The shear in their static models is successively increased until a critical value is reached, after which there are no equilibrium solutions; this critical point has been interpreted as the threshold for the onset of a flare.

Recently, observational evidence for the existence of such a critical shear has been reported by Hagyard et al. (1984a). In their study, these authors analyzed the degree of shear along the neutral line of AR 2372 at a time midway through its early period of flare activity, April 5-7, 1980. They defined the degree of shear, $\Delta \phi$, to be given by the difference at the photosphere between the azimuths of a potential field and the observed field, where the potential field satisfies the boundary conditions provided by the observed line-of-sight field; these fields are depicted in Figure 1.3.8. Using these data, the parameter $\Delta \phi$ was evaluated at 55 points along the neutral line; points 1 and 50 are designated in Figure 1.3.8b. Figures 1.3.8c and 1.3.8d show the variations of the magnitude of the transverse magnetic field ($B_T$) and $\Delta \phi$, respectively, along the neutral line. In Figure 1.3.8d, the asterisks mark points for which $B_T$ is less than or about 100 G; there probably are substantial errors in the observed azimuth at these points, so the corresponding values of $\Delta \phi$ should be regarded with skepticism. Excluding these points, one can see in Figure 1.3.8d that the degree of shear is non-uniform along the neutral line, and has two negative maxima of values $-85^\circ$ and $-80^\circ$ along the segments marked A and B, respectively. In addition, from comparisons of $B_T$ with $\Delta \phi$, these very large shears seem to occur preferentially at locations of maximum values in the transverse field strength. The authors argued that the configuration of the magnetic field at the time of the observations (21:10 on April 6) represented the most sheared state attained by the field in the period April 5-8. During the period 14:00 to 21:00 on the 6th, there were no significant changes in the observed azimuth, even though four major flares then occurred.

The sites of flare onset for the 1B/X2 flare at 14:18 UT on April 6, as inferred from the most intense chromospheric flare emissions observed in off-band Hα, were located on either side of the magnetic neutral line along the segments corresponding to A and B in Figure 1.3.8d, that is, at the sites of maximum photospheric shear. Furthermore, in a later flare for which spatially-resolved X-ray data were available (00:48 UT on April 7), the locations of soft X-ray onset were placed at A. Because the flares occurring in AR 2372 in this time period were homologous, the sites of flare onset for these two observed flares are probably representative of the sites for most of the flares during this period.

Based on these results, the authors proposed a scenario for these flares wherein continued magnetic evolution caused the field's maximum shear to exceed a critical value ($> 80 - 85^\circ$), resulting in a flare at and above the site of maximum photospheric shear. The flare signaled a relaxation of the shear to a value somewhat smaller than the critical value, with further evolution increasing the shear above threshold, another flare, and so on. This scenario, based on observational evidence of persistently sheared fields throughout a flaring epoch, argues against the idea that relaxation of the magnetic field, due to the release of energy in the form of a flare, must proceed until the local shear is negligible. This argument gains support from the preceding analysis of Wu et al. (1984) who showed that energy is more efficiently

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Table 1.3.1 Energy growth in erg day$^{-1}$ per km depth

<table>
<thead>
<tr>
<th>Shearing Velocity km s$^{-1}$</th>
<th>Initially Untwisted Magnetic Field</th>
<th>Initially Twisted Magnetic Field (A 40° Twist)</th>
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</thead>
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<td>$\beta_o = 1.0$</td>
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<td>$1.94 \times 10^{26}$</td>
<td>$2.07 \times 10^{25}$</td>
</tr>
<tr>
<td>1.0</td>
<td>$1.3 \times 10^{28}$</td>
<td>$2.27 \times 10^{27}$</td>
</tr>
<tr>
<td>20</td>
<td>$2.66 \times 10^{30}$</td>
<td>$3.24 \times 10^{29}$</td>
</tr>
<tr>
<td></td>
<td>$1.08 \times 10^{27}$</td>
<td>$1.12 \times 10^{29}$</td>
</tr>
</tbody>
</table>

stored in a field that is already significantly deformed, and that this energy is more concentrated near the neutral line for such a deformed field.

1.3.3 Electric Currents in the Preflare Active Region

The presence of sheared, photospheric magnetic fields in the pre-flare state implies the existence of electric currents in the atmosphere above the photosphere in which superpotential energy is stored and subsequently released in the outbreak of a solar flare. This release of energy is generally considered to result from resistive MHD instabilities that involve currents flowing either parallel to the magnetic field or perpendicular to the field as in the case of an X-type neutral point. Thus, the concept of a critical value of magnetic shear may have its counterpart in "critical" values for these currents.

Observational data that yield information on the magnitudes and distributions of these currents provide useful constraints on their models of solar flares. The most direct measure of solar currents available comes from observations of the vector magnetic field at the photosphere, from which we can derive the vertical component ($J_z$) of the electric current density passing through the photosphere, using the relation $(\nabla \times B)_z = \mu_0 J_z$. Quantitative values of $J_z$ have been estimated with an uncertainty of $25 \times 10^{-4}$ Am$^{-2}$ which is inherent in the measurement of the magnitude and azimuth of the transverse component of the magnetic field.

1.3.3.1 $J_z$ Concentrations in Flaring Active Regions

The study by J.B. Smith, Jr. (Section 1.3.2.2) of sheared magnetic fields in active regions was extended by deLoach to include the vertical component of the photospheric electric current density, $J_z$. This study utilized the magnetic field data for the regions and times listed in Table 1.3.2 with notable flares. The $J_z$ patterns shown in Figure 1.3.2f and in the bottom panels of Figure 1.3.3 correspond to the regions listed in that table. In a majority of these regions, concentrations of $J_z$ were seen along the magnetic neutral line. Indications of additional strong currents often appeared well away from the neutral line; but most of these latter $J_z$ features are probably artifacts of the computational techniques used to resolve the 180° ambiguity in the direction of the magnetic field's transverse component or of the small signal-to-noise ratio in umbral areas. There is a greater level of confidence in the $J_z$ patterns calculated from the sheared transverse magnetic fields in the vicinity of the neutral line where these complications are not a factor.

With these caveats in mind, examination of the data showed that $J_z$ concentrations exist in neutral-line regions where flaring occurs; the strength of these currents depends upon the degree of shear present in the vicinity. As discussed in Section 1.3.2.2, a notable increase in field strength and gradient took place in AR 2776 on November 5, and the transverse field directions were closely aligned along the principal neutral line. The $J_z$ calculations for that region show strong currents in that same area, as seen in Figure 1.3.2f. In the case of AR 2725 (Figures 1.3.4c and d), in which the transverse field is highly sheared along the north-south portion of the principal neutral line, strong currents are present in those locations as well. It was also noted that the X-ray flare which took place in this region on the 11th at 17:41 UT had a loop structure that crossed, and was centered over, this area of strong shear and $J_z$.

The example shown for AR 2522 in Figure 1.3.4a reveals that an area of weak shear lies along the neutral line to the east. Once again the strongest currents lie in the vicinity of these same areas of the neutral line. Finally, in the example of AR 2544, a rather active region of very little magnetic complexity, the amount of shear present was weak and located near the top of the loop-shaped neutral line at the right of Figure 1.3.4b; that is also the site of the only area of significant $J_z$.

Examination of these and other data for $J_z$ reveals that the existence and general behavior of the photospheric currents in flare-productive active regions are consistent with the degree of persistence and amount of shear exhibited by the transverse magnetic field along the magnetic neutral line. We infer from these observations that the somewhat stable nature of the sheared field configuration throughout the ac-
tive lives of these regions applies to $J_z$ as well, and that the continued presence of magnetic shear and electric currents at and near flare sites indicates that further activity is likely to occur.

1.3.3.2 Correlations of $J_z$ Concentrations with Sites of Flares

For one active region studied in detail, Hagyard et al. (1984b) found a strong correlation between the sites of flare knots and concentrations of $J_z$, thus confirming the previous work of Moreton and Severny (1968). The observations were carried out on April 6, 1980, at 21:10 UT in active region 2372 (see also section 1.3.2.4); the results are shown in Figure 1.3.9 which shows the observed magnetic field and derived electric currents. In Figure 1.3.9b, one can pick out seven compact areas of maximum $J_z$ with $J_z = 0.025$ A m$^{-2}$; these maxima are designated by the numbered labels indicated in Figure 1.3.9b. Since the maxima at areas 1, 3,
### Table 1.3.2 Date and Times (UT) of MSFC Magnetograms (B) and SMM Events (E) Flare Precursor Matrix Study

<table>
<thead>
<tr>
<th>AR 2522</th>
<th>AR 2544</th>
<th>AR 2725</th>
<th>AR 2776</th>
</tr>
</thead>
<tbody>
<tr>
<td>19 — 1839 E</td>
<td>30 — 2044 B</td>
<td>9 — 2116 B</td>
<td>5 — 1754 B</td>
</tr>
<tr>
<td>20 — 1722 B</td>
<td>30 — 2135 B</td>
<td>10 — 1504 B</td>
<td>5 — 2223 E</td>
</tr>
<tr>
<td>20 — 2025 B</td>
<td>30 — 2312 B</td>
<td>10 — 1809 B</td>
<td>6 — 1445 B</td>
</tr>
<tr>
<td>25 — 1550 E</td>
<td>1 — 1628 E</td>
<td>11 — 1529 B</td>
<td>11 — 1741 E</td>
</tr>
<tr>
<td>.25 — 1757 B</td>
<td>1 — 1651 B</td>
<td>11 — 1630 B</td>
<td></td>
</tr>
<tr>
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<td>1 — 2052 B</td>
<td>11 — 1857 B</td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>29 — 0235 E</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>29 — 1041 E</td>
<td></td>
<td></td>
<td></td>
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</table>

and 7 occur for only one data pixel, they should be viewed with some skepticism in comparison with the other four maxima.

These locations of maximum \( J_z \) were compared with the spatial distribution of flare intensities observed for the 1B/X2 flare that began at 14:18 UT on the 6th, about 7 hours prior (see Section 1.3.3.3 following) to the time of the \( J_z \) data. In Figure 1.3.9, the locations of the most intense \( H_e \) emissions for that flare are shown with respect to the magnetic neutral line derived from an observation of the magnetic field near the time of the flare. In addition, "A" indicates the location of onset for a flare at 00:48 UT on the 7th (4 hours after the \( J_z \) observations) as seen in soft X-ray observations from SMM (Machado et al., 1983). Comparison of Figures 1.3.9b and 1.3.9c shows that the areas of enhanced \( J_z \) were approximately co-spatial with the sites of flare onset.

#### 1.3.3.3 Evolution of \( J_z \) Patterns

The sheared configuration of region AR 2372 persisted during the period of these flares on the 6th and early 7th, with no perceptible relaxation taking place following the flares (Hagyard et al., 1984a). From this observation, one infers that the pattern of \( J_z \) concentrations also showed no significant changes during this particular period. However, during most of the interval April 5-7, intense and rapid magnetic evolution took place in the area of the \( \delta \) configuration with significant flare eruptions. Thus, one suspects that the \( J_z \) configuration also was undergoing significant changes during this interval. To investigate this further, deLoach has studied the emergence and evolution of the \( J_z \) patterns in the \( \delta \)-area of AR 2372 from April 5-7. His aim was to determine whether the patterns changed rapidly in strength and/or location, or were in fact maintained over periods long in comparison with the observed flare activity. The region history has been discussed in a previous section (1.3.2.3) and in Krall et al. (1982). Although the region emerged very early on 1-58 April 4, the first vector magnetic field data were not obtained until about 14:00 UT on the 5th. Thus it was not possible to see the initial emergence of a \( J_z \) pattern as the region appeared and grew on the 4th.

For the study of the evolution on the 5th, vector magnetograms obtained at five intervals between 14:00 and 19:00 UT were selected for \( J_z \) calculations; the results are summarized in Figure 1.3.10. The sheared nature of the magnetic field along the neutral line is evident in each of the panels depicting the transverse field (\( B_T \)); the azimaths are closely aligned with the neutral line. This nonpotential field configuration implies a non-zero curl in these areas and, hence, that electric currents are present. This expectation is borne out in the maps of \( J_z \) shown in the bottom panels of Figure 1.3.10. In that figure obvious changes appear in the magnitudes of the line-of-sight and transverse components of the magnetic field as well as in the azimaths near the neutral line. These might be expected because of the evolving magnetic complexity during this period, although some of the subtler changes are seeing effects. The most significant change in the transverse field occurred between the magnetograms obtained at 14:07 and 16:03 UT. This observation is especially interesting since a flare classified as 1B/M5 took place in the region at 15:54 UT. Despite its restructuring the field remained highly sheared at the neutral line. Furthermore, the site of the strongest current density, which was seen in the earliest observation at 14:07 UT, persisted in its location relative to the neutral line throughout the series of observations, that is, just above the "dip" in the neutral line and extending along the left section of that part of the neutral line.

To extend the study of the evolution of \( J_z \) in this active region, deLoach used the maps of \( J_z \) generated by Krall et al. (1982) for April 6 and 7; these show that the sites of strongest current density on the 6th remained along the neu-
Figure 1.3.9 Concentrations of electric currents at flare sites in AR 2372 on April 6, 1980. (a) The line-of-sight magnetic field observed at 21:10 UT in the area of the magnetic dipole lying to the southeast of the leader spot (see also Figure 3.5b). This area was the site of most of the early flares in AR 2372. Solid (dashed) curves represent positive (negative) contours of the field. (b) Calculated vertical electric current densities ($J_z$) for the same field-of-view ($1.67' \times 1.67'$) as panel a. The heavy solid curve delineates the magnetic neutral line in panel a to aid in orientation. Five contour levels of $J_z$ are shown in the panel: 50, 100, 150, 200, and 250 $\times 10^{-4}$ A m$^{-2}$; solid (dashed contours) represent positive (negative) values of $J_z$, with "positive" indicating a $J_z$ flowing upward out of the photosphere. Note the seven areas of concentrated maxima of $J_z$. (c) Locations of flare intensities in AR 2372 for the IB/X2 flare at 14:18 UT on April 6, 1980. The $2' \times 2'$ field-of-view of this figure is centered on the dipole area of Figure 1.3.14a, and the heavy dashed curves locate the two segments of the neutral line corresponding to those shown in Figure 1.3.14. The hatched regions show the areas of most intense off-band emission, while the dots outline areas of fainter emission. The loops sketched at "B" are inferred from the emission seen at line center and $\pm 0.4$ Å in Hα. The area designated by "A" is explained in the text.
tral line, with the primary maximum still located in its western "dip" but migrated westward along with the isolated positive polarity. On April 7th, although still present, the $J_z$ maxima are less clearly defined above the background noise.

Throughout the period studied (April 5-7), the persistent positive $J_z$ concentration is situated in approximately the same location relative to the neutral line. However, the more notable negative $J_z$ areas seem to shift. On the 5th, the primary negative concentration of $J_z$ is located north of the neutral line, coincident with the negative polarity region seen in the panels of the line-of-sight magnetic field ($B_L$) in Figure 1.3.10 (April 5th). This suggests that the electric currents are flowing along force-free like paths that connect the positive and negative magnetic polarities. From the 5th to the 7th, significant proper motion of the spots associated with these two fields was observed. The changes in the current distributions are consistent with these magnetic changes; as the fields and currents restructure, the currents still flow across the neutral line.

1.3.3.4 $J_z$ Correlations with Preflare Brightenings

Observations with the SMM/UVSP instrument have revealed numerous intensity enhancements in various bright
points in an active region prior to a flare (Cheng et al., 1982). Studies show that these preflare bright points are sometimes, but not always, associated with the UV flare kernels. For example, for the flare on April 8, 1980, at 03:03 UT in AR 2372, Cheng et al. inferred that four UV bright points observed prior to the flare were footpoints of two loops crossing the magnetic neutral line; the ensuing flare occurred in one of these preexisting loops. To investigate the source of these preflare UV brightenings deLoach et al. (1984) have compared distributions of vertical electric current density, J_z, with UV spectroheliograms. If ohmic heating from the electric current is a significant contributor to these brightenings, these comparisons should show that sites of maximum J_z underlie areas of UV enhancements.

The active region chosen for the study was, again, AR 2372, for the period April 6-7, 1980. Two series of UV spectroheliograms were used, one in Lyα (1216 Å) and the other in N V (1239 Å). The complete series of Lyα and N V spectroheliograms indicate that the region showed persistent internal structure with preferentially bright and dark areas. In addition, the area of strongest J_z maintained its pattern within the δ-region during the period covered by the UV data. When the J_z and UV data were spatially registered, the maximum concentration of J_z fell in an area that was persistently enhanced in the Lyα/N V series.

While this result encourages the view that these brightenings are due to ohmic heating, there is no simple relation between the measured J_z and the heating. For example, there were other areas of enhanced UV emission with no coplanar current at the level of the lowest J_z value measurable. Moreover, the measured J_z maximum of 0.01 A m^{-2} would supply only about 0.1% of the average Lyα flux (∼ 10^8 erg cm^{-2} sec^{-1}) radiated from active regions. deLoach et al. concluded that although resistive heating may be important in the transition region, the currents responsible for the heating are largely unresolved in the measurements of their study (∼ 5 arc sec resolution). This conclusion is substantiated by recent work of Rabin and Moore (1984), who suggest that the lower transition region is heated by filamentary, fine-scale electric currents flowing along the magnetic field.

