A STUDY OF SURGES AND FLARES WITHIN AN ACTIVE REGION

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Abstract. Active region 2684 was observed by the Solar Maximum Mission and ground-based observatories simultaneously for over 12 hours on September 23, 1980. During these observations, recurrent surges were detected above an area with complex parasitic magnetic polarity located at the periphery of the active region. The time evolution of the Hα surges, C IV brightenings and X-ray spikes leads to the conclusion that the energy source is in the corona, from magnetic reconnection. The energy is transported by energetic charged particles along the loops, thereby heating the chromosphere as the particles lose their energy. The divergent motion of the spots corresponding to small dipoles at the base of the surge indicates that there is important magnetic reorganisation. According to the magnetic field-line configuration (large loop or open structures), X-rays can (or cannot) be associated with surges.

1. Introduction

Chromospheric mass ejections are a common phenomenon in active regions, especially when the region is flaring. By a mechanism that is only poorly understood, the energy releases that are responsible for the flare activity are also capable of driving large amounts of generally cool material into the corona. When the velocity is not sufficient for the material to escape from the Sun, the ejection is called a surge. Surges do not originate from precisely the same part of an active region as the flares, and it is therefore tempting to view the surge as an energy release that ‘failed’ to produce a flare.

Surges may be recurrent, such that they appear at the same position many times, with a duration of 10–20 min and a repetition rate of an hour (Tandberg-Hanssen, 1977). This is also quite typical for the low-level flare activity within an active region, which also appears many times at the same place. The behaviour is highly available, and in a particularly active region surges may recur every 10–20 min (Schmieder et al., 1983, 1984; Kovács and Dezsö, 1990).

Early studies found little association of surges with soft X-rays (Rust, Webb, and MacCombie, 1977). This is probably a question of sensitivity, as we have found, both in this paper and previously (Schmieder et al., 1988; Simnett, Sotirovski, and Simon, 1990) that when the X-ray imaging detector on the Solar Maximum Mission is used as a monitor, then there is usually some weak activity present around the base of the surge. On the disk the shape of the surge is uncertain and it is difficult to match precisely the location of the X-ray emission to that of the surge. Limb observations (Harrison, Rompolt, and Garczynska, 1988) have also shown evidence of such soft X-ray activity in association with prominences, sprays, and surges; however, the limb observations suffer from perspective effects, which make it difficult to identify if the X-ray emission comes from the base of the surge, or from a closely related point.

Surges and ejection of material have signatures in the corona such as type III bursts (Chiuderi-Drago, Mein, and Pick, 1986), which typically occur around the time of the maximum ejection velocity as seen in Hα. The existence of type III bursts indicates that there are at least some open structures connected to the base of the surge. We suggest here that it is appropriate to take a more global view of the active region and treat the solar atmosphere as a volume in which magnetic reconnection, with its attendant release of energy, is occurring quasi-continuously. If the energy deposition site in the chromosphere is at the base of a large, relatively open structure, then the pressure build-up is relieved by the ejection of cool, surge material. If the energy is more confined, the temperature increases to the level that the mass ejection becomes a flare. Such a distinction between magnetic structures has already been proposed by Schmieder et al. (1988).

Given the properties we have outlined, we have sought to understand the differences in the photospheric magnetic field in the region of the base of the surge, compared with the structure of the region where the associated flares were occurring. But both flares and surges occur generally in a region of parasitic polarity visible in the photospheric longitudinal magnetic field maps. As the events proceed, there are distinct changes to the magnetic fields, often in the vicinity of the parasitic polarity. We have consequently followed the evolution of an active region over 12 hours, concentrating on the part where the surges are occurring. We use UV and X-ray data from the Solar Maximum Mission (SMM) and ground-based observations from the Meudon and Debrecen Observatories.

We show the evolution of the photospheric magnetic field and how this is related to the ejection of surge material, X-ray emission and C IV brightening. We conclude with the suggestion that the surge and flare are different manifestations of the same basic phenomenon, namely energy deposition leading to a pressure build-up in the chromosphere. The differences are merely in the way in which the local magnetic field either confines the energy, within a low-lying, strong magnetic field loop, where it manifests itself as a flare, or allows it to be removed as kinetic and potential energy, plus enthalpy, into the high corona.
2. Instruments

Our observations are from instruments operating in different wavelength ranges.

The Hard X-ray Imaging Spectrometer (HXIS; Van Beek et al., 1980) on board SMM provided a 6′24″ × 6′24″ coarse field of view with a resolution of 32″ × 32″. Our events were out of the fine field of view.