1.3.3.5 Stochastic Joule Heating

In addition to these preflare UV brightenings, it appears that a broad range of smaller-amplitude brightenings are present in most active regions, according to the results of a study by Porter, Toomre and Gebbie (1984) reported at the workshop. Using observations obtained with the UVSP instrument, they found frequent and rapid fluctuations in Si IV and O IV line emission at sites of enhanced intensity within an active region. These brightenings were smaller in amplitude than the UV bursts that have been studied in some detail through observations from the OSO-8 satellite in the C IV and Si IV spectral lines (e.g., Lites and Hansen, 1977; Athay et al., 1980).

The observations reported by Porter et al. (1984) were carried out during seven consecutive orbits of the SMM satellite on October 27 and 28, 1980, in Active Region 2744. Large spatial rasters were performed intermittently to locate the brightest pixel in the region. Subsequent to this, the Si IV and O IV counts in the brightest pixel were measured 1500 times with 0.08 s temporal resolution. 3" × 3" and 4" × 4" entrance slits were used. A total of 67 such sequences was obtained, covering several bright points in the region.

Though the nature of the experiment was to wander from brightest point to brightest point throughout the active region, the pointing did return a number of times to a few consistently bright points. In Figure 1.3.11, the data are shown for one of the brightest sites during the first two orbits on the 27th; this point was perhaps a footpoint of a loop that flared at 02:24 UT on the 28th. Many of the more rapid intensity variations in time were due to small-amplitude jitter in the satellite pointing. By comparing their observations with satellite-pointing data, the authors attempted to remove these effects. The relatively smooth curves drawn through the data points represent their best estimates of the actual solar output. From these and similar high-time-resolution observations of bright points in this active region, the authors showed that significant increases in Si IV intensity occurred almost continually on time scales of 10 to 60 s. The intensity enhancement during the brightenings was commonly 20 to 100%, and sometimes larger. These brightenings were present throughout the period of observation, and were so prevalent as to be found in about two-thirds of the selected observing intervals. The analysis of pointing errors leads to an estimate of the possible size of the bright elements as 1" or less.

Evidently, the spectrum of heating responses in the transition region extends from flares and the large amplitude bursts down to the smaller, and usually short-lived (20 s to 60 s), brightenings reported in this study. The transition region is apparently subjected to a variety of heating events on a broad range of spatial and temporal scales. The timing for these smaller events is compatible with an almost instantaneous local heating within the transition region followed by radiative cooling.

1.3.4 Characterization of the Preflare Velocity Field

Of equal importance to sunspot motions in characterizing the preflare state are the Doppler velocity patterns that are observed in active regions. These cover the spectrum from filament activation and eruption, surges, and preflare mass ejections to the predominantly horizontal shearing patterns that are suggestive of cyclonic motions in the photospheric areas where flares occur. For example, some of the most easily recognizable flare precursors are the distinct Doppler patterns observed in the ascending phase of erupt-
ing filaments (Martin, 1980). Furthermore, detailed studies of photospheric velocity fields in active regions show that flares tend to be associated with complex velocity patterns (e.g., Martres et al., 1971). Harvey and Harvey (1976) reported that flares seem to occur in areas of strong horizontal velocity shear along the magnetic polarity-inversion line. They concluded that the velocity field is at least as significant as the magnetic field in the flare-buildup process, and urged that equal emphasis be placed on the study of the velocity field. During the SMM observing period in 1980, this council initiated many coordinated observing programs in which ground-based Doppler measurements were obtained in conjunction with observations of transition-region velocities using the UVSP instrument. In the following sections we report on results of those observations that pertain to the preflare active region.

### 1.3.4.1 Preflare Ejecta

During SMM, the Meudon group, represented in the Preflare Group by Schmieder and Martres, observed many surges in their investigation of the flare-buildup process. They were specifically interested in determining whether surges are produced by the same mechanism(s) as flares. They carried out several programs in conjunction with UVSP observations to define the geometrical, thermal and dynamical characteristics of surges (Schmieder et al., 1983).

In one of these programs, they obtained simultaneous ground-based Hα and UVSP C IV observations of recurrent surging in an active region prior to a period of flare activity. The active region (AR 1646) was observed on September 1, 1980, during the time period 12:30-14:08 UT, near disk center. This region developed as a new active center on August 28; there followed a complex evolution over the next few days with a new dipole emerging to the east of the initial one on the 29th (Figure 1.3.12). The new preceding spot increased in size during the 31st and began to move toward the first preceding spot with a velocity of 0.1 km s⁻¹. This motion led to a compression of the following (inverse polarity) spots between the two preceding spots and caused recurrent ejections of matter on September 1 with time intervals of about 10 minutes. Frequent but minor flaring also occurred on the 1st, beginning with a SN/C3 event at 14:08 UT and ending at 22:06.

The Multi-Channel Subtractive Double Pass-Spectrograph (MSDP) in the solar tower of Meudon provided two-dimensional observations of velocities and intensities in the Hα spectral line with a spatial resolution of 1" × 1" and...
a repetition rate of one minute. The UVSP provided a dopplergram and an intensity map in the C IV (1548 A) line over a 4' x 4' field, followed by a set of 24 intensity maps with a reduced field of 2' x 2' with spatial resolution of 3'' x 3'' which focused on the surge event.

The intensity maps in both Hα and C IV showed recurrent maxima in brightness of the facula, but the brightenings in C IV tended to occur a few minutes prior to those in Hα. Three surge events were observed during the time period 12:32-13:15 UT. In Figure 1.3.13, the Hα velocities and intensities are shown for times near the beginning and end of the first event. The surging is clearly located between the two sunspots, along an axis perpendicular to the line joining these spots. The intensity and velocity in the transition region near the beginning of the first surge show that the C IV brightness is elongated in the same direction as the Hα emission but with a slightly greater extension. Only one UV velocity map was obtained for the first surge, at 12:32 UT. This showed upward velocities of 30 km s⁻¹ and a more extended (> 2') velocity structure than the one seen in Hα (< 1'). The C IV velocity structure also is more extended than the emission structure seen in C IV.

The time evolution of the surge was obtained from the sequence of MSDP Hα data. The brightening of the facula occurred a few minutes before the maximum extension and velocity of the absorbing feature at 12:36 UT. The redshifted area, which initially corresponded to the emission feature, progressively enveloped all of the absorbing material. The horizontal velocity along the axis of the surge was derived from the position of the absorbing matter and found to be 60 km s⁻¹.

In order to interpret the Hα data in terms of radial velocities, the Hα profiles must be carefully studied. In their interpretation, Schmieder et al. (1984) proposed a "cloud model" to represent the absorbing feature and considered the measured line profiles to be a convolution of two profiles corresponding to the cloud overlaying the chromosphere. The observed temporal behavior of the spectra was consistent with a cloud whose velocity reversed direction. Radial velocities were evaluated to be 25-30 km s⁻¹ in the ascending phase of the ejection, and 40 km s⁻¹ in the descending phase.

Analysis of the complete set of data indicated that recurrent ejecta lasting 10 minutes occurred on September 1 with intervals of about 20 minutes. The observations were consistent with the following scenario. A loop emerging from the brightened facula was compressed by the two merging sunspots. In the first phase, the cold material visible in Hα followed the field lines of this loop with motions upward from the feet. However, the kinetic energy of the material was not sufficient to propel the matter along the whole length of the arch. Instead, the matter fell back along the loop, and the process was repeated periodically. Because of this periodic reorganization, it was conjectured that energy sufficient to trigger a flare could not be built up.

1.3.4.2 Observations of Velocity and Magnetic Shears in Flaring Regions

Evidence of sustained magnetic and velocity shears in an active region, reported by Athay et al. (1984), was discussed at the SMM Workshop by H. P. Jones. The authors com-
pared UVSP Dopplergrams and spectroheliograms in C IV, Si IV, and other UV lines for Hale region 16918 (Boulder region 2517) with ground-based magnetograms, Dopplergrams, and spectroheliograms taken at Kitt Peak, and with Hα filtergrams taken at Big Bear Solar Observatory. The active region was in a complex which passed across the solar disk in the latter half of June 1980. The region was characterized by an unusually long magnetic neutral line that ran more or less eastward from its western extremity for some 300°, and then curved rather sharply to southeastward direction for about 600°. A set of six Kitt Peak photospheric magnetograms is shown in Figure 1.3.14; the two segments of the neutral line are quite evident on the magnetogram for June 19. A complex, time-varying system of Hα filaments paralleled the magnetic neutral line; several filaments with footpoints anchored in regions of opposite polarity were spaced at wide intervals along the neutral line. Along the east-west segment, the filaments tended to be long, gently curved, and frequently quite broad in their north-south dimension. Filaments along the second segment of the neutral line were shorter, more curved and of shorter lifetime than those in the east-west segment.

UVSP Dopplergrams were made simultaneously in Si II and C IV several times per day during the period of observations of this region. Dopplergrams in C II were made during one orbit on June 17, and a series of Dopplergrams were made in Fe XII on June 17, 18 and 19. Figure 1.3.15 exhibits examples of the Dopplergrams made in these four ions. Ground-based Dopplergrams were made in the Fe I (8688 A) and Ca II (8542 A) lines on June 18, 19 and 20. The authors found similar velocity patterns in C IV, C II and Ca II, although the areal extent of the observed pattern decreased in the order given. Examination of the magnetic and velocity data showed an inversion line in the line-of-sight velocity fields in the transition-region and chromosphere which conformed to the extended, stable, magnetic inversion line. The lateral gradients in both magnetic and velocity fields across this "neutral" line were strong and sharp; this structure maintained its general character for well over a week. From the C IV Dopplergrams, they found velocity differ-
Figure 1.3.14 Magnetic evolution of AR 2517 for the period June 17-24, 1980. The individual frames are portions of six full-disk photospheric magnetograms taken at Kitt Peak. White and dark areas denote positive and negative line-of-sight magnetic fields, respectively.
Figure 1.3.15 UV Dopplergrams of AR 2517 for the period June 17–19, 1980. All frames are to the same scale with fields-of-view of $4' \times 4'$ for the larger frames. Red shifts are shown in white. The C IV and Si II Dopplergrams are corrected for solar rotation to mimic the observing times of the corresponding magnetograms in Figure 1.3.14. Note the absence of any clear pattern in the Doppler signals for the Si II and Fe XII lines.
ences between adjacent red and blue shifted bands either side of the velocity inversion line that frequently exceeded 20 km s\(^{-1}\). The average velocity gradient across the inversion line was approximately 2 km s\(^{-1}\) arcsec\(^{-1}\), and this steep gradient often persisted for distances of 9''.

In the chromospheric Ca II data, these values were reduced: the maximum velocity gradient was 0.5 km s\(^{-1}\) arcsec\(^{-1}\), and the maximum velocity difference across the inversion line was about 1.8 km s\(^{-1}\). The authors inferred that there was a strong horizontal component of the velocity field since the flow pattern weakened as the region approached central meridian and changed sense after meridian passage. This effect is illustrated by the three C IV dopplergrams for June 17, 18, and 19 in Figure 1.3.15. The authors identified the orientation of the fluid flow in the region with the orientation of the magnetic field, assuming that the fluid flow follows the magnetic field.

The resultant picture of the magnetic field near the neutral line was one of extreme shear at the level of the transition region where C IV is formed, diminishing to greatly reduced shear at the photosphere where the magnetic field was observed. Moreover, the simplest velocity pattern consistent with the data was that of material flow diverging from the tops of low-lying, sheared loops that were closed over the neutral line. The data did not provide obvious clues regarding the supply of material to these loops, but the authors suggested that the sheared magnetic and velocity configuration might be sustained by an underlying, large-scale circulation pattern such as the slow convergence of two giant cells of opposing magnetic polarity.

Numerous small flares and emerging flux regions were reported around the neutral line by Martin et al. (1983), and the observed transition-region line intensities showed continual brightenings. However, the segments of the magnetic neutral line that showed the most evidence of shear produced very little flare activity; the majority of the activity was mainly associated with emerging flux regions. Evidently, this configuration, with strong magnetic shear in the transition region diminishing to reduced shear in the photosphere, is either rather stable or does not contain an abundance of free energy.

### 1.3.4.3 Vortical Velocities Near Flaring Sites

The Solar Department at the Paris-Meudon Observatory carries out simultaneous observations with \( \approx 2'' \) spatial resolution in H\(\alpha \) and photospheric spectral lines to study chromospheric structures, line-of-sight magnetic and velocity fields, and flare locations. These studies led to the recognition of large-scale (15-20") structures in both the magnetic and velocity fields: evolving magnetic structures (e.g., Martres et al., 1968) and star-shaped and vortical velocity patterns (Martres et al., 1973). The appearance of combinations of these patterns has been related to magnetic evolution and solar flares (Martres et al., 1974, 1977).

During the workshop series, the Preflare Group tried to identify flare events for which there were observations of vortical motions and transverse magnetic fields. Only one active region was found, AR 2490, which was discussed previously to illustrate the correspondence between the occurrence of vortex motions and flares on June 7 and 8, 1980. Figure 1.3.16a shows the line-of-sight field as measured by the MSFC vector magnetograph on the 7th at 17:40 UT; an area of parasitic polarity is indicated by the arrow. The corresponding transverse magnetic field is seen in Figure 1.3.16b; the area of parasitic (opposite) polarity has been superposed on this image to aid in orientation. The field direction appears sheared along the eastern and western sections of the magnetic neutral line separating the parasitic polarity from the field of the large sunspot. However, it is difficult to interpret these data because the area is so small. The location and sense of rotation of the vortex pattern observed by the Meudon group at 8:49 UT on the 7th is indicated on a plot of the sunspot's intensity in Figure 1.3.16c. The observation of the vortex motion took place during a flare (8:45 – 8:52 UT) in the vicinity of the vortex cell; later observations at 12:09 UT on the 7th showed no signature of a vortex cell in this area. It is interesting to note that this vortical pattern occurs in an area of large horizontal gradients of the transverse field: just to the south of the parasitic polarity in Figure 1.3.16b the transverse field is very weak, whereas to the west of the neutral line the transverse component is larger than in any other area of the field-of-view. Since the vector field was observed almost 9 hours after the detection of such correlations. Clearly, future coordinated observations are needed to study these interesting phenomena.

A preliminary simulation of the short-term evolution of vortex cells by Rayrole and Berton was outlined at the workshop by Martres. The study involved the observation and analysis of magnetic and velocity data for AR 2438 on May 10, 1980. Observations of the velocity field in this region are shown in the top row of Figure 1.3.17; they show the evolution of the velocity during the interval 13:20 to 14:00 UT.

To interpret these observed patterns, Rayrole and Berton performed numerical simulations that combined different vortical flows with typical Evershed motions. The parameters for the simulations were (1) the profiles of the vertical and horizontal components of velocity, \( V_Z (r) \) and \( V_H (r) \), where \( r \) is the distance from the origin of the coordinate system chosen for the structure, (2) the profile of \( \phi (r) = \tan^{-1} (V_{HT}/V_{HR}) \), where \( V_{HT} \) and \( V_{HR} \) are the tangential and radial components of \( V_H (r) \), and (3) the maximum values \( V_Z \), \( V_H \) and \( \phi \) of the respective velocity profiles. The assumed horizontal velocity patterns are shown along the bottom row of Figure 1.3.17. Initially, the velocity pattern was a pure Evershed flow. This was followed by the development of a central vortex cell and then an outer vortex cell. The middle row of Figure 1.3.17 depicts the resulting "Doppler-
Figure 1.3.16 Vector magnetic field in the area of a vortical velocity cell. (a) The line-of-sight magnetic field observed in AR 2490 on June 7, 1980 at 17:40 UT. Positive (negative) fields are outlined by solid (dashed) curves. The arrow points to the region of parasitic polarity where a vortical velocity cell was observed. (b) The observed transverse magnetic field. The line segments represent the strength (length of segment) and direction (orientation of segment) of the field. The region of parasitic polarity has been superposed to aid in orientation. (c) The observed sunspot and vortex cell. Contours represent levels of intensity of the sunspot. The heaviest contour shows the umbral boundary. Again, the region of parasitic polarity has been superposed on this panel. The arrow indicates the location and sense of circulation of the vortex cell that was observed in this region at 8:49 UT. All fields-of-view are 1.67' × 1.67'.
Figure 1.3.17 Comparison between observed velocity patterns in AR 2438 and numerical simulation. Top row: Dopplergrams observed on May 10, 1980, during the period 13:20 to 14:00 UT. Blueshifted (redshifted) velocities are represented by white (dark) shadings. The arrows point to features that are modeled in the numerical simulation. Middle row: "Dopplergrams" generated by numerical simulation. The shadings are similar to those shown in the observed Dopplergrams. Bottom row: the velocity patterns assumed in the numerical simulations. The velocity parameters used in the simulations for each panel are the following: 13:20 UT a pure Evershed flow with a small torsion \( V_Z = \phi, V_H = 1500 \text{ m s}^{-1}, \phi = 10^\circ \); 13:30 UT the same Evershed flow but with a central vortex cell with \( V_Z' = \phi, V_H' = 1800 \text{ m s}^{-1} \) and \( \phi' = 20^\circ \); 13:45 UT: the Evershed flow (unchanged), the central vortex but now with a reversed horizontal component \( V_Z'' = \phi, V_H'' = -2000 \text{ m s}^{-1}, \phi'' = -20^\circ \), and an outer vortex cell with components \( V_Z''' = -400 \text{ m s}^{-1} \) (downward), \( V_H''' = 1800 \text{ m s}^{-1} \) and \( \phi''' = 100^\circ \); 1400 UT: the same Evershed flow, the central vortex with \( V_H' = 2000 \text{ m s}^{-1} \) (reversed from the previous time) and \( \phi' = 100^\circ \), and now with a strong upward component \( V_Z'' = 1500 \text{ m s}^{-1} \), and the outer vortex with a decreased horizontal component, \( V_H'' = 400 \text{ m s}^{-1} \), the same torsion (\( \phi'' = 100^\circ \)), and an increased downward flow (\( V_Z''' = 1600 \text{ m s}^{-1} \)). Note the appearance of the "horseshoe-shaped" structure in the Dopplergram at the site of the central vortex in the simulation for 14:00 UT. This is a result of the nearly equal horizontal and vertical velocities: \( V_Z'/V_H' = 1 \).
grams" that would be observed as a result of these configurations of velocity. Comparisons of the middle and upper panels of Figure 1.3.17 show that the numerical simulations show similarities with parts of the observed Dopplergrams.

The appearance prior to flares of these intriguing vortex patterns in the vicinity of the flaring areas raises the question of their relationship to the sites of maximum shear observed in the magnetic field at flare onset. Certainly, observations imply that the magnetic shear is a fairly persistent feature throughout a flare epoch, whereas the vertical flows only appear 10-60 min before the flare. Thus, the available observations do not support a scenario wherein the vortex motions produce the increased shear at the flare sites. However, more coordinated observations of the vertical velocity patterns and the transverse magnetic field should be carried out to investigate this further. Perhaps the magnetic shear is caused by vortex flows of smaller magnitude than can be detected at the present time. To resolve weak shear motions, it is necessary to average a number of Dopplergrams to overcome the effects of atmospheric seeing, short-lived vertical motions and the 5 min oscillations.

1.3.5 Emerging Flux

The long-established association (Giovanelli, 1939) between flares and changing, especially growing, magnetic fields has been confirmed and extended by many subsequent analyses (Martres et al., 1968, Smith and Howard 1968, Rust 1972). Observations of flare-associated filament eruptions over growing pores (Rust and Roy 1975, Rust et al., 1975) led to the proposal of a specific mechanism to produce two-ribbon flares: the reconnection of newly emerging flux with an overlying filament (Canfield et al., 1974). This mechanism is central to the Emerging Flux Model developed by Heyvaerts et al. (1977). Now emerging flux figures in several models of the preflare state as either continuously driving a flare or triggering it from a metastable state in which magnetic energy has accumulated.

Although the Emerging Flux Model is rooted in observations, its empirical verification in the form pictured by Heyvaerts et al. (1977) is by no means simple. A basic problem lies in the profusion, over a wide spatial range, of magnetic changes. Magnetic flux frequently appears as intensely concentrated bundles in the presence of existing flux. Such changes arise, for example: at the birth of new active regions in the "old" chromospheric network (Bumba and Howard 1965, Born 1974) in already growing active regions at the rate of one or two pairs of bipolar "points" per hour (Schoolman 1973); as "satellite spots" (Rust 1968); as ephemeral regions scattered over the entire solar surface, of which hundreds form and disappear per day (Harvey and Martin 1973); and as "complexes of activity" (Gaizauskas et al., 1983). With enough spatial resolution and magnetic sensitivity, one should not be surprised to find, during high solar activity, some changing magnetic fields conveniently close to any flare.

How then to discriminate between those changes in magnetic flux whose proximity to a flare is coincidental and those which could conceivably initiate reconnection (e.g., Priest, 1984a, 1984b) or some other process of destabilization (e.g., Hood and Priest, 1980; Kuperus and van Tend, 1981)? The evolution of the flux and the thermal history of its environs must be followed continuously from its first appearance in order to test its relevance to any associated flare. Ideally, we need to measure: the rate, duration, magnetic field intensity and total flux of the new magnetic fields; the magnetic topologies of the emerging flux and of its surroundings; the relative orientation of new and pre-existing magnetic fields; the relative motions of interacting magnetic field patterns, including internal shears; and the changing radiative output with time from photospheric to coronal heights above the increasing magnetic flux. The opportunities to make such measurements existed during the coordinated observations of the Solar Maximum Year. The practical difficulties are such, however, that these ideals were not fulfilled for a single flare.

Evidence that at least some flares are produced by reconnecting "new" and "old" magnetic flux is confused because important details are obscured or still beyond our grasp. Basic concepts about preflare process thus remain unsettled. We shall discuss specific flares associated with the appearance of magnetic flux, which were discussed during the SMM Workshop. But first we examine the background of basic empirical facts concerning flux emergence; for more details, the reader is referred to reviews by Zwaan (1978, 1981).

1.3.5.1 Signatures of Emerging Flux

(i) Chromospheric. The emerging flux model presupposes that magnetic flux rises vertically from beneath the photosphere as bundles of flux tubes in the shape of loops. This fundamental concept is firmly rooted in the customary pattern of growth of bipolar concentrations of magnetic flux ranging in size from ephemeral regions to sunspot groups (Zwaan 1978). While an active region is in its phase of rapid growth, it is referred to as an Emerging Flux Region (EFR, after Zirin, 1970, 1972). The EFR usually has a characteristic signature in the chromosphere which is an important diagnostic for locating new magnetic flux and for tracing its evolution, the Arch Filament System (AFS, after Bruzek, 1967). An AFS consists of a succession of parallel, low-lying arches which bridge the dividing line between opposite polarities in a newly forming group of sunspots. These arches have a distinctive velocity pattern: an ascending motion at the top (< 10 km s⁻¹) and stronger flows (≈ 50 km s⁻¹) down each branch to the footpoints (Bruzek 1969, Roberts 1970). The arches are embedded in conspicuously bright and amorphous Hα plage which extends along the entire length of the arches while an EFR is evolving with its greatest vigour.
An EFR will sometimes be resolved into tightly-packed clusters of Ellerman bombs ("moustaches") and their attendant surges when the region is viewed at $\mathrm{H\alpha \pm 1.0 \, \AA}$ (Bruzek 1972). The pronounced flow patterns, the intense (almost subflare-bright) plage, and the underlying Ellerman bombs, plainly distinguish AFS from other low-lying arches, the Field Transition Arches (Zirin, 1974), which sometimes replace an AFS in its later evolution. The AFS lasts for 3-4 days in the case of an EFR which matures into bipolar spots with penumbrae and with typical lifetimes of 2-3 weeks (for details, see Weart, 1970; Frazier, 1972; Zirin, 1974; Zwaan, 1978). For ephemeral regions and short-lived active regions, the AFS may last from a few hours to about a day.

Observations at high spatial and temporal resolution of the pre-AFS phase are still so sparse that few key properties of this critical phase of the growth of active regions can be stated with assurance. For example, Martin (1983) claims the existence of an earlier state of development of an active region: a succession of very small flares and associated surges seen one or more hours before the appearance of an AFS. The relation has yet to be determined between the onset of this dynamic stage and the first appearance of a new bipolar field at the photosphere. There is general agreement however that the first chromospheric response to an emerging bipolar is the conspicuous brightening of chromospheric faculae observed in $\mathrm{H\alpha}$ and $\mathrm{Ca\,II\,K}$ (Bumba and Howard 1965; Born 1974, Glackin 1975, Kawaguchi and Kitai 1976). But for an estimation of the delay between the detection of a bipolar at the photosphere and the chromospheric response, we must appeal to studies of the more numerous ephemeral regions which are believed to be indistinguishable from active regions at their onsets. It takes about 15 min to be sure that a new ephemeral region bipolar has formed, depending upon spatial resolution and sensitivity of the magnetograph; the $\mathrm{H\alpha}$ brightening is detectable within another 30 min (Harvey and Martin 1973). The first arch of an AFS then appears from an hour (Glackin 1975) to about 1.5 hour later (Kawaguchi and Kitai 1976).

Once an AFS forms, the lifetime of individual flat arches is about 20 min; they fade without individually changing length and are continually renewed as long as the AFS is active (Bruzek 1967). On the assumption that every $\mathrm{H\alpha}$ arch traces a magnetic loop, Born (1974) estimated that each brings $\approx 10^{19} \, \text{Mx}$ to the surface. Few ephemeral regions form an AFS; there is some suggestion that a threshold of $\approx 1.5 \times 10^{20} \, \text{Mx}$ for the total flux of an ephemeral region must be exceeded in order to support an AFS (Harvey and Martin 1973).

(ii) Coronal. The morphological description given in the review by Sheeley (1981) of the multithermal coronal plasma associated with emerging flux is based on XUV spectroheliograms obtained with the NRL Skylab/ATM slitless spectrograph. No examples have yet been published of simultaneous chromospheric and coronal observations at high temporal resolution sustained over the birth of an EFR. Most of the following summary, taken from Sheeley (1981; 1980), pertains to the coronal geometries of partially evolved EFR's.

The low temperature EFR plasma (at the $0.5 \times 10^{6} \, \text{K}$ temperature of Ne VII) is confined to the footpoints and legs of magnetic field lines; it rarely forms complete loops. The most striking Ne VII features are long spikes which diverge from the outer ends of an EFR, i.e. from the outer edges of the spots which are normally growing at each end of a bipolar EFR. The spiky structures project $10^{4}-10^{5} \, \text{km}$ from their footpoints; each lives on the order of 30 min. The high temperature plasma (at the $2.0 \times 10^{6} \, \text{K temperature of Fe XV}$), on the other hand, is confined to relatively diffuse loops or systems of unresolved loops which join opposite poles within the same EFR or between adjacent active regions, presumably along closed magnetic field lines. Unlike the low-temperature features, the high-temperature loops fade out toward the footpoints. Individual high-temperature structures evolve on a time scale of roughly 6 hr while their collective patterns endure for several days or more.

Sheeley and Golub (1979) were able to establish variability on the scale of $\approx 6 \, \text{min}$ in the multiple, small, elongated, high-temperature (Fe XV) structures in both the active region and a coronal "bright point" (possibly associated with an ephemeral region). Their observations suggest that the life history of a single "bright point" consists of continuous sequence of miniature loops which evolve rapidly and independently of each other.

Coordinated observations of ephemeral regions and coronal bright points were performed briefly during the Solar Maximum Mission (Tang et al., 1983). These limited data show that more ephemeral regions are found at the photosphere than are their counterparts at higher levels in the atmosphere. There is no indication that UV bright points (observed in the $\lambda1548 \, \text{A}$ line of CIV, characteristic of the transition zone) are enhanced before their associated ephemeral regions are born in the photosphere. Partial UV light curves are available for only two bright points which can be identified with specific ephemeral regions. Brightness of these points maximizes 1/2 and 1 hr after their corresponding ephemeral regions are detected; the brightness drops drastically in the final hour of these two ephemeral regions. (These times are strongly influenced by the sensitivity and spatial resolution of the magnetograph used for their estimation).

At the time of this Workshop, no account existed of the evolution from birth of the spatially-resolved microwave emission from ephemeral regions or EFRs.

(iii) Photospheric. The onset of flux emergence is defined with respect to the photospheric level – specifically by the first detection (e.g., by a magnetograph) of elements paired as a bipolar ephemeral region or a new EFR. Discussion of this aspect of emerging flux has been deferred in order to emphasize the following point: the photospheric feature so
commonly cited in the literature on solar flares, the growing pore, is preceded by other well-defined phenomena in both the photosphere and chromosphere.

Thus Bray and Loughhead (1964) found anomalous alignments and darkenings of intergranular lanes which preceded the appearance of a pore by 3 hr. Strong downdrafts, amounting to 1-2 km s\(^{-1}\) or more as measured with photospheric lines (Kawaguchi and Kitai 1976, Bumba 1967, Brants et al., 1981) occur near protopores. The downdrafts are localized in small patches (≈ 2") beside, not inside, a protopore (Zwaan et al., 1984). The downflow lasts for at least an hour and stops after the initial detection of the associated photospheric dipole (Harvey and Martin 1973), or after the appearance of the first arches in an AFS (Born 1974).

An existing pore in an EFR grows by adding new flux at the edge facing the centre of the growing active region (Brants 1983). This behaviour is consistent with the later developments in an active region (Zirin 1974): sunspots invariably form at the outer ends of an active region while new flux is added near the middle. The leading and trailing umbrae grow by coalescence of pores of the same polarity (Vraber 1974, McIntosh 1981). A major region will attain its maximum flux of \(3 \times 10^{22} \text{ Mx}\) in several days. A new group of spots spreads apart in longitude at a typical rate of 0.1 km s\(^{-1}\) which can be sustained for 5-6 days (Kiepenheuer 1953). At birth, the velocity of separation within an EFR can range from 1 to 2 km s\(^{-1}\); some hours later it drops to 0.5 km s\(^{-1}\) or less (Born 1974).

In the simpler circumstances of the more abundant ephemeral regions a conspicuous spreading, at 5 km s\(^{-1}\), is evident in the first minutes after the bipolar pair of magnetic elements are detected (Harvey and Martin 1973, Martin 1984). In about 30 min, the expansion rate of an ephemeral region drops by an order of magnitude and remains roughly steady for typically 6 hr (Harvey and Martin 1973).

In summary, the emergence of new magnetic flux is marked in the photosphere by rapidly spreading bipolar fragments, in the chromosphere by conspicuous brightening of chromospheric faculae followed by the formation of an AFS with distinctive strong downflow at its roots. Pores appear several hours later.

We do not yet have the observations to relate fine-scale structures in the corona with their individual counterparts in the lower atmosphere during these initial few hours. We specifically exclude, as evidence for emerging flux at coronal heights, rapidly expanding structures such as: coronal transients; coronal loops or arches seen in the \(\lambda 5303\) Å line; filaments and other mass ejected from a polarity inversion line. Phenomena such as these may rise from other causes than emerging flux, such as for example, reconnection.

### 1.3.5.2 Flare-Associated Emerging Flux

The association between flares and EFR is strong. But the numerous flares which erupt within an isolated growing region while it is still in the AFS stage are minor ones (Brueck 1967, Weart and Zirin 1969). More intense flaring is observed when new flux appears within an existing active region, especially if the emergence places following polarity ahead of normally preceding polarity (Zirin 1970, Vorpahl 1973). The importance of interactions between adjacent flux patterns prevails as well as the scale of ephemeral regions. Miniature flare-like events in Hz occur when a spreading bipolar ephemeral region interacts with neighbouring elements in the network (Marsh 1978).

For the larger, more interesting flares, we therefore look at the magnetic changes which can be thought of as flux emerging in a well-developed active region. These can be placed in two broad categories: changes associated with new flux bearing the AFS trademark or changes within already developed patterns of flux without AFS. We consider as well the influence of observed magnetic changes in an active region on the way a filament erupts preceding a flare.

#### (i) Development of Magnetic Complexity by Emerging Flux

In dealing with the first category of changes, we note that active regions do not form at random. They show a remarkable tendency to cluster in space and time (Gaizauskas et al., 1983) as complexes\(^*\) of active regions which last for many solar rotations. Liggett and Zirin (1984) measured a rate of flux emergence 27 times higher within active regions than in quiet background areas at the same latitudes. If the packing density of new regions within a complex becomes high enough, we can expect greater magnetic complexity also, and therefore enhanced flare productivity (Giovanelli 1939, Smith and Howard 1968, Bell and Glazer 1959). This is not a common occurrence. Present knowledge indicates that complexity can develop in several ways when two or more bipolar EFR overlap: either beginning with their simultaneous appearance as AFS (Weart 1970), or from the later intrusion of an EFR into a mature, closely-spaced active region (Zirin and Tanaka 1973, Tang 1983, Zirin 1983), or even from the expansion and interpenetration of adjacent bipolar active regions at the same latitude (Tang 1983). The time in the evolution of the region and speed of superposition are probably key factors.

For the SMM Workshop, Gaizauskas and McIntosh (1984) investigated how the rejuvenation of magnetic flux in complexes of activity affects flare productivity. They compared two sets of homogeneous data for the same 27 solar rotations between 1977 and 1979; the set of flares classed M₃ or stronger from among all 1900 X-ray flares recorded in that period by the SMS-GOES satellites; and the set of synoptic maps of the photospheric magnetic field produced by the Kitt Peak National Observatory (Harvey et al., 1980). The subset of 384 flares so defined is not distributed randomly among the 934 active regions enumerated during the same interval. One-half of the flare subset is accounted for

\(^*\text{"Complex" used in this sense and without a modifier refers exclusively to spatial and not magnetic complexity.}\)
by only 12 regions, the other half by another 65; a tenth of
the subset erupted in one hyperactive region, McMath 15403
(CMP on 15 July 1978).