The Ultra-Violet Spectrometer and Polarimeter (UVSP; Woodgate et al., 1980) provided a large raster (4′ × 4′) at 10:20–10:28 UT in the C IV line during the interesting period of a surge followed by small rasters (1′ × 1′) covering the basis of the surge with a spatial resolution of 3″ until 10:48 UT.

The Multi-channel Double Pass spectrograph (MSDP) operating in the Solar Tower at Meudon records simultaneously 9 images of an 8′ × 1′ area of the solar surface at 9 wavelengths in the Hα line. The spatial and temporal resolution are ~ 2″ and 10 s, respectively. Maps of intensity fluctuations and Doppler shifts are derived using the standard method (Mein, 1977). A larger field of view (5′ × 8′) is obtained by adding five elementary fields obtained within 60 s.

The longitudinal magnetic field in the Fe I (λ6303 Å) with a spatial resolution of 1.2″ × 2″ was obtained by the Meudon magnetograph (Rayrole, 1981).

White-light photoheliograms and series of Hα filtergrams (Hα±1 Å, Hα±0.5 Å, Hα) at the Heliophysical Observatory in the Hungarian Academy of Sciences in Debrecen and at the Gyula Observing Station were obtained and analysed by using the data processing techniques described by Dezső, Gerlei, and Kovács (1988).

3. Activity in Active Region 2684

We have studied active region 2684 on 1980, September 23. This has already been the object of a coordinated study and the results have been discussed by Foing and Bonnet (1984), Haisch et al. (1986, 1988), and Gary et al. (1987). These studies concentrated on the flaring activity which was seen primarily from region 2684, at N17 W18 but also from the adjacent region 2687, at N10 W09. In region 2684 the flares occurred in several loops between the main sunspots and the discussion in the above papers concentrated on flares and arch filament systems.

We have looked in X-rays at these regions from September 22, 15:44 UT to September 23, 22:08 UT and there is a wealth of minor activity but no large flares; the largest event was a C3 flare at N17 W13 which started around 02:21 UT on September 23. We will focus our study on the part of the region where the surges are observed, which is about 1′ east of the site of the larger flares.

Figure 1(a) shows the spots of the AR 2684. The flares occur between the two main spots in the vicinity of a complex magnetic inversion line; on the other hand the surges originate to the south of the westerly sunspot, virtually at the periphery of the main activity in the region where a number of small pores show significant evolution over the period up to 15:00 UT, namely f1, f2, f3, f5, and p1, p2 and occasionally p3. Figure 1(b) illustrates this evolution schematically; the dots
indicate their successive positions. The general motion throughout this period of $p1$, $f3$, and $f5$ is indicated by arrows in Figure 1(b). We note that $p1$ moves with a proper motion of around 200 m s$^{-1}$, which is similar to the motion of $f5$ in the opposite direction. The pores $p1$, $p2$, $p3$ are contained in a small island of positive polarity embedded in the large negative area of the following main spot group, as shown in Figures 1(c) and 1(d). The numbers in Figures 1(c) and 1(d) correspond to the measured field strength in gauss. Each pore can be associated with one or two small opposite polarity pores: $p1 - f1$, $f5$ $f3 - p2$, $f2$ $p3$. The horizontal gradient between two opposite polarity pores, which have a diameter equal to 10″ (the typical size for each polarity), is relatively large: 50–85 G per arc sec. This is a typical value for flare occurrence (Schmieder et al., 1991).

Between the times of the magnetic maps the field strength of $f3$ had diminished from 400 to 200 G, while the strength of $f5$ had increased from 400 to 700 G. It is as though the magnetic flux associated with the parasitic polarity had stayed approximately constant, while the return flux into the $f$-spots underwent some readjustment, in addition to the motions described above. The area where the more significant changes took place was in the vicinity of $f3$ and $f5$, which was precisely the location of the base of the surges. Such motions can indicate displacement of magnetic field lines favouring magnetic reconnection.

The observations of the active region in different wavelengths are presented in Figure 2: (a) in H$\alpha$ (Meudon MSDP), (b) in C IV lines. The facular region is spatially well-correlated with the emission region in C IV. In H$\alpha$ this region is overlaid by an east–west oriented filament system. At 10:44 UT the ejection of H$\alpha$ material (commonly named a surge) is large, extending from points E (bright region) to H along a loop-shape absorbing feature (a). In Figure 2(b) we have indicated the field
Fig. 1b–d.