The 77 regions with strong flares, clustered in 37 com-
plexes of activity, are marked according to the class of their
strongest flares on the chronological arrays shown in Figure
1.3.18 of active-belt strips from the KPO synoptic maps (cf.
Figures 2 to 4, Gaizauskas et al., 1983). For half of the com-
plexes, flaring continues above the M1 threshold for 2 or
more rotations. In extreme cases, powerful flares do occur
on the fifth (in an X-class region) or even on the ninth rota-
tion (for an M-class region). But in at least 7 complexes,
flares in the X-category occur without an episode of even
M-class flares during the preceding rotation. The most con-
spicuous example of an immediate output of very intense
flares in just one rotation is McMath 15403. Its behaviour
is compared in Figure 1.3.19 with another flare-rich com-
plex, the so-called "great complex" (Gaizauskas et al.,
1983).

For the great complex, Figure 1.3.19a, the magnetic flux
jumps suddenly from a low initial level to a high level which
remains roughly steady over 6 rotations before it subsides
quickly. But the incidence of strong flares in this same com-
plex is more erratic as indicated by the X-ray Flare Index
(XFI, hatched bars). The XFI is both high and low during
the strong outbreak of flux sustained for 6 rotations. When
the XFI is high, the great complex consists of extended
clusters of large spots with many EFR and strong shears;
later, when the XFI is low, the great complex contains only
one large spot, some EFR and considerable flux distributed
throughout the photospheric network. In contrast, hyperactive
region McMath 15403 reaches a relatively high flux level
and very high XFI in just one rotation (Figure 1.3.19b). Dur-
ing its visible passage, it is a compact and formidably com-
licated δ-configuration.

Another example of rapid, highly localized development
of magnetic complexity occurs during the evolution of the
complex containing Hale Regions 16862, -3, -4 from 1980
(Gaizauskas 1983) to June 1980 (Martin et al., 1983).
Only one new region formed during the first passage of this
complex: a very compact δ-configuration which formed in
less than a day and produced the only energetic flares for
that entire disk passage. On its second passage, 17 new bipo-
lar regions were identified within the evolved complex in
an 8-day interval. The great majority of flares, mostly sub-
flares, then erupted within EFR or on their boundaries
(Martin et al., 1983), or in locations where new flux appeared
adjacent to recently evolved flux from the same rotation
(Schmahl 1983).

The build-up of severe complexity is thus more likely to
involve new patterns of flux appearing within a few days
rather than patterns differing in age by as much as one rota-
tion of the Sun. This finding is consistent with the rapid dis-
appearance, in situ, of large quantities of magnetic flux and
its rapid replacement by new, differently arranged flux in
a still-active complex (Gaizauskas et al., 1983). The months-
long survival of complexes of activity is not in itself sufficient
to buildup magnetic complexity as supposed by Bumba and

Currents flowing in the strongly sheared and twisted mag-
netic fields in magnetically complex regions are presumed
to buildup a reservoir of "free energy" which is then released
in flares (Nakagawa and Raadu 1972). These concepts en-
counter difficulty, however, with the phenomenon of flare
homology. Experience during the SMY indicates that hom-
ology is not at all rare (Woodgate et al., 1983) and must be
included among the constraints on flare models. If prior
storage of energy is a necessary condition, it must be released
by the same process in the same spatial domain in order to
reproduce the geometries and time profiles of the flare emis-
sions in a chain of homologues. Now, if flares are "released"
by a mechanism which operates as a simple safety valve at-
tached to a constantly stressed reservoir, the output energy
ought to remain the same for each flare in a homologous
chain. On the other hand, if the release mechanism is not
continuously operative, the output energy per flare ought to
be proportional to the build-up time between activations of
the release mechanism.

Neither steadiness nor proportionality of output were evi-
dent for the chain of 5 homologous flares observed within
13 hours, 28-29 May 1980 in a compact δ-region (Gaizaus-
kas 1983). The compactness makes it difficult to distinguish
with certainty between relative motions of pores (Nagy 1983)
and their appearance or disappearance in a few hours, with
new flux possibly appearing in nearly the same place. Yet
it seems implausible that new flux, if it were to be acting
as the flare-release mechanism, would re-emerge in precisely
the same location and in the same manner so many times
in succession. The variation of output energy per flare,
despite the close homology in this instance, suggests that
flares could be driven from the source whose energy supply
determines the ultimate flare energy. For example, this chain
of flares could have arisen from the shearing action produced
during the rapid relative motions of adjacent pores in such
a way that the deformation of the magnetic field was not uni-
form with time.

At some point in the growth of a bipolar active region,
the emergence of its flux must stop. Other new bipoles may
continue to appear nearby as part of a process for sustaining
a complex of activity. Their signatures are easily recognized
(§1.3.5.1) and correspond, to the best of our knowledge, to
flux which emerges from well below the photosphere. But
other prominent changes in magnetic flux happen in well-
developed active regions without these signatures; they too
figure in flares. The origin of these features being uncertain,
they are designated here as "appearances" rather than "emergences".

For example, magnetic flux outflow (Vrabec 1974) ap-
pears around the edges of some large-spot penumbrae as a
rim of reversed polarity moving radially away from the spot

Provided by the NASA Astrophysics Data System
Figure 1.3.18 Chronological arrangement of KPNO synoptic magnetograms of magnetic flux density adapted from Gaizauskas et al. (1983). The Carrington rotation number for each strip is shown in the extreme left column. (a) Latitude belt 10°-40°N for each strip of 0-360° in longitude. (b) Equatorial belt of latitudes, 10°S-10°N for each strip of 0-360° in longitude. (c) Latitude belt 10°-40°S for each strip 0-360° in longitude. The regions in which they occur are designated as "m", "X", or "Z" according as they contain at least one flare classed, respectively, from M₁ to M₉, X₁ to X₉, or X₁₀, in the SESC system.
with steady speeds \( \approx 0.2 \text{ km s}^{-1} \) and greater (Sheeley 1969, Harvey and Harvey 1973). It appears without forming AFS and without enhanced H\alpha emission even though its average flux may be \( \approx 10^{19} \text{ Mx} \) (Harvey and Harvey 1973). Magnetic flux outflow can produce many small surges and even small subflares (Roy and Michalitsianos 1974). Its relationship to other persistent flaring sites on the periphery of sunspots, the so-called ‘satellite sunspots’ (Rust 1968) is uncertain. During observations coordinated with SMM in May 1980, a location of intermittent magnetic flux outflow activity on the rim of the leading spot in Hale 16863 was found to persist for several days as a favoured site for miniature surges and subflares (Gaizauskas 1983). Magnetic flux outflow is believed to be part of a process whereby a sunspot dissolves through fragmentation of its flux tubes (Harvey and Harvey 1973). In that sense, magnetic flux outflow is conceived as a redistribution of already emerged flux, rather than an emergence from a great depth.

Even less understood than magnetic flux outflow is the appearance of pores and small spots without AFS in the middle of mature bipolar active regions. Pores can be found in profusion around the polarity-inversion lines underlying the field-transition arches in large, slowly spreading regions like Hale 16863, -4 (Gaizauskas 1983). At the SMM Workshop, Schadee provided examples of transient miniature X-ray events in the lowest energy (3.5-5.5 keV) channel of the HXIS. The low background noise in this instrument allows the detection of very weak X-ray sources. These sources are abundant in field-transition arches and in general along polarity-inversion lines of mature active regions (cf. Gaizauskas 1983, Figure 10). Some sources enact the 2-ribbon flare scenario in miniature, such as the tiny subflares in mature region Hale 16850 which erupted adjacent to the very long filament which separates still-evolving network of opposite polarities (Schadee and Gaizauskas 1984). VLA observations at 6 cm of other bipolar regions show that radio sources over similar areas of transverse magnetic fields are brighter than those associated with sunspots (McConnell and Kundu 1984).

No systematic study has yet been made to explain why a bipolar AFS transforms into a bipolar region with field-transition arches, why coronal emission is enhanced and eruptive along these polarity inversions, or whether the pores appearing at this stage bear any special relation to the field-transition arches. We may speculate that some of the rapid appearances of new photospheric structures in the middle of mature active regions represent a concentration of superficial flux rather than the emergence of deep-rooted flux. Whatever the origin of these new concentrations, it is in just these circumstances of late development in the active regions that the 2-ribbon flares, advanced in support of the emerging flux model, have occurred (Rust and Roy 1975, Rust et al., 1975, Rust and Bridges 1975, Canfield and Fisher 1976, Hoyng et al., 1981, Simon et al., 1984, Moore et al., 1984).

(ii) Filament Activations and Emerging Flux. Strong circumstantial evidence links the appearance of new pores with flares for the events just cited. But an attempt to extract from
them the quantities needed for a rigorous test of the Emerging Flux Model is soon frustrated by the lack of essential pieces of information. Missing most frequently from the examples cited above are the velocity fields associated with emerging flux and the morphologies of fine structures which would yield the relative orientations of new and pre-existing magnetic fields. Breaks in the data at critical periods further amplify the uncertainties. Conclusions drawn from changing patterns of magnetic fields remain inferences based on the premise that rising flux creates the changes.

The small pores of opposite polarity which are believed to figure in the destabilization of a filament as described by Simon et al. (1984) approach each other, contrary to the normal spreading action in an EFR. No direct evidence is provided that these pores are linked magnetically to each other or to the filament; their presence and proper motions are suggestive but enigmatic. For the well-studied class 2B flare of 1980 May 21, Hoyng et al. (1981) attribute the destabilization of a long filament over an extended polarity-inversion line to the emergence nearby of a bipolar region containing a new pore. Subsequent analysis of magnetograms by Harvey (1983) suggests that the pore formed not by emergence but by the compression of existing flux at the surface. New flux did appear nearly as patches of polarity opposite to their unipolar surroundings and in such a way that the shape of the polarity-inversion line was sharply altered. The net flux at a location directly beneath the activated filament actually decreased. These changes may have destroyed the equilibrium between the filament and its surroundings without recourse to reconnection.

An example of preflare filament eruption without associated emerging flux is the 1980 June 25 class 1B flare at 1552 UT studied by Kundu et al. (1985) and discussed at length during the SMM Workshop. The filament was located in the trailing part of AR 2522 (Hale 16931). This region contained two sites of emerging flux which produced several subflares on that same day: on the northern rim of the large leading spot, and in a small magnetically complex region immediately SE of the erupting filament. An adjacent region of comparable size, AR 2530 (Hale 16923) had even more extensive emerging flux in its mid-section. The flare-associated filament was only 40,000 km long; its midpoint passed close to a compact cluster of pores which had no associated chromospheric activity. A close examination of KPNO magnetograms taken hours before and after the flare shows minor, subtle changes in the magnetic flux of photospheric structures adjacent to the filament (Kundu et al., 1985). Nothing observed in 7 hours of rarely interrupted wavelength-sweeping across Hα at high spatial resolution with the photosheillograph at the Ottawa River Solar Observatory can be suspected as adjacent emerging flux which might trigger a filament eruption.

Strong proper motion of the leading sunspot in AR 2530 ($\approx 150 \text{ m s}^{-1}$) implies strong shearing near the inter-region boundary which intersects the active filament at its western footpoint (Schmahl 1983). There were no significant proper motions of the spots in which the filament terminated or of the pores near its mid-point. The regions were sufficiently far from the center of the disk that perspective aids the determination of the velocity structure of the filament. Its lateral displacement can be followed with respect to the fixed pattern of photospheric features. Doppler shifts indicated by off-band filtergrams give the sense and an estimate of the line-of-sight velocity. The combined measurements show that the center of the filament began rising slowly ($< 1 \text{ km s}^{-1}$) about 3 hours before the flare and accelerated steadily but not uniformly right into the eruptive stage. Matter drained down each end of the filament. About 2 hours pre-flare, the downflow at the eastern footpoint gained a sudden impetus coincident with the activation of a huge boundary filament on the southern side of AR 2522. This larger structure was co-terminal with the flare-associated filament inside the large, trailing sunspot.

At 20 and 10 min preflare, the Hα blue shifts towards the eastern half of the structure increased substantially while at the same time the lateral movement of the filament ceased entirely. This indicates that the suddenly enhanced Hα blue shifts observed during this period had to arise from axial flow rather than an accelerated upheaval. For these two episodes of enhanced flows, filtergrams at Hα ± 0.6 Å were subtracted in pairs. They reveal that the filament was rapidly untwisting in the fashion described by Rust et al. (1975) for an event in which new spots strengthened or first appeared adjacent to a filament during its eruption and a subsequent flare. Yet there were no comparable flux changes in the 1980 June 25 event. Bright Hα kernels and an additional short velocity structure appeared behind (and presumably beneath) the most twisted portion of the rising filament for just several minutes during the last episode of enhanced axial flows. These transient features are co-spatial, in projection, with briefly enhanced blue-shifted C IV emission ($\approx 10^{5}$ K plasma) detected by the UVSP onboard SMM. We may speculate that these transients are counterparts of the short-lived velocity feature also recorded by Canfield and Fisher (1976) for another erupting filament.

Emerging flux did not figure as a direct trigger of the flare of 1980 June 25. This is not to deny that flux emerging elsewhere in AR 2522 and AR 2530 may have played a direct role in modifying the global magnetic structure. Or the growth of instability in the filament may have been initiated by a major disturbance in a magnetically connected structure in the same active region.

The emergence of flux is clearly necessary to set the stage for subsequent flare activity on a major scale. That stage-setting is very important and takes place over many hours or even a few days. Of all the flares studied so far, the 1980 May 21 event comes closest to providing direct evidence that further emergence of a small amount of flux triggers release
of a vast amount of energy stored in a sheared filament. But the details of that particular flux emergence are subtle (Harvey 1983); it is by no means clear how the interaction between the filament and emerging flux should be conceived when the adjacent net photospheric flux decreases during the emergence. The experience with the 1980 June 25 flare, where adjacent emergent flux could not be found, should caution us that the flare triggering process is still elusive.

### 1.3.5.3 Summary and Recommendations for Studies of Emerging Flux

The vigorous advance of theory (Priest 1984a, 1984b) has brought into sharp focus the observational requirements to test the Emerging Flux Model. From an observational perspective, however, even the conceptual role of emerging flux in the flare process is clouded. Growth of magnetic flux is a necessary pre-condition for flares: small flares are common during the AFS stage of an active region: large flares often have their initial kernels rooted in new, rapidly growing flux. But the vast bulk of magnetic flux appears at the surface without producing flares as strong as a M1 event in X-rays. The published cases of flare-associated filament eruptions lack key facts which are needed either to validate the reconnection inherent in the Emerging Flux Model or to constrain the model in terms of our understanding of flux emergence in the absence of flares. One study of a flare-associated filament eruption on 1980 June 25, observed in detail for many hours at heights in the photosphere, chromosphere, transition zone and corona, rules out local emerging flux as either a driver or a trigger of the activation of that particular flare.

An important new result is the association of Cancelling Magnetic Features with Flares (Martin, 1984). These may have a similar role to emerging flux in triggering flares (Priest, 1985), since what is important is the interaction of flux, whether through material vertical or horizontal motions.

A major advance towards clarifying this situation would come from coronal observations aimed specifically at the problem of emerging flux. Jackson and Sheridan (1979) found general increases in activity of Type III radio bursts prior to flares, which imply that energy, originating in the emergence of new flux, is entering the corona on a time scale of many hours. We badly need to supplement the detailed chromospheric and photospheric observations of emerging flux, now available, with simultaneous multi-wavelength coronal observations of comparable spatial resolution (≈ 1") and comparable duration (many hours, even days, preceding the emergence). Target regions of emerging flux need to be followed long enough at all levels of the atmosphere to come to grips with the formation of AFS and field-transition arches, and in contrasting emergences of flux accompanied by their well-established signatures from simple appearances of new flux without those signatures. More than semantics are at stake; our concepts of the magnetic interconnections in the latter situation are woefully inadequate. Finally, we need to clarify the association between ephemeral regions and coronal bright points on an individual basis. In so doing, we should gain insight into the dissipative mechanisms which seem to occur with great frequency on a basic scale, and which might be applicable to ordinary flares.

### 1.4 CORONAL MANIFESTATIONS OF PREFLARE ACTIVITY


#### 1.4.1 Introduction

Recent observations confirm the view that the initial release of flare energy occurs in the corona, with subsequent emissions arising from the interchange of mass and energy between different levels of the solar atmosphere. Knowledge of coronal preflare conditions is essential to understanding how energy is stored and then released in flares. Observational evidence for storage is, however, difficult to interpret owing to our inability to observe the three dimensional structure of the magnetic field and to the lack of coordinated observations with high resolution in space and in time.

More than sufficient energy to power flares can be stored in local magnetic fields on time-scales of hours. Long-term changes include emerging and evolving magnetic flux regions, satellite sunspots, sunspot motions, and velocity patterns (Martin, 1980; Section 1.3 these proceedings). Although such evolutionary changes are considered necessary for the storage of energy leading to especially large flares, it is very difficult to relate specific long-term changes to particular flares since similar changes occur in their absence.

More rapid changes can occur within minutes or a few hours preceding a flare, and they can be more unambiguously interpreted as flare precursors. Clearly, this distinction is arbitrary, but it does provide a useful operational definition of preflare patterns. These more rapid changes, especially in the corona, were the subject of the third subgroup of the Preflare Activity Team.

#### 1.4.1.1 Review of Previous Studies of Coronal Precursors

Earlier searches for rapid flare precursors involving coronal phenomena recognized the physical importance of the corona for storage and release of flare energy. Reported coronal precursors have included X-ray brightenings associated with filament activations (Rust et al., 1975), expanding and brightening green-line arches (Bruzek and DeMastus, 1970), gradual enhancements and spectral hardening of soft X-ray and microwave flux (Webb, 1983), "forerunners" of white-light transients (Jackson and Hildner, 1978), changes
in circular polarization and intensity at centimeter wavelengths (Lang, 1974; Kundu et al., 1982; Willson, 1983), pre-burst activity at 1.8 cm (Kai et al., 1983) and preflare type III burst activity at meter wavelengths (Jackson and Sheridan, 1979).

Filament activations and associated manifestations, which are frequently observed with two-ribbon flares, have been the most readily observed and most studied forms of rapid flare precursors (Smith and Ramsey, 1964; Martin and Ramsey, 1972). The enhanced darkenings, organized motions and reconfigurations which constitute an "activation" were summarized by Smith and Ramsey (1964) and more recently by Martin (1980). The prevalence of the phenomenon is evident in the statistic (Martin and Ramsey, 1972) from a sample of 297 flares (importance >Class 1) that about half the flares in that sample exhibited preflare filament activity. Prior to or during a filament activation, changes in certain photospheric and chromospheric structures occur, which have been taken as evidence of evolving or emerging magnetic flux (e.g., Rust, 1976).

Preflare observations in soft X-rays have been used in a number of studies. Culhane and Phillips (1970) observed 7 precursor events at 1-12 A, one occurring 15 min before flare onset, using an OSO-4 full-sun detector. Thomas and Teske (1971) performed a statistical study using a full-sun detector on OSO-3 and found a tendency for the onsets of X-ray events to precede those reported in Hα. For a small number of events Roy and Tanga (1975) found specific enhancements in full-sun X-ray flux to be associated with different stages of preflare filament activity.

With better spatial resolution (20 arc-sec) Rust et al. (1975) identified OSO-7 EUV and soft X-ray enhancements with a filament activation 30 minutes before flare onset. Van Hoven et al. (1980) studied the preflare phase of a set of 12 flares observed by the same OSO-7 detectors with one-minute time resolution. Eight of the 12 showed definite enhancements in both X-ray and EUV 2-20 min prior to the onset. Interestingly, in 6 of these 8 cases the enhancements were observed simultaneously in both cool He II and hot Fe XXIV lines. Although the Skylab experiments had excellent spatial resolution (arc-sec), the operational modes limited the availability of preflare data to a few specific observations of EUV and soft X-ray precursors (see Van Hoven 1980 for details). Petrossos et al. (1975) and Levine (1978) observed pre-existing coronal loops to brighten 5-10 min before they flared. The XREA full-sun X-ray detector typically detected preflare enhancements 2-20 min before the impulsive phase. There was evidence for slight temperature increases in these events, and an increasing tendency for large flares to have associated precursors.

In more comprehensive, statistical studies, Vorpahl et al. (1975) found many cases where X-rays from the flare regions were enhanced prior to onset, but Kahler and Buratti (1976) and Kahler (1979) found that there were no systematic preflare X-ray brightenings at the locations of subsequent small flares, and therefore no requirement for coronal preflare heating of the flare loops. However, coronal preflare brightenings were observed in the Skylab X-ray data in areas of the active region adjacent to the flare site.

Recently, Webb (1983) studied similar sets of the AS&E Skylab X-ray data with the goal of determining whether X-ray precursors systematically occurred within the flare active region and what their characteristics were. The study differentiated between observations relating to the preheating of flare structures, and precursors which might have time and spatial scales and locations different from that of the flare. High time-resolution Hα and daily photospheric magnetograms were also used. A majority of the flares studied had preflare X-ray features, but typically not at the flare site, occurring within 30 minutes prior to onset. The X-ray precursors consisted of one to three brightened loops or kernels per interval, with Hα emission at the feet of the loops or co-spatial with kernels. Electron pressures of a few dyne cm⁻² were derived for several typical coronal features. In half of the cases the X-ray precursors were associated with preflare Hα filament activity. The preflare and flare events occurred on or near the main active-region neutral line. Using moderately resolved (arc-min) OSO-8 X-ray observations, Mosher and Acton (1980) and Wolfson (1982) reported no systematic enhancement in active regions in 20-minute intervals preceding flare onsets. But their detector was less sensitive to the lower energy, cooler precursors reported earlier from Skylab.

Radio observations provide important data on coronal emission and changing magnetic fields before flares. Individual observations of microwave preflare activity in the form of increased intensity and changing polarization have been reported in the past. With the increasing sensitivity and spatial resolution of such instruments as the VLA, these observations have become better defined, as discussed in Sections 1.4.2 and 1.4.5.

Green line (5303 Å) observations above the solar limb showed acceleration and expansion of coronal arches up to one hour before two flares (Bruzek and DeMastus 1970). Skylab observations of white light mass-ejection "forerunners" (Jackson and Hildner 1978) indicated that such activity might precede Hα flare onset. Recent SMM results, together with improved metric radio and lower altitude K-coronameter data (Wagner 1982) support the overall picture that a large volume of the corona can become activated up to an hour or so before a flare.

### 1.4.1.2 Objectives

Our objectives in studying preflare coronal phenomena were threefold: to select a suitable data set, to determine appropriate physical parameters, and to search for associations among events so as to identify the relevant physics in preflare phenomena.
A wealth of new information about active regions and preflare activity is now available from the coordinated observations conducted during the Solar Maximum Year by the Solar Maximum Mission satellite, by other spacecraft, and by ground-based observatories. The wavelengths accessible to a study of the preflare coronal condition range from centimeter-wavelength microwaves to hard X-rays. Table 1.4.1 summarizes the data that were used in our study by wavelength and instrument, and the references to publications of events covered in this report. Previous multi-wavelength studies of this sort (Martin, 1980; Van Hoven et al., 1980; Webb, Krieger and Rust, 1976; Rust, Nakagawa and Neupert, 1975; Webb, 1983; Kahler and Buratti, 1976) were more limited because of sporadic or slower image cadences, lower sensitivity, poorer resolution, or fewer wavelengths available. In addition to a broader range of data with better coverage, we also had the advantage of observing the sun at its maximum level of activity, with flares occurring six times more frequently than during the Skylab period.

Our approach was to assemble all available preflare data for a number of well-observed events and the results of several "cross-sectional" studies in specific wavelength ranges. We have selected good simultaneous observations at as many levels of the solar atmosphere as possible, from the photosphere through the chromosphere and transition region to the lower and middle corona. We concentrated on data with time resolution ranging from tens of seconds to minutes, collected over a time interval ranging from about one hour before the flare up to impulsive onset as defined in hard X-rays by HXRBS. In very few cases were observations at all levels of equally high quality, but a sufficiently large set of well-

<table>
<thead>
<tr>
<th>Table 1.4.1a</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
</tr>
<tr>
<td>---------------</td>
</tr>
<tr>
<td>Microwave</td>
</tr>
<tr>
<td>(spatially resolved)</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Microwave patrols</td>
</tr>
<tr>
<td></td>
</tr>
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<td></td>
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<tr>
<td></td>
</tr>
<tr>
<td>Hα</td>
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<tr>
<td></td>
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<td></td>
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<td></td>
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<tr>
<td></td>
</tr>
<tr>
<td>White Light</td>
</tr>
<tr>
<td>Corona</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Ultraviolet</td>
</tr>
<tr>
<td>X-rays, Soft</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Medium-Hard</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Hard</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Gamma Rays</td>
</tr>
</tbody>
</table>

1-50

Provided by the NASA Astrophysics Data System
covered events was available for comparative and statistical analyses. The study of this large set of data continues in order to test the associations noted here between various preflare signatures.

Among the questions guiding this study were:

- Where is the flare trigger located?
- Is flux emerging at the photospheric level a necessary condition for preflare coronal activity?
- Do flares "try" to start, fail, and "try" again?
- Do flare precursors have both thermal and non-thermal components?
- Are there two distinct classes of precursor, some associated with filament activation and some not?

We have organized material leading up to a discussion of these questions as follows. In the next section we define the onset phase and precursors and explain how we distilled our preflare data set. In Section 1.4.3 are presented several key events which illustrate the connections that we discovered among their preflare phenomena. In Section 1.4.4 we describe an important comparison of the location of preflare activity in FCS and UVSP images. In Sections 1.4.5 and 1.4.6 are reviewed the observations of certain radio precursors which are taken as evidence favouring preheating and non-thermal particle acceleration. Finally Sections 1.4.7 and 1.4.8 describe HXIS observations of X-ray precursors.

### 1.4.2 Defining the Preflare Regime

We follow Svestka (1976) and Sturrock 1980, (especially p.413) in defining the "onset" of the flare as the time of the first rise in emission at the site of the flare itself. We adopt a somewhat more general definition of "precursor" than used in the Skylab studies (Sturrock, 1980). We take a "precursor" to be a transient event preceding the impulsive phase, possibly even before the onset and not necessarily at the precise site of the flare itself.
The initial sample of preflare events included 54 flares selected by Woodgate to have sufficient coverage in time by UVSP and BCS before the impulsive hard X-ray burst recorded by HXRBs. When multiple bursts occurred, the largest was taken to be the primary flare. In this respect, the study was similar to that of Webb (1983), in that “minor” flaring was included as “preflare” activity. From a combination of Woodgate’s sample with 12 other events which showed interesting preflare activity in microwaves, Hz, white light and/or in X-rays, we selected 26 events which had the best overall coverage in data for concentrated study. These events along with key precursor observations and references to publications are summarized in Table 1.4.4.

1.4.2.1 The Onset Phase

We defined two onset times for each of the primary flares in Table 1.4.2. One was the impulsive onset observed in hard X-rays (HXRBs). The other was the soft X-ray onset, commonly defined as the start of the rise of the flare flux profile. Webb determined the onset time in this manner, using the full sun 1-8 Å X-ray flux recorded by the NOAA/GOES satellite for the events in this study. On average, the soft X-ray onset occurred ~ 2 minutes before the onset of the hard X-ray burst, in agreement with previous results (Svestka 1976). Schmalh, Strong and Waggett used background-corrected BCS light curves in a similar way to determine the soft X-ray onset times. These onset times and the hard- X-ray minus soft-X-ray time differences are shown in Table 1.4.2.

There was surprising agreement between the GOES and BCS (Ca XIX: ~ 3.2 Å) timings, with onsets rarely differing by 1 minute in the two X-ray regimes. When differences arose the BCS data were used since its 6' x 6' (FWHM) field of view minimized confusion from flares in other regions. Since Ca XIX is formed at ~ 1.5 x 10^7 K, the onset profiles indicate the existence of pre-impulsive plasmas as hot as ~ 10^7 K.

Harrison, Schadie and Schrijver plotted onsets for a number of flares using the softest channel (3.5-5.5 keV) of the HXIS instrument. Several onset profiles are shown in Figure 1.4.1a. The profiles of Figure 1.4.1a were integrated over the full core field of view (6'.2 x 6'.2), and therefore may represent the sum of more than one onset source. Figure 1.4.1b illustrates the comparison of onsets for the full field of view and for four areas of a few pixels each at and near the flare site, 18:17-19:03, 28 June 1980. We shall return to this flare later, but for now we note that the full field-of-view integration shows an earlier onset than the flare itself. Pre-onset activity has been noted outside of the flare structure before, especially in the Skylab data (e.g., Van Hoven 1980, Webb 1983, Kahler and Buratti 1976) and SMM data (e.g., Machado et al., 1982). However, at this stage it is not clear how to compare the results from Skylab and SMM.

For instance, the X-ray filters on the Skylab AS&F experiment defined plasmas of lower temperature (~ 1.5 x 10^6 K for the softest filter) than the SMM BCS (>8 x 10^6 K) and HXIS (greater than or about 10^7 K) experiments. There was no hard X-ray detector aboard Skylab so it was not possible to compare directly the distribution of soft X-ray to impulsive onsets. Since the Solrad or GOES maximum almost always followed the impulsive maximum by a few minutes, the Skylab onset times would have to be modified for comparison with this study.

The fact that a gradual onset in soft X-rays or microwaves is always present suggests a thermal origin for the first phase of flares (e.g., Svestka 1976). Machado et al. (1982) have suggested that the preflare gradual phase is a manifestation of the same phenomenon as the post-flare gradual phase. However, while this is conceivably true of the soft X-ray emitting regions, the gradual phase in microwaves shows remarkable differences (in polarization or source-size changes) preflare and post-flare (e.g., Kundu et al., 1985, Hurford and Zirin 1982). More study is required to determine the nature of the gradual onset of flares. We show below, in examples reported by Team members, several physical interpretations in terms of heating, upheavals or reconfigurations of magnetic flux.

1.4.2.2 Flare Precursors

The SMM data base is much more continuous than that of Skylab, and it is therefore possible to make stronger distinctions about flare precursors. In the more sporadic Skylab coverage (Webb, 1983; Kahler and Buratti, 1976; Kahler, 1979), it was more difficult to distinguish precursors from the onset phase. When such a precursor was observed, we defined the onset of the flare “conservatively” by the last pre-impulsive phase minimum of the light curve.

Since it is difficult to distinguish a true precursor signal from the flare onset or rise phase itself, when it occurs within a few minutes of the impulsive phase (Kahler 1979), we emphasized analysis of observations from about 60 to 5 minutes before impulsive onset. SMM images sometimes revealed precursors which were physically distinct from the flare, during what would otherwise be defined as the gradual onset phase.

X-rays. Precursors in the high resolution X-ray photographs from Skylab appeared as loops or kernels close to, but not necessarily, at the flare site. Often these sources were multiple and small (several arc-sec). In many cases, the precursors were closely associated with activated filaments (Van Hoven 1980, Webb et al., 1976, Webb 1983).

Examples of all of these effects are present in our SMM data set. In terms of the SMM X-ray light curves, gradual-rise-and-fall (GRF) precursor signatures were frequently detected in X-rays (Figure 1.4.1) and microwaves. Such a signature is considered indicative of coronal heating and is strongly associated with filament activations (Martin 1980,
### Table 1.4.2 Event Summary of SMY Precursors