Fig. 1. Active region 2684 on September 23, 1980. (a) The white-light image from Debrecen at 10:15:23 UT (130'' × 210''), the box represents the field of view of the lower panel figures (85'' × 95''). (b) The evolution of the 'pores' (from Debrecen white-light observations) is represented by a small dot every 50 min from 08:35 to 15:00 UT on September 23, 1980. The arrows indicate the direction of the displacement of the pores versus time. The pore $p_1$ moves towards the east, while $f_5$ moves towards the southwest with a proper motion of around 200 m s$^{-1}$. (c) and (d) Magnetic field contours from Meudon observations at 08:56 UT (c) and at 17:47 UT (d). The dashed-dotted line indicates the position of the magnetic inversion line, and the arrows indicate the section between the opposite polarity areas corresponding to the pores where the base of the surges is located; the dashed line represents negative magnetic field and the full line positive magnetic field. The contour levels are: 40, 100, 200, and 400 G.
of view of the HXIS instrument and superimposed the bright points A–H which exhibited flaring or microflaring during the 25 hours of the X-ray observations. Where there are pairs of points, such as C1 and C2, this may indicate the presence of hot loops joining the points, in which case the bright points would represent the footpoints of the loops. The four points marked G1 and G2 indicate a very complex region which showed a variety of X-ray emitting structures linking them at various times. All the identified points showed activity at several independent times during the period of the observation. Some of these events are short-lived spikes, lasting less than 1 min in some instances; others are more gradually-varying small flares. The X-ray activity from point E, which is at the base of the surges, only appears as short-lived spikes.

4. Timing of the Events in Point E

The region in the vicinity of the base of surge was the site of a large number of spikes during the period of our observations. Figure 3 shows the 3.5–8.0 keV X-ray intensity from the region E which is represented by three 32" pixels (51, 62, 63).
(The numbers refer to those assigned to these pixels in the HXIS image plane, and they have no other significance.) The times covered by Figure 3 are SMM orbits where the emission from E shows a significant burst, starting around 03:40 UT and ending at 10:55 UT. In each of the four panels a 3.5–5.5 keV image is shown inset for a period covering all or part of the burst; the exact times of these images are given in the figure. The energy range for the image is restricted to 3.5–5.5 keV, as the 5.5–8.0 keV band has a relatively high background which introduces noise into the image. There are several intensity fluctuations from E between 04:05 and 04:15 UT. At point A to the northwest a primary increase occurs as the intensity from E is falling, and the onset of the small burst at 04:10:12 UT (shown with hatching in Figure 3(a)) is simultaneous (to within the 15 s resolution) at both E and A. Figure 3(b) shows the next event, where it is evident that there is a structured burst which reaches a maximum at 06:07 UT.

The next spike from E occurred at around 07:14 UT, and this is shown in Figure 3(c). In order to enhance the visibility of the spike, the data are plotted at a time resolution of 60 s. The 3.5–5.5 keV image from 07:13:29–07:17:28 UT clearly shows some emission from H, and from a large structure linking G1 to B. Corresponding to this event we observe an Hα flare in MSDP data visible in the first frame at 06:57 UT and slowly decreasing with time. The X-ray image shown in Figure 3(c) illustrates an important feature of the activity from this general region, namely that there are frequently several discrete hot points, hot enough to emit 5 keV X-rays, present at the same time.

The next spikes observed from E correspond to Hα surges seen to start at 10:29 UT. The first event from 10:25–10:29 UT is probably a series of three superimposed spikes. After the X-ray emission decays to background levels at ~10:30 UT there is a second event which reached maximum intensity at 10:33 UT. The 3.5–5.5 keV image from 10:24:15–10:29:32 UT is remarkably similar to that seen at 04:05 UT (see inset in Figure 3(a)), and in fact the X-ray intensity time profiles are remarkably similar also.

We saw no further X-ray activity from E, possibly because the observing duty cycle from this time up to the end of the Hα observations is only ~40%. For example, the surge observed at the beginning of the Debrecen observations at 11:53 UT occurred during SMM night. By the time the X-ray observations resumed about 10 min later there was no X-ray emission from E. However, as shown in Figure 3(d), 10 min after the onset of the 10:29 UT surge the emission from E had vanished. Therefore, because of the short-lived nature of the surge-associated X-ray activity we cannot eliminate an X-ray association with the 11:53 UT surge.