<table>
<thead>
<tr>
<th>Date</th>
<th>Flare Peak Flux</th>
<th>Impuls. Onset (HXRBS)</th>
<th>SXR ΔT</th>
<th>Hα flare* or burst</th>
<th>Fill. Act. Onset</th>
<th>Rising Loop or Trans.</th>
<th>Brightenings*</th>
<th>Microwave Patrol Intensity</th>
<th>Microwave Pol. Change</th>
<th>Radio Spectral Events</th>
<th>Event References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mar 23</td>
<td>C7</td>
<td>1558.3</td>
<td>(4)/--</td>
<td>N</td>
<td>Y-1600; 1648</td>
<td></td>
<td>Hα</td>
<td>Inc:1648</td>
<td>Inc. + Rev.</td>
<td>NONE</td>
<td>10,47,78.</td>
</tr>
<tr>
<td>Mar 29</td>
<td>C31</td>
<td>2041.3</td>
<td>4/--</td>
<td>Y-2016</td>
<td></td>
<td></td>
<td>Hα, UV, Hα</td>
<td>Inc:2016</td>
<td>III, V</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td>Apr 6</td>
<td>C7</td>
<td>0716.5</td>
<td>(7)/?</td>
<td></td>
<td></td>
<td></td>
<td>Hα</td>
<td>Inc:1300-1830</td>
<td>I, III</td>
<td>7,27,40,48, 68,74,83,84.</td>
<td>1,36,37,39,72.</td>
</tr>
<tr>
<td>Apr 10</td>
<td>M4</td>
<td>0917.1</td>
<td>7/22</td>
<td></td>
<td></td>
<td></td>
<td>Hα, UV</td>
<td>Step:0903</td>
<td>NONE</td>
<td>4,47,51,52,85,131.</td>
<td>10,47,78.</td>
</tr>
<tr>
<td>June 19</td>
<td>M1</td>
<td>1838.2</td>
<td>(8)/(8)</td>
<td>N</td>
<td>Y-1250</td>
<td>Inferred</td>
<td>Hα</td>
<td>Inc:1300-1830</td>
<td>I, III</td>
<td>29</td>
<td></td>
</tr>
<tr>
<td>June 22</td>
<td>M1</td>
<td>--</td>
<td>(--/50)</td>
<td>Y-1250</td>
<td></td>
<td></td>
<td>Hα</td>
<td>Inc:1300-1830</td>
<td>I, III</td>
<td>29</td>
<td></td>
</tr>
<tr>
<td>June 25</td>
<td>M1</td>
<td>1551.3</td>
<td>11/31</td>
<td>Y-1522</td>
<td>Y-1530</td>
<td>Inferred</td>
<td>Hα</td>
<td>Inc:1300-1830</td>
<td>I, III</td>
<td>29</td>
<td></td>
</tr>
<tr>
<td>June 26</td>
<td>M4</td>
<td>2339.8</td>
<td>1/8/</td>
<td>Y-2315</td>
<td>Y-2330</td>
<td></td>
<td>Hα</td>
<td>Inc:1300-1830</td>
<td>I, III</td>
<td>29</td>
<td></td>
</tr>
<tr>
<td>June 28</td>
<td>C5</td>
<td>1845.3</td>
<td>3/--</td>
<td>N</td>
<td>Y?</td>
<td></td>
<td>HXIS trans.</td>
<td>Inc:1300-1830</td>
<td>I, III</td>
<td>29</td>
<td></td>
</tr>
<tr>
<td>June 29</td>
<td>C4</td>
<td>0233.0</td>
<td>0/24</td>
<td>N</td>
<td>Y?</td>
<td></td>
<td>HXIS trans.</td>
<td>Inc:1300-1830</td>
<td>I, III</td>
<td>29</td>
<td></td>
</tr>
<tr>
<td>June 29</td>
<td>M4</td>
<td>1040.2</td>
<td>0/11</td>
<td>N</td>
<td>Hel Loop &lt;1040</td>
<td></td>
<td>HXIS trans.</td>
<td>Inc:1300-1830</td>
<td>I, III</td>
<td>29</td>
<td></td>
</tr>
<tr>
<td>June 29</td>
<td>M4</td>
<td>1822.0</td>
<td>0/20</td>
<td>Y-1803</td>
<td></td>
<td></td>
<td>HXIS trans.</td>
<td>Inc:1300-1830</td>
<td>I, III</td>
<td>29</td>
<td></td>
</tr>
<tr>
<td>July 1</td>
<td>M5</td>
<td>1626.8</td>
<td>5/8</td>
<td>Y-1626</td>
<td></td>
<td></td>
<td>Hα, UV</td>
<td>Inc:1300-1830</td>
<td>I, III</td>
<td>29</td>
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</tr>
<tr>
<td>Oct 11</td>
<td>X2</td>
<td>1304.3</td>
<td>1/--</td>
<td></td>
<td></td>
<td></td>
<td>Hα</td>
<td>Inc:1300-1830</td>
<td>I, III</td>
<td>29</td>
<td></td>
</tr>
<tr>
<td>Oct 11</td>
<td>C2</td>
<td>1740.2</td>
<td>0/(40)</td>
<td>Y-1700</td>
<td>N</td>
<td></td>
<td>Hα</td>
<td>Inc:1300-1830</td>
<td>I, III</td>
<td>29</td>
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</tr>
<tr>
<td>Nov 5</td>
<td>C6</td>
<td>2225.9</td>
<td>0/--</td>
<td>Y for 2232 Active Fibrils</td>
<td></td>
<td></td>
<td>SXR,HXR,Hα</td>
<td>Inc:1300-1830</td>
<td>I, III</td>
<td>29</td>
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<tr>
<td>Nov 8</td>
<td>M4</td>
<td>1440.3</td>
<td>1/8</td>
<td>Y-1354*</td>
<td></td>
<td></td>
<td>Hα</td>
<td>Inc:1300-1830</td>
<td>II</td>
<td>71</td>
<td></td>
</tr>
<tr>
<td>Nov 11</td>
<td>C8</td>
<td>0626.3</td>
<td>1/&gt;21</td>
<td>N</td>
<td></td>
<td></td>
<td>Hα</td>
<td>Inc:1300-1830</td>
<td>II</td>
<td>71</td>
<td></td>
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<tr>
<td>Nov 11</td>
<td>M1</td>
<td>2051.4</td>
<td>10/23</td>
<td>?</td>
<td></td>
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<td>Inc:1300-1830</td>
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<td>Nov 12</td>
<td>C5</td>
<td>2231.1</td>
<td>6/43</td>
<td>Y-2155</td>
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<td>Hα</td>
<td>Inc:1300-1830</td>
<td>II</td>
<td>71</td>
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<tr>
<td>Nov 13</td>
<td>M1</td>
<td>--</td>
<td>--?</td>
<td>?-1712</td>
<td></td>
<td></td>
<td>Hα</td>
<td>Inc:1300-1830</td>
<td>II</td>
<td>71</td>
<td></td>
</tr>
<tr>
<td>Nov 23</td>
<td>M2</td>
<td>1840.2</td>
<td>(7)/(50)</td>
<td></td>
<td></td>
<td></td>
<td>Hα</td>
<td>Inc:1300-1830</td>
<td>II</td>
<td>71</td>
<td></td>
</tr>
<tr>
<td>May 1, 83</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td>Hα</td>
<td>Inc:1300-1830</td>
<td>II</td>
<td>71</td>
<td></td>
</tr>
</tbody>
</table>

**NOTES:**

1. GOES-2 1-8Å flux: Cl = 10^-6 w/m², M1 = 10^-5 w/m², X1 = 10^-4 w/m².
2. Time difference: HXRBS Impulsive onset minus SXR flare onset from BCS. GOES data used when BCS not available. GOES Data in ( ).
3. Time difference: HXRBS Impulsive onset minus earliest SXR precursor in BCS.
4. Hα subflare or flare, radio burst or X-ray peak in preflare interval. Y=Yes; N=No.
5. Preflake brightenings in active region: SXR = soft X-rays, HXR = hard X-rays (>15 keV), UV = UVSP, Hα = from Hα images.
6. No Hα flare patrol: 1415-1515 UT.

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effect, a threshold effect or a function of the pre-flare energetics or production mechanisms.

**Ultraviolet.** Some examples of UV precursors include preflare surging motions in C IV (Kundu et al., 1985, Woodgate et al., 1982), and rising loops (Woodgate et al., 1981); these enhancements will be discussed for individual events below. In Section 1.4.4 Waggett and Bentley report on the correspondence of precursors in ultraviolet and X-rays.

**Coronal White light.** Various observers (Gary 1982, Sime et al., 1980, Harrison et al., 1985, Gary et al., 1984, Wagner 1982) have discussed the early appearance of coronal mass-ejection transients. SMY observations of transients in the low (HXIS) and mid-corona (Mauna Loa) have given a manifestation of pre-onset activity, which is clearer than the Skylab ‘forerunners’ (Jackson and Hildner 1978). The physics of the relation of coronal transients to flares and their respective precursors remains unclear but some preliminary concepts will be presented in Section 1.4.7.

**Common Precursor Factors.** The variety of precursors seen during the SMM period is surprisingly large but as we shall show, there appear to be common factors that connect them. Emergence of flux at the photospheric level is one such factor, but does not appear to be a necessary condition for the precursor, as shown by the discussion of the 25 June 1980 event in Section 1.4.3.1.

A particularly important question for flares in which a filament eruption occurs is whether the uplift of the filament signifies a reconfiguration of the magnetic field that causes the main phase of the flare to begin. There is no question that, typically, a significant amount of energy is released before the impulsive phase begins and before the most violent part of the filament eruption (Webb et al., 1976, Martin and Ramsey 1972, Moore et al., 1984). But precisely where the preflare heating occurs, relative to the observed filament motions and the flare site, is a more central question. Several important flares with well-observed preflare activity are described below in an attempt to access the important parameters and common features of such activity. These features will be summarized in the last section.

### 1.4.3 Specific Illustrative Events

We have selected 12 well-observed events from our preflare study to illustrate the diverse physical phenomena observed in the corona before flares. These include data with the best imaging and spectral coverage. This selection rules out spurious instrumental effects or unwarranted interpretations that might arise from the data from a single instrument. In a few cases the preflare and flaring periods have been thoroughly analyzed, and the interpretations are not likely to change significantly. But for most of these cases, the analyses are still very preliminary. The reader is cautioned, therefore, that this discussion is only meant to provide some initial
Figure 1.4.1b Comparison of time profiles integrated over the coarse field of view and sets of 1 to 4 individual pixels of the HXIS instrument.
summaries and interpretations of these preflare coronal manifestations.

1.4.3.1 A Filament Eruption Without Emerging Flux (25 June 1980)

The initial source of interest in this event was the set of preflare microwave maps made at 6 cm using the VLA. In the hour before the flare onset (1548 UT), according to Kundu (1981), the region around the flare site showed intensification in several compact (less than or about 20") sources whose polarization increased up until flare onset. In the 15 minutes before onset, the polarization of one bipolar source reversed sign, and the subsequent 6 cm burst occurred at the site of that reversal (Kundu et al., 1982). It was deduced that magnetic changes were taking place during the pre-flare period (Kundu 1981). When he realized that the preflare period contained a well-observed filament activation, and that its subsequent eruption had been well observed in both on- and off-band Hα at the Ottawa River Solar Observatory (ORSO), Gaizauskas undertook an exhaustive analysis of the kinematics of the event (Kundu et al., 1985, Gaizauskas 1984). Woodgate (Woodgate et al., 1982), recognizing the significance of simultaneous C IV upflows before the same flare, also undertook a complete analysis of the UVSP dopplergrams. We briefly summarize the details of this event, which have been described at greater length elsewhere (Kundu et al., 1985, Schmahl 1983).

Figure 1.4.2 shows the time line of the preflare period as observed in hard X-rays, soft X-rays, Ultraviolet, Hα and microwaves. The main (1B) flare began at 1548 UT (HXRBS), with an earlier minor burst at 1522, which corresponded to an Hα subflare seen in the 1 '×1' UVSP field of view and recorded in the BCS Ca XIX and Fe XXV channels. (There were no imaging X-ray observations of this flare from either SMM or P78-1). Although the subflare had kernels within 20"-30" of the flare-associated filament, the filament motion was not affected. The filament showed steady transverse motion (see Figure 1.4.2) as early as ~ 3 hours before onset, with upward doppler shifts near its midpoint and axial flows and twisting motions along its length. Brightenings at 6 cm were seen in a 5 minute VLA map at the time of the subflare, but the source of emission was ~ 1' from the Hα and ultraviolet brightenings. It is likely that this prior radio brightening was related to the magnetic field changes taking place before the onset of the main flare. Just after the subflare, (15:33-15:38), a brightening and upflow occurred in the C IV dopplergram image, coincident with the rising portion of the Hα filament which also showed enhanced axial flows. The brightening and upflow reappeared more strongly from 15:42-15:46 in approximately the same location. Finally, a third brightening and upflow reappeared even more strongly at impulsive onset (15:49). By this time the transverse motion of the Hα filament had carried it further southward, so that the blue-shifted, impulsive, C IV brightening seen in the last UVSP image at 15:52 UT was clearly north of (and presumably below) the rising filament.

In the last VLA preflare map (15:30-15:40) there was a polarity reversal in one of the bright active region components ("B" in Kundu et al., 1982). The location was cospatial with the subsequent ultraviolet and microwave impulsive onset at ~ 15:50. This was interpreted as possibly due to the interaction of new magnetic flux with pre-existing flux, creating increased 6 cm opacity through the gyroresonance process.

However, careful examination of the ORSO Hα films (Gaizauskas 1984, Kundu et al., 1985) and magnetographic data revealed no signature of emerging flux at the chromospheric or photospheric level (Section 1.4.3b). The main conclusion was that changes in magnetic field strength were mainly coronal, with photospheric changes being gradual or evolutionary in this event.
Gaizauskas (1984) has argued that the instability of the filament developed out of a major disturbance in a magnetically connected structure in the same active region. The slow upheaval of the entire structure exhibited enhanced axial flows leading to a rapid twist, consistent with the weak kink instability (Sakurai, 1976; Hood and Priest, 1979; Sung and Cao 1983).

The three preflare rising motions, seen in the ultraviolet, occurred beneath the Hα filament (see Figure 1.4.3), which responded with enhancements of axial flows from its midpoint towards the eastern footpoint. The first two episodes of rising motions in C IV were of lower velocity and density than the third. Kundu et al. (1985) have suggested that the coronal conditions were such that the first two uplifts were not sufficient to trigger the final disruption of the filament, but that the third one was. The restructuring of magnetic fields before 15:45 UT, suggested by the VLA map must be related to the rising, twisting motions of the filament and its supporting field lines.

1.4.3.2 Filament Eruption with Colliding Poles (22 June 1980)

The preflare activation of a filament on June 22, 1980 serves as an interesting counterpoint to the event of June 25. The region in which the activity occurred, Hale 16918, was studied extensively as part of an SMY FBS interval (Martin et al., 1983), and the filament activity was initially described by Malherbe et al. (1983). At the workshop, Simon presented results of a more complete study of the event with an interesting interpretation in terms of current sheets (Simon 1984).

The hard X-ray burst associated with this event was not recorded by SMM because of orbital night. (P78-1 Monex data may exist, but has not been reduced). The microwave impulsive phase of the event occurred between 13:03 and 13:06 UT. At 5.2, 8.4, and 11.8 GHz, an impulsive burst was recorded at Berne from 13:02:40 to 13:03:40. At 3.2 GHz (Bern) and 2.8 GHz (Ottawa) the strongest impulsive burst occurred about two minutes later (13:05:20). Almost simultaneously (±1 minute) another flare occurred in a neighboring region making the full-disk data difficult to interpret. This second flare occurred along the same neutral line and the two flares may have been related.

The Hα flare began in close coincidence with the impulsive bursts, with the central Hα intensity in the brightest kernel rising most rapidly from 13:03 to 13:06 UT (Malherbe et al., 1983). The Hα intensity and velocity profiles are shown in Figure 1.4.4. The filament associated with this flare showed activity as early as 12:36 UT in the form of red and blue shifts at various locations along its length (Figure 1.4.5). Figure 1.4.5 shows the Hα intensity and velocity maps at 13:00 UT. Systematic blue shifts began at about 12:45 in the filament, where it passed through region designated “O” by Martin (1983). At the western end of the field of view, where the filament was darkest, the velocities were generally small but became redshifted during the main phase of the flare. At the opposite extremity of the filament (C2) on the other side of “O”, blue shifts also changed to red shifts during the main phase. Near the midpoint (C1) of the filament and “O”, the Doppler shifts became large toward the blue side. This behavior is qualitatively similar to that of the June 25 filament. The Hα profiles made north of the neutral line showed evidence of absorbing material moving transversely.

Figure 1.4.3 Rising motions and intensity fluctuations as shown in C IV dopplergrams and spectroheliograms for the preflare period, 25 June 1980. (Kundu et al., 1985).
(northward) away from the neutral line between 13:00 and 13:03. The transverse velocity was about 35 km s\(^{-1}\) and the vertical velocity was at least 50 km s\(^{-1}\). The ejected material remained connected to the filament at a point near "O" until 13:05, at the time of the impulsive phase.

During the rise of the filament, 12:59-13:04 UT, the brightest H\(\alpha\) knot near "O" moved systematically toward the neutral line with a transverse velocity of 20 km s\(^{-1}\). On the other side of the neutral line, the knots did not show significant motion. At the time of the H\(\alpha\) explosive phase (~13:06) the absorbing material north of the neutral line separated. The filament reformed soon after the flare, as it did on June 25. The moving knot was interpreted (Simon et al., 1984) as the foot of a current sheet separating emerging and pre-existing fluxes.

**Figure 1.4.4** Time profiles of H\(\alpha\) and microwaves for the preflare period, 22 June 1980 (Simon et al., 1984). Upper: H\(\alpha\) intensity. Middle: H\(\alpha\) velocity. Lower: Microwave flux.

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Common Features of the June 22 and 25 Preflare Activity

Although the instrumentation observing the events of June 22 and 25 was different and the published descriptions emphasize different physical phenomena, it is clear that there were several common features in these events.

- **Filament Kinematics** – The upward motions of the filaments occurred near their midpoints, with downward motions near the ends. The driving force which lifted the magnetic arch apparently did not constrain the material from falling down the ends of the structures. In the analysis of both events it was concluded that not all of the filamentary material was ejected.

- **Multiple Motions** – Several kinds of motions were observed. In the June 25 case, there were axial and twisting motions as well as upflows and downflows. The upflows occurred as three successive events in the 20 minutes before onset. On June 22, upflows occurred during the preflare 25 minutes as three or four upheavals at the brightest point of the filament, but axial and twisting motions were not reported.

Figure 1.4.5 Intensity and Velocity in Hα at 13:00 UT, 22 June 1980. The arrow in the second panel shows the blue-shifted material at "O". C₁ and C₂ in the third panel show the locations of the features of Figure 1.4.4.
Exciting Agent – The trajectory of the ejected material appeared to be directed away from a bright ‘‘exciting agent’’ at lower levels. On June 25, a bright surging feature was observed in the C IV line which could be inferred as triggering the eruption (Kundu et al., 1985, Woodgate et al., 1982). On June 22, the bright feature was an Hα knot which moved toward the neutral line as the dark absorbing structure on the other side moved away from it. The bright moving knot was interpreted as the footpoint of the current sheet between colliding lines of force (Simon et al., 1984). Although the two ‘‘exciting agents’’, seen at lower levels, were morphologically different, a common interpretation in terms of moving magnetic fields is possible for both.

Filament Reformation – In both events, the filament reformed within a few minutes of the impulsive phase. This implies that the boundary conditions of the configuration, especially in the photosphere, remained sufficiently similar that the preflare magnetic field structure was restored postflare (Kundu et al., 1985).

Dissimilarities: Is Emerging Flux Necessary? For the June 25 flare, a clear case has been made that no emerging flux existed below the filament. For the June 22 flare, the evidence is not so clear, but the colliding poles seen below the filament certainly are not characteristic of the classic emerging regions, which overlie diverging bipoles. However, such cancelling Magnetic Features (Martin, 1984) may have a similar effect to emerging flux in triggering flares (Priest, 1985). In both flares, the triggers for the eruptions may have been slow changes of magnetic field in the neighborhood of the filament. Similarly, one can ask whether the apparently different ‘‘exciting agents’’ (the surging C IV emission and the moving Hα knot) be interpreted by similar mechanisms. We return to this question after summarizing another event which shows both common and different features of preflare activity.

1.4.3.3 Rising Loop at the Limb (April 30, 1980)

Hα observers (e.g., Martin 1980, Rust et al., 1981, Rust et al., 1980, Webb 1983) have shown that Hα emission can precede the impulsive phase by a few to tens of minutes. The April 30, 1980 flare illustrates the case where the initial burst is preceded by a bright Hα mound at the site of developing new magnetic fields. (The flare occurred close to the limb where chromospheric footpoints typically are hard to detect.) The above-the-limb Hα emission was cospatial with a C IV loop (Woodgate et al., 1981) and was interpreted as an arch-filament system (Rust et al., 1981). Foreshortening at the limb, however, makes it impossible to determine the extent of the loop along the line of sight. For example, the loop might have been an elongated helical structure like a filament seen end-on, as suggested by line-of-sight flows seen in the UV, and by the fact that its southern footpoint was further onto the disk than the northern footpoint (Woodgate et al., 1981).

The preflare period for this event was well observed by all the SMM instruments and the details of the preflare activity were summarized by de Jager et al. (1983). Figure 1.4.6 shows the schematic UVSP loops (Woodgate et al., 1981) along with the HXIS light curves (de Jager et al., 1983). The two major HXIS structures in the flare, the ‘‘kernel’’ and the ‘‘tongue’’, both appeared spatially coincident (+8") with the UVSP structures AB and DE (respectively). The brightenings in HXIS X-rays and in UVSP C IV were also in temporal coincidence as were the softer X-rays seen in the BCS Ca XIX and GOES 0.5-4 Å channels.

According to the HXIS observers (de Jager et al., 1983), after the maximum of the ‘‘kernel’’ precursor at 19:55 until

Figure 1.4.6 HXIS light curves (adapted from de Jager et al., 1983) for the April 30, 1980 flare. Schematic loops (Woodgate et al., 1981) are shown above.
the onset of the flare at 20:22, the intensity decline was consistent with conductive losses (no radiative losses) of a gas at $T_e = 1.5 - 2 \times 10^7$ K and $n_e = 3.2 \times 10^9$ cm$^{-3}$. In the "tongue" of particle energization occurred continuously from the onset of the precursor to the impulsive rise.

During the rise phase (20:17-20:22) of the burst, the H$\alpha$ and soft X-ray emission increased, and material rose in the C IV loop leg, with Doppler shifts ($\simeq 20$ km/s) toward the observer. At the time of the main burst, "breakout" occurred at the top of the loop where a new feature appeared in H$\alpha$.

Two explanations have been suggested (Woodgate et al., 1981) for the observed developments, the first being that a smaller loop filled with heated gas, pushing it upward into the larger loop and creating the flare at the junction. The second explanation was that the small loop became unstable at the top after the injection of gas and released the gas into the surrounding medium.

The first of these explanations is similar to the scenario developed for the June 25 flare (Kundu et al., 1985), where in the destabilized H$\alpha$ filament was accompanied by rising C IV loops. The question of the existence of emerging flux in these events may not be as significant as the similarities in the triggering of the impulsive phase by a rising loop. Whether there was continuous high-energy preflare energization in the June events (as there appeared to be in the April 30 flare) is not known because HXIS did not observe the later pair.

The time profile of soft X-rays [BCS, GOES, HXIS] for April 30, the time profile of C IV intensity and H$\alpha$ velocity for June 25, and the H$\alpha$ velocity profile on June 22 all suggest that the flare "tries to start" and fails until the final agent (rising loop?) triggers the explosive phase.

1.4.3.4 X-ray Precursor Not at Flare Site (April 10, 1980)

The BCS Ca XIX and GOES flux started to rise at ~09:00, or about 20 minutes before the onset of the HXRBS burst (09:16). During this rise there was a Ca XIX burst (~09:05) which is considered a flare precursor. This peak was also recorded by HXIS (Machado et al., 1983) in the two softest channels. Preflare emission in N V was observed in three regions which were postulated (Machado et al., 1983) to be the footpoints of the subsequent flare loops. The 09:05 HXIS precursor appeared mainly at the southeastern and northern footpoints. The UVSP time profile in a 21" $\times$ 21" raster centered on the western footpoint showed impulsive brightening at that footpoint. Woodgate, Waggett and Bentley found that the small UVSP raster precluded an analysis of correlations between preflare ultraviolet bright points and FCS activity.

The combined HXIS and UVSP data imply that the precursor activity occurred in loops displaced ~ 8" - 16" away from the main hard X-ray brightening. Machado et al. (1983) estimated the emission measure ($\sim 5 \times 10^{67}$ cm$^{-3}$) and temperature ($\sim 1.3 \times 10^7$ K) for the precursor. The data permitted a multithermal interpretation, but counting statistics did not warrant the computation of differential emission measures.

The authors conjecture that the preflare gradual phase was a part of the overall gradual phase upon which the impulsive phase was superposed.

1.4.3.5 X-ray Preflare Emission From Filament Disruptions

On June 26 1980, Boulder Region 2522/30 produced what Martin classified as a "predictive filament" activation starting at approximately 23:30 UT. The BCS Ca XIX intensity showed a small precursor superposed on the rise at ~23:33. According to Harrison there were two precursors seen by HXIS at 23:35 (Figure 1.4.7), one located west (limbward) of the subsequent flare site and the other to the east. The BBSO H$\alpha$ film showed that the precursor appeared as a subflare/surge in the penumbra of the leader spots to the west.

During liftoff (23:30-23:40) the activated H$\alpha$ filament went from absorption into emission at 23:39:29 UT, close to the 23:39:35 impulsive onset. For the approximately two minutes of the H$\alpha$ explosive phase, the filament rose rapidly, much like one leg of an expanding loop, after which ribbons formed on either side of the neutral line. Immediately following the flare, the filament reformed.

Preliminary colignment suggests that the western HXIS precursor at ~23:32 coincided with the subflare/surge event. The eastern precursor was not obviously associated with any H$\alpha$ activity. Several similarities in the preflare activity of the June 22nd, 25th and 26th events are discussed below.

On June 28, 1980 the leading portion of region 2522/30 was near the west limb and produced prominence and flare activity that was well observed at Mauna Loa Solar Observatory (MLSO) and by SMM. The first sign of activity in the hour before the flare was an eruptive prominence observed by MLSO from 17:12 - 18:44 UT (Rock et al., 1983). Subflares in the region occurred from 18:19 - 18:24. Associated activity was observed by UVSP in the Si IV line from 18:23 - 18:27. The flare itself appeared as two bright knots on the limb, seen in both H$\alpha$ and Si IV. The preflare brightening occurred between the knots, then at the main flare site (18:23 - 18:27). Waggett and Bentley reported what may be an X-ray precursor in Mg XI inside the limb at ~18:18:26 (Figure 1.4.8b-d) and then subsequently at the flare site at 18:27 (Figure 1.4.8). The same precursor at the flare site was observed by HXIS in maps prepared by Schadee and Schrijver.

H$\alpha$ flare onset was at ~18:24 before the onset of hard X-rays and continued as an upflow until at least 18:34 UT. The onset of the flare in X-rays appeared to start at 18:37 in the soft HXIS channel. The Mg XI images (Figure 1.4.8)
Figure 1.4.7 HXIS images showing the 23:32 precursor before the 23:40 flare on 26 June, 1980. The arrows on the time axis of the burst profile show the times of the individual maps.
showed onset at later than or about 18:42 and a double flare. In Si IV a brightening occurred near the northern flare knot at \( \sim 18:41 \), maximizing at \( \sim 18:45 \), the time of the hard X-ray burst. The H\( \alpha \) upflows apparently continued through 18:54, with motion paralleling the previous prominence eruption. The outflowing prominence material moved above the MLSO occulting disk at \( \sim 18:59 \) at the same position angle as the previous eruption.

**Common Activity in the June Events**

In the June 26-28 events, preheating of the filament was inferred from X-ray brightening during its liftoff. Both events had H\( \alpha \) "double-ribbons"; the June 28th flare was also
double in ultraviolet and X-rays. Preflare brightenings were observed displaced from the flare site. On the 26th, two HXIS preflare brightenings occurred west and east of the flare site. On the 28th, the early Mg XI brightenings were displaced laterally and possibly above the limb flare. Both of these flares require considerably more analysis before firm conclusions can be drawn. Nevertheless, one striking similarity to the June 22 and 25 events stands out. In all four events preflare brightenings (in Hα on the 26th and in ultraviolet on the 28th) occurred beneath the filament or between the flare knots, suggesting that the flare was triggered from below. But the subflares preceding the June 25 and 26 flare, and the June 26th and 28th X-ray precursors were all displaced from the flare site and had no obvious relationship to the subsequent flare.

1.4.3.6 Homologous Flaring – November 5, 1980, 22:26 and 22:32 UT

Woodgate (1983) suggested that a majority of flares might be homologous in the sense of having footpoints reappearing very near the same places. The importance of homologous flares is that differences in initial conditions between flares can be minimized in order to isolate which factors are significant in terms of the site of flaring, timing, field strengths and energy release.

The November 5, 1980 flares were a good example of well-observed, homologous events. The hard X-ray profiles were similar (see Figure 1.4.9), although the second burst was an order of magnitude stronger. The microwave burst profiles were also similar, but the second burst at 17 GHz (Enome et al., 1981) was ~ 40 times larger than the first. The first burst was observed by the VLA at 15 GHz (Hoyng et al., 1983) and by various patrols from 1-17 GHz. The microwave spectrum went as $v^{-2.9±0.1}$ up to 17 GHz, and the maximum of the spectrum was therefore above 17 GHz. The patrol data (Nobeyama, Nagoya, and Toyakawa: (Enome et al., 1981, Kosugi and Shioml 1983, S.G.D. 1981) show that the second burst had a very similar spectrum, also with a maximum $\geq 17$ GHz (but less than 35 GHz). The amplitudes of two events were in rough proportions of $\sim 40:1$ at all frequencies from 1-17 GHz. Helium D3 film from BBSO showed that the two bursts were optically similar (see Chapter 5, §5A.5, Figure 5A.13). The bright D3 kernels of the impulsive phase appeared and disappeared with close simultaneity to the hard X-ray bursts, and the two ‘‘kernels’’ of the second event were cospatial with those of the first. One important difference between the two events was a weak “outlier” seen in D3 far from the main kernels.

According to Martin (see Chapter 5) the outlier appeared to correspond to the weak impulsive source reported by HXIS (Duijveman 1982). Both flares showed strong Ca XIX blue shifts (~ 300 km/s) during the impulsive phase (Antonucci et al., 1984). This bears on the question: did the first flare trigger the second? X-ray observations have shown (Strong et al., 1984) that a flare closely following a previous one can be affected by the presence of thermal electrons exceeding a certain critical density which are “quenched” in the flux tube where the impulsive acceleration of the second flare takes place. If the critical density (~ $3 \times 10^{12}$ cm$^{-3}$) is exceeded, the beam electrons will lose their energy at high altitudes, and no chromospheric evaporation will occur (as was the case in the double flare of August 31, 1980). The measurements of strong Ca XIX blue shifts in both flares on November 5 indicate that “quenching” of the second flare did not occur. Since the observations all suggest that the main components of the two flares were co-spatial (not including the outlier), it is likely that both flares occurred in one flux tube and that the critical density was not reached.

Longevity of the X-ray Loops

Martens et al. (1985) conjectured that two fairly stable loops in region 2776 dominated the HXIS emission from November 5, 12:30 to November 6, 03:50. These loops were labelled AB and BC (Figure 1.4.10). During this time loop AB flared twice at 22:26 and 22:34 UT with several other flare-like brightenings at 15:04, 17:20, 20:47 and 23:50 on November 5. In the second flare the footpoint C of the impulsive phase was connected to the common footpoint B of the two loops. Apparently, loop BC was quite long-lived (Martens et al., 1985) with small variations correlated with the brightnesses in loop AB.

Because loop BC was stable in emission we can assume that it was in static thermal equilibrium. We can therefore use scaling laws (Rosner et al., 1978) to derive the electron
density ($n_e$) and the heating rate in the loop ($E_h$) from the observed loop length ($L$) and temperature ($T_{\text{obs}}$) from HXIS. (We note, however, that the usefulness of the static loop scaling law has been questioned by Roberts and Frankenthal (1980)). From the observed emission measure ($Y$) and the derived density an estimate of the emitting volume $V_{\text{em}} = Y/n_e^2$ of the loop could be made. This emitting volume was, surprisingly, much smaller than the observed volume $V_{\text{obs}} = \pi R^2$ of the loop. The loop filling factor: $\phi = V_{\text{em}}/V_{\text{obs}}$ had an almost constant value of $10^{-3}$. These results are summarized in Table 1.4.3.

Table 1.4.3
General Data on Loop BC, November 5/6, 1980

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Length</td>
<td>$(93.4 \pm 1.5) \times 10^4$ cm</td>
</tr>
<tr>
<td>Mean Diameter</td>
<td>$(11.4 \pm 0.3) \times 10^4$ cm</td>
</tr>
<tr>
<td>Mean Temperature</td>
<td>$(10.4 \pm 0.2) \times 10^6$ K</td>
</tr>
<tr>
<td>Mean Electron Density</td>
<td>$(9.8 \pm 0.4) \times 10^{10}$ cm$^{-3}$</td>
</tr>
<tr>
<td>Mean Filling Factor</td>
<td>$(1.4 \pm 0.3) \times 10^{-3}$</td>
</tr>
<tr>
<td>Mean Heating Rate</td>
<td>$(0.64 \pm 0.04)$ erg cm$^{-3}$ sec$^{-1}$</td>
</tr>
</tbody>
</table>

Similar data on loop AB could not be derived, since it was unresolved by HXIS and its emission was highly variable. During quiescent periods loop AB had a temperature of $10^7$ K and an emission measure per $(8'' \times 8'')$ pixel of about $1.5 \times 10^{46}$ cm$^{-3}$. Duijeman et al. (1982) derived an electron density of $2.4 \times 10^{10}$ cm$^{-3}$ from the observed temperature and an emission measure of loop AB by assuming a filling factor of unity, while FCS observations of Ne IX were used to derive $n_e = 1.5 \times 10^{12}$ cm$^{-3}$ (Wolfson 1983). Agreement between these observations is obtained by using a filling factor of $2.6 \times 10^{-4}$, which is of the same order of magnitude as that of loop BC.

Together these observations suggest the continuous dissipation of a current which is present in loops AB and BC, with the actual loss taking place in a very thin region. Clearly during flares the dissipation mechanism changes qualitatively in character.

It is still an open question whether the first and smaller burst late on November 5 triggered the second burst, or whether both were triggered by earlier events. The preflare manifestations of these flares have not yet been reported in sufficient detail to assess their significance. It appears, from the BBSO Hα film, that the first flare started in a fibril crossing the neutral line. This fibril went into emission at 22:23:29, approximately simultaneously with a rise in OV seen by UVSP, a small rise at 15 GHz (Hoyng et al., 1983) and a rise at 9400 MHz (Enome et al., 1981). Earlier subflares occurred on the same neutral line.

This double flare is important not only for the questions associated with homology, but as a possible test case for double flares in general. It has been estimated (Strong et al., 1984) that ~ 43% of the ~ 200 largest flares seen by the XRP in 1980 were "multiple" (on the basis that the Ca XIX flux did not fall to background between maxima). The importance of such "multiple" flaring for preflare studies lies in their possible relation to precursors, triggering and the repeated "attempts" of a flare to start.

1.4.4 Comparison of Preflare X-rays and Ultraviolet

Waggett, Bentley and Woodgate compared BCS and UVSP images for those of the 26 events in the Table 1.4.2 that showed pre-impulsive activity in the UVSP images. As both the FCS and UVSP are capable of performing a vari-

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ety of different size rasters within large fields of view it is possible for them to be looking at different areas within the same active region. Coalignment of the instruments' fields of view left 10 events with good overlapping spatial and temporal coverage in both UVSP and FCS images.

Two time intervals were considered: the preflare period prior to the HXRBS onset and the impulsive phase prior to the HXRBS peak. The spatial separation of the UVSP preflare bright points and the FCS flare site were divided into three distance categories: less than 20° (adjacent to or at the flare site), between 20° and 40° (close to the flare site), and greater than 40° (far from the flare site). The results are given in Table 1.4.4 where the separation of the nearest preflare pixel is indicated by a ‘Y’ in the appropriate distance column. The BCS column indicates whether there was significant activity in the BCS Channel 1 light curve during the preflare period and the BDIP column indicates whether the preflare pixel brightened during the impulsive phase in the FCS data.

With only 10 events it is difficult to form meaningful conclusions. It is hoped that coordinated observations with special observing sequences during the SMM 2 mission will expand the sample. The inclusion of XRP data has improved the results of the UVSP analysis by confirming the position of the flare site and by removing events that were initially confusing. It is clear that the correlation of preflare UV bright point position and the flare site is good since 6 (possibly 7) of the nearest 10 preflare events are coincident with the subsequent flare site.

### 1.4.5 Preflare Microwave Intensity and Polarization Changes

We discussed in Section 1.4.3 some interferometer observations which showed preflare polarization changes.