There was a similar circumstance surrounding the onset of the next surge, which was observed both in Debrecen and in Meudon. The onset of the surge is at 15:18 UT. The X-ray orbit begins 2 min later, with a slightly different pointing, as discussed above; the point E now corresponds to pixels 34, 35 in the HXIS image plane. We saw some small X-ray spikes at 15:22–15:26 UT just above the noise level which could correspond to a reactivation of the surge.
Fig. 3 The X-ray emission observed from E (a) between 03:43 and 04:33 UT, (b) at 06:07 UT, (c) at 07:13 UT, and (d) at 10:24 UT. The images inset confirm the compact nature of spikes. In (d) is drawn the C IV intensity variation with dashed lines in arbitrary units. During the decrease in the C IV intensity a small maximum is observed around 10:34 UT.
5. Multi-Wavelength Observation of a Surge

The X-ray spikes observed at 10:25–10:33 UT correspond clearly to surge events. The other surges are not necessarily associated with X-ray spikes due to the fact that the X-ray observation times were later by 10 or 3 min than the Hα surges. We will focus our study on the surge observed from 10:29 UT in different wavelengths.

5.1. THE UV BRIGHTENING

There are UVSP observations at 10:24 UT (large raster) and after 10:27:35 UT (only smaller rasters) shown in Figure 2, which cover the base of the surge. The UV intensity is maximum at 10:24 UT and afterwards decreases with time. The C IV intensity from this region is plotted against time after 10:27:35 UT in Figure 3(d). We note that there is a good correlation between the onset of the secondary C IV brightening at 10:33–10:34 UT and the end of the second X-ray burst from E. This is consistent with earlier disk observations of Schmieder et al. (1988) who emphasized that C IV brightness overlying surge events remains for a significant time after the ejection of material. Haisch et al. (1988) also presented UV images of this region, taken several hours later at 18:05 UT, which showed a bright point at the position of the base of the surge.

5.2. Hα EJECTION VELOCITY DETERMINED BY THE CLOUD MODEL METHODS

The Hα surge appears as follows: the initial brightening at the base of the surge (10:27 UT) coincides with the primary X-ray maximum (Figure 3(d)). There is a second weaker Hα brightening around 10:36 UT. Material is observed going upwards with some fine structure at 10:29 UT; later, from 10:36 UT until 10:39 UT, the structures appear thicker. In the third phase some material begins to go down following the same field lines, while other material continues to go up and along a loop-shaped structure which developed at 10:44 UT (see Figure 4). By 11:00 UT all the material is going down. The timing of the surges cannot be as accurate as the X-rays because of the time delay between the observations (60 s). It is clear that two successive energy releases occur, one corresponding to the flare flag of the UVSP at 10:24 UT and a second one 10 min later. The levels of X-ray and C IV emission are larger for the first event, while the ejection of chromospheric material is more important for the second event.

The standard method used to derive velocities from Hα line profiles is a bisector method and leads to minimum values for the velocities. More realistic values can be obtained for surges by using a ‘cloud model’ method. If we assume that the surge material is not optically thick in the Hα line, the chromosphere can be seen through the surge. The Hα line profiles can therefore be interpreted as the combination of a stationary reference profile emanating from the lower chromosphere and a moving absorption profile from the overlying ‘cloud’. The cloud model (DCM1), first introduced by Beckers (1964) has been developed by Mein and Mein (1989) and used for surges by Schmieder et al. (1988). The reference profile is obtained
by averaging all the profiles of a quiet-Sun region, avoiding flares, faculae and absorbing features.

We have applied this technique to the observations of the large surge loop at 10:44 UT, which had a completely blue-shifted structure (BS) at one end and at the opposite end a half blue- and half red-shifted structure (BRS) (Figure 4(b)). Figure 4 (right panels) indicates the cloud velocity values $v_c$ in the points where the computation was possible (gaussian form of the contrast profiles). At 10:37:50 UT, only a few points are computed; at 10:44:33 UT more data are available. Using these latter data we have made a cut along the axis of the surge, from the upward leg to the downward leg (Figure 5). Velocities up to 40 km s$^{-1}$ have been detected.

The Hα profiles of BS have enhancements in the blue wing and may be interpreted using the cloud model method (DCM1), while BRS profiles with broadened wings in the red and in the blue sides cannot be interpreted with one cloud. These profiles are a combination of material going in both directions. It is frequently observed that upward material and downward material follow the same field lines and can be observed along the same line of sight (Schmieder et al., 1983). The displacement of the two maxima in the contrast profiles is very significant, of the order of 50 km s$^{-1}$. This velocity is near the limit that can be measured from the MSDP frames. Due to the nature of the MSDP spectrograph the Hα line profile is
observed in a narrow wavelength interval of 2.4 Å. The largest displacement of the line center which can be measured is around 1 Å, which corresponds to a velocity of 50–60 km s$^{-1}$. 