<table>
<thead>
<tr>
<th>Date</th>
<th>Distance of Pixel</th>
<th>BCS</th>
<th>BDIP</th>
<th>UVSP Line</th>
<th>Pixel Size (arc sec)</th>
<th>Preflare Intensity (UVSP C/S)</th>
<th>Impulsive Phase Intensity (UVSP C/S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>29/3/80 (2014 UT)</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>CIV</td>
<td>3</td>
<td>$1.42 \times 10^4$</td>
<td>$3.42 \times 10^4$</td>
</tr>
<tr>
<td>27/4/80 (0106 UT)</td>
<td>Y(*)</td>
<td>N</td>
<td>?</td>
<td>CIV</td>
<td>3</td>
<td>$3.42 \times 10^4$</td>
<td>NOT SEEN</td>
</tr>
<tr>
<td>30/4/80 (2023 UT)</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>CIV</td>
<td>3</td>
<td>$6.13 \times 10^3$</td>
<td>$2.76 \times 10^4$</td>
</tr>
<tr>
<td>20/6/80 (0488 UT)</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>CIV</td>
<td>3</td>
<td>$2.92 \times 10^3$</td>
<td>$2.34 \times 10^4$</td>
</tr>
<tr>
<td>29/6/80 (2022 UT)</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>CIV</td>
<td>3</td>
<td>$1.08 \times 10^4$</td>
<td>$1.66 \times 10^4$</td>
</tr>
<tr>
<td>10/7/80 (2126 UT)</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>SiIV</td>
<td>3</td>
<td>$4.07 \times 10^2$</td>
<td>$7.00 \times 10^4$</td>
</tr>
<tr>
<td>11/10/80 (1741 UT)</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>OV</td>
<td>10</td>
<td>$3.80 \times 10^2$</td>
<td>$4.28 \times 10^3$</td>
</tr>
<tr>
<td>2/11/80 (0211 UT)</td>
<td>Y</td>
<td>N</td>
<td>?</td>
<td>OV</td>
<td>10</td>
<td>$2.99 \times 10^2$</td>
<td>NOT SEEN</td>
</tr>
<tr>
<td>11/11/80 (2054 UT)</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>OV</td>
<td>10</td>
<td>$9.06 \times 10^2$</td>
<td>$1.63 \times 10^3$</td>
</tr>
<tr>
<td>12/11/80 (2231 UT)</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>OV</td>
<td>10</td>
<td>$1.46 \times 10^2$</td>
<td>$2.59 \times 10^2$</td>
</tr>
</tbody>
</table>
Although it may be true (Hurford and Zirin 1982, Willson and Lang 1984) that preflare polarization changes at centimeter wavelengths are not generally detected, there is evidence (Hurford and Zirin 1982) that certain microwave signatures are relatively reliable predictors of flares.

In a study of a sample of 81 major flares observed at 10.6 GHz with the Owens Valley Radio Observatory (OVRO) interferometer, Hurford and Zirin (1982) found a variety of preflare behavior. The most common preflare signature was a step-like increase in signal amplitude, accompanied by a decrease or reversal in the polarization signal during the last 10 to 60 minutes before the flare. This signature was found in the first half of the data base (Feb. 19 – Sept. 1, 1980), and when applied by a computer program to the second half (Sept. 1, 1980 – March 31 1981) succeeded in predicting five out of 54 flares. This low success rate limits its practical value as a flare predictor but the microwave signatures do illustrate the coronal manifestation of some kind of magnetic activity. Figures 1.4.11a,b show two examples of flares observed at 10.6 GHz by OVRO on July 1 and October 11, 1980. The first shows a signature of increasing I and decreasing V, while the second shows only increasing V. Kundu (1981) suggested that the cause of microwave enhancements and polarization changes may be increasing magnetic field strength at the coronal level. The increasing magnetic field causes new loops to become optically thick at low harmonics (2nd, 3rd, and 4th) of the gyro-frequency. Depending on the relative orientation of the pre-existing and new loops, the polarization can increase (Lang 1974, 1979), flip (Kundu 1981, Kundu et al., 1982) or decrease (Hurford and Zirin 1982). Only two-dimensional interferometry (VLA) can resolve the loop geometry, and there are still too few examples from OVRO to infer the loop geometry statistically. Hurford and Zirin (1982) showed in 3 cases that microwave changes were associated with sub-flares or filament changes. The July 1 event illustrates an example of a preflare brightening in Hα (at ~ 16:18), near the start of the increase in one of the polarization channels. The June 25 flare reported above in Section 1.4.3.1 illustrated another association between microwave and Hα changes.

The gradual rise in preflare microwave intensity can be observed with patrol instruments, and is presumably associated with “preheating” and gradual rises in soft X-rays (see Section 1.4.2). These gradual increases in microwaves are frequently associated with filament activations (Webb et al., 1976, Sheeley et al., 1975, Webb and Kundu 1978) and were observed by patrol instruments for the June 22, 25 and 26 flares discussed above. The OVRO amplitude for the July 1 X-ray flare (Figure 1.4.11a) showed a preflare increase that was not observed by patrol instruments or in the Ca XIX time profile. Thus the heating effects may have been too small to be observed in X-rays, but a microwave increase was observed possibly because of the extreme sensitivity to the magnetic field in the cyclotron emission mechanism. More recently the OVRO system has been made into a microwave spectrometer, examining typically 30 – 40 frequencies from 1 – 18 GHz with a time resolution of seconds. With this system Hurford (1983) found that some microwave precursors were characterized by narrow-band spectra with sharp high and low frequency cutoffs. He has interpreted these data in terms of gradual loop heating.

1.4.6 Non-Thermal Precursors

Long before SMM, it was argued that non-thermal processes occurred during the “buildup” phase of solar flares (Kane and Pick 1976) and in the absence of flares (Webb and Kundu 1978). Several preflare team members presented new evidence and theoretical arguments for non-thermal, non-flaring activity as seen in radio waves. Kosugi summarized a number of preflare activities observed at 17 GHz using the Nobeyama interferometer. He and his co-workers (Kai et al., 1983) examined 25 pairs of bursts which occurred within 10 to 50 minutes of each other. These pairs were coplanar (in one dimension) to < 50° in 12 out of 15 cases. In most cases, the prebursts were impulsive, and therefore were not likely to be signatures of gradual preflare heating. However, they also noted that in more than half of the cases, Hα flaring started before the “preflare” burst, which argues in favor of preflare heating. They suggested three possible mechanisms for prebursts:

- A process related to the main energy release such as joule heating in current sheets.
- Pre-acceleration of electrons prior to the main acceleration.
- Manifestation of “leakage” of accelerated electrons.

They pointed out that the “leakage” mechanism is probably not consistent with the long time interval between bursts. Kosugi also showed evidence for statistical association in the number of type III (meter wave) bursts within minutes of prebursts at 17 GHz (Kosugi et al., 1985). No spatial locations were available for the type III bursts. Finally, Jackson reported that a study of spatially located type III’s observed at Culgoora showed a statistically significant tendency to occur an hour or so prior to large Hα flares. If these associations between prebursts at 17 GHz, Hα flares and type III’s are valid, then the mechanism of pre-acceleration appears to be favored.

Harisson presented a model (Simnett and Harrison 1984) of precursors in which 10^2-10^3 keV protons heat a high coronal loop, destabilize the pressure balance and heat the chromospheric plasma to produce the precursor X-rays. The acceleration mechanism is a small shock, which primarily heats protons within a large-scale magnetic loop. The model is directed primarily at the situation where precursors are widely separated preceding a coronal mass ejection with or without a flare.

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Figure 1.4.11a The July 1, 1980 flare time profiles at 10.6 GHz (Owens Valley Radio Observatory, (Hurford and Zirin 1982)) showing the "onset" signature of increasing I and decreasing V. The middle panels show the amplitudes of R and L (right and left circular polarizations); $V = (R-L)/V$.

Figure 1.4.11b The Oct. 11, 1980 flare time profiles at 10.6 GHz (OVRO, Hurford and Zirin 1982).
There is evidence for electron acceleration in the absence of flares. Chiuderi-Drago pointed out that sometimes bright non-flaring sources \( \left( T_b > 5 \times 10^6 \text{ K} \right) \) appear on microwave maps, and these sources may be explained (Chiuderi-Drago and Melozi 1984) in terms of gyrosynchrotron emission from accelerated electrons trapped in coronal loops, where they may survive for \( \sim 10^5 \text{ sec} \). This is consistent with the lifetime of some precursors, and if continual acceleration occurs, the mechanism could explain some long-lived microwave sources. If the number of electrons is sufficiently high, then the gradual-rise-and-fall events commonly associated with filament disruptions (Webb et al., 1976, Sheeley et al., 1975), can be explained by a thermalization process (Webb and Kundu 1978) which follows the precursor acceleration.

### 1.4.7 Precursors of Coronal Mass Ejections

Although most of the SMM preflare data are for disk events, three coronal transient events on June 29 were well observed as region 2522/30 neared the limb.

All of these limb events were observed by HXIS and C/P (Harrison et al., 1985) and the 02:33 and 18:22 events were also well observed by XRP and UVSP. These were possibly homologous events because the flares occurred in the same location and had similar X-ray profiles with GRF precursors and long flare decay times (Stewart, 1984; Woodgate et al., 1984).

Figure 6.5.1a,b (Chapter 6) shows the HXIS flux profile for June 29 and the extrapolated C/P coronal transient onset times for two of the three events. The detailed HXIS data and their interpretation are presented in Chapter 6 and only summarized here.

A long-lived 160 MHz noise storm preceded the 02:33 flare but ended at 02:21 (Gary et al., 1974). The flare was associated with two moving white-light loops whose height-time profile extrapolated back to the surface about 6-8 minutes before flare onset. The HXIS precursor began at about 02:10. Shine prepared Figure 1.4.12 which shows the preflare period 02:17-02:29 in Si IV and O IV rasters, as well as the flare itself (02:33-02:37). At the time of the first UVSP preflare rasters, the BCS, FCS and HXIS all recorded a brightening at the flare site at 02:19. Later, the point brightened again at \( \sim 02:28 \), but was not visible in X-rays. The onset of the Si IV/O IV burst was at 02:33:56 and appeared as multi-pixel brightenings within \( \sim 10^5 \) of the preflare UV brightenings.

The 10:40 UT event was not well observed by the C/P or UVSP, but a preflare He I "jet" was observed (Schmah 1983). The white-light loop transient associated with the 18:22 flare had a projected surface start before 18:15 (Sime et al., 1980, Harrison et al., 1985). A small Hα and X-ray flare occurred at 18:05 at a position slightly displaced from the later flare site. The UVSP observed a preflare OV loop and Fe XXI brightening (Poland et al., 1982), and BCS analysis revealed turbulent line broadening up to 4 minutes before onset (Antonucci et al., 1982).

The relationship between coronal mass ejection (CME's) transients and flares is far from clear, and it is fairly well established that one may have CME's without flares and vice versa.

However, Harrison et al. (1985) argue that the flare precursor and the mass ejection precursor may be one and the same. In Section 3 of Chapter 6 Harrison gives examples in which the X-ray precursor of the mass ejection may be very small, as large as a flare, or "a lone precursor", without a folowing flare. At this stage of the analysis it is premature to assess the reality of the possible relationships among precursors of flares and CME's, but research along these lines may well provide a broader understanding of the role precursors play in the energy release process.

### 1.4.8 Short-Lived and Long-Lived HXIS Sources as Possible Precursors

Owing to its low background, particularly in its lowest energy band (3.5-5.5 keV), HXIS is capable of detecting very weak X-ray sources. The X-ray precursors reported by HXIS observers (Sections 1.4.3.3, 4 above) have been interpreted as thermal events, with temperatures \( 1-2\times10^7 \text{ K} \). HXIS images often showed (Schad et al., 1983) short-lived sources (SLS) and long-lived sources (LLS) in the 3.5-5.5 keV band. The short-lived sources (lifetime less than or about 15m) appeared indistinguishable per se from HXIS precursor sources but did not always precede flares. The long-lived (hours-days) sources were of larger scale. Both had band-ratio temperatures of \( \sim 10^7 \text{ K} \).

In the context of our study, HXIS LLS's preceded two large flares with precursors, namely, May 21 20:55 and the June 22 flare discussed in Section 1.4.3.2. Although not part of this study, the May 21 X1 flare is one of the best analyzed SMM flares and is discussed elsewhere in this monograph. As in the June 22 case, it was preceded by a compression of pre-existing flux. See Section 3.5.4(iii), Harvey (1983). Discrete LLS's cospatial with the curving filament persisted for many hours on May 20 and 21. One source was located near the site of the EFR where the filament broadened then parted 10 minutes before impulsive onset.

Figures 1.4.13a (coarse FOV) and 1.4.13b (fine FOV) show accumulated HXIS images during 20 hours preceding a two-ribbon flare on June 21, 00:55. LLS's were frequently present, cospatial with the neutral line and filament curving from SE to WNW through the center of the FOV. LLS's occurred along the filament until its eruption before the flare of June 22, \( 13:04 \). Even though the filament soon reformed, no further LLS's were observed after this event.

As evidenced by Figure 1.4.13, long-lived sources extend over a large area, often persisting for several hours.
June 29, 1980 2:34 GMT
M2 Flare on West Limb

pre-flare large rasters

Si IV 1402  O IV 1401

2:17 to 2:21 GMT

small rasters during flare

Si IV 1393A and O IV 1402A
each 7 x 7 raster covers 28'' x 28''

pre-flare event

Figure 1.4.12 Preflare and flare images in Si IV and O IV (UVSP), 02:17-02:37, 29 June 1980.
Figure 1.4.13 Long-Lived HXIS sources seen preflare June 22, 1980. Post-flare images do not show these sources. Coarse field-of-view maps are shown on the left and fine field-of-view maps are shown on the right.
The characteristics of LLS's are: durations of tens of minutes to hours; temperature \( \sim 10^7 \) K; and emission measures of \( \sim 10^{48} \) cm\(^{-3}\). They often show gradual intensity changes.

Most LLS's appear to result from activity along neutral lines. They may represent the high temperature tail of the thermalized plasma associated with filament activity as observed during Skylab (e.g., Webb et al., 1976, Webb and Kundu 1978, Kahler 1977). The Skylab soft X-ray filament enhancements had emission measures an order of magnitude higher and temperatures of an order of magnitude lower than the HXIS LLS's.

If the LLS's originate beneath the filament, then the model of Kopp and Pneuman (1976), Van Tend-Kuperus (1978) and Hood and Priest (1980) may be applicable. In that model the convergence of magnetic flux towards the neutral line in the photosphere results in energy dissipation by reconnection below the filament in the corona. Interestingly, other observations (Athay et al., 1984) show evidence of magnetic flux converging at the neutral line in the Martin region. They suggest a process of continuing reconnection. At this stage it is not clear whether the X-ray emission results from filament activation, from continuing reconnections, or both.

1.4.9 Summary: Are all the Blind Men Looking at the Same Elephant?

We have reported a variety of coronal manifestations of precursors or preheating for flares and have found that almost everyone with a telescope sees something before flares. Whether an all-encompassing scenario will ever be developed is not at all clear at present. The clearest example of preflare activity appears to be activated filaments and their manifestations, which presumably are signatures of a changing magnetic field. But we have seen two similar eruptions, one without any evidence of emerging flux (Kundu et al., 1985) and the other with colliding poles (Simon et al., 1984). While the reconnection of flux is generally agreed to be required to energize a flare, the emergence of flux from below (at least on short timescales and in compact regions) does not appear to be a necessary condition. In some cases the canceling of magnetic flux (Martin, 1984) by horizontal motions instead may provide the trigger (Priest, 1985).

We have found many similarities and some differences between these and previous observations. The similarities, besides the frequent involvement of filaments, include compact, multiple precursors which can occur both at and near (not at) the flare site, and the association between coronal sources and activity lower in the atmosphere (i.e., transition zone and chromosphere). Because of differences in instrumentation and improvement in multi-wavelength coverage with high time resolution, we have been able to identify several new aspects of preflare activity in the SMM data. These include the facts that: precursors were observed over a wide range of temperatures and heights; there were long-lived, hot (\( > 10^7 \) K) X-ray sources preceding some flares; and there was evidence for high energy phenomena, particularly electron and possibly proton acceleration before flares. The fairly rapid reformation of some filaments after their explosive eruption suggests that the photospheric boundary conditions remain unchanged, at least after some flares. Concerning filament-eruption flares, we saw suggestive examples in Section 1.4.3 of a flare exciting agent (at least as detected by its emission) first arising under the central portion of the filament.

Finally, our results leave us with several important questions. We have shown examples of preflare X-ray enhancements and small impulsive-like bursts. Are these signatures of a incremented instability, in which the flare "tries to start and fails" or are they signatures of a separate process that energizes the corona first with the flare following as a separate phenomenon?

Is the preflare gradual phase caused by the same mechanism as the postflare phase? Alternatively, does the gradual preheating occur through thermalization of an energetic population signified by nonthermal prebursts? Do microwave signatures signify changing coronal magnetic fields during the preflare hour, and (if so) what can we learn of the field strength and configurations? While the observational analysts continue to wrestle with the study of the vast SMM data store, the theoreticians must continue to synthesize and interpret these diverse phenomena in a consistent fashion.
1.5 REFERENCES


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