Fig. 5. Intensity, velocity, and DCM1 cloud velocity cuts through the surge at 10:44:33 UT corresponding to the maps of Figure 4(b).
5.3. OTHER SURGES

There were four other surges seen in $H\alpha$ during the period under discussion. Two were detected at Yunnan Observatory in Kunming at around 05:05 and 08:23 UT (X. M. Gu, private communication); unfortunately both these occurred when SMM was behind Earth. The other two were seen at the Debrecen Observatory. A comparison of these surges with the 10:29 UT surge shows that the same magnetic structure is involved. Furthermore, the qualitative behaviour of the X-ray activity in the hours surrounding the surges was similar to that seen from the active regions 2684 and 2687 from the previous 18 hours.

During this long period of common observations (~12 hours) around ten events were observed but only one with all three instruments. Coordinated observations of an event with different wavelength instruments present a real challenge.

6. Discussion and Conclusions

During surge events energy is released partly through radiation, partly through dynamical processes. The radiative signatures, i.e., $H\alpha$ brightening emission in UV lines and in X-rays are correlated with some delay. The timing of the surge events at 10:30 UT, for which we have the best-correlated data, is of interest. The enhancement of the brightening at the base of the surge is observed first at 10:27 UT and then, more weakly, at 10:36 UT. The X-ray spikes are 3 to 4 min earlier than $H\alpha$ surges, while the UV brightening is 2 to 3 min earlier. Such a timing between X-ray emission, UV and $H\alpha$ brightenings has been previously observed for surges (Schmieder et al., 1988), and we believe we should be able to use this fact to understand how the whole process evolves. The ejection of material lasts nearly half an hour with clearly two injections of energy. The maximum of the ejection velocity was reached around 10:44 UT. Such an acceleration process has already been analysed by Schmieder et al. (1983). There it was shown that the maximum of the upward velocity occurred 6 to 10 min after the $H\alpha$ enhancement of brightening.

If we start from the premise that the surge material is pressure driven, then we need some way to deposit energy in the chromosphere. There are only two options open: (1) the magnetic free-energy in the loop is released *in situ* for example by a reconnection process between the field lines or (2) it is released elsewhere, and transported to the chromosphere at the base of the surge. During the period of our study there were many small X-ray brightenings from many different parts of the active region, as indicated by the bright points A–H which we have shown in the upper part of Figure 2. Some of these events actually appear simultaneously (within say 30 s) at points separated by over an arc min. The relationship between the X-ray emissions in the two points E and G1 (Section 4) also suggests deposition of energy in loops at a level high in the corona, rather than at the base of the surge. The multitude of X-ray activity is interpreted as evidence for a quasi-continuous release of magnetic energy within the complex of the two active regions in the corona. The energy release can occur during the reorganisation of magnetic field
lines by reconnection processes (Mandrini et al., 1991). The fast proper motion of
the small pores $f_3$, $f_5$, $p_1$ ($\pm 200$ m s$^{-1}$) at the base of the surge is the signature of
such magnetic field line evolution (Section 3). The energy is transferred initially
to energetic particles, and these particles are guided by the magnetic field lines to
different parts of the region. The response of the chromosphere depends on the
local topology of the magnetic field. If the energy deposition occurs close to the
legs of a large magnetic loop or close to an open magnetic structure anchored
in the chromosphere, there is no time to heat the chromospheric material to high
temperatures before its ejection into the corona; therefore the H$\alpha$ surge occurs with
no signature in X-rays.

For a more closed structure, or for a larger energy release, the temperature of
the chromosphere rises to the level where UV and soft X-ray emission is produced.
The chromospheric material expands upwards, until the gas is cooling such that the
UV and X-ray emission ceases. In this case we get an X-ray-associated surge. For
events which are even more energetic, the response is what we know as an H$\alpha$ flare,
and the upward moving material is referred to as chromospheric evaporation. Flares
are generally observed to involve some relatively compact magnetic loops, and this
is entirely consistent with our picture that the cool surges are typically observed
in open magnetic fields where the energy flux cannot build up to a high enough
value to produce a flare-like response. Open magnetic structures have already been
proposed for surge modelling (Schmieder et al., 1983, 1988). Large loop structures
favor dynamic events while compact loops lead to flares (Harrison, Rompert, and
Garczynska, 1988). X-rays and H$\alpha$ events may be related to small and large-scale
evolving structures, respectively. It is difficult to distinguish definitively between
steady-state and evolving configurations.

The events studied here fell within an overall active period where there were
no large flares. The energy which is being released is in a relatively small amount,
which is manifested in widely separated points. There is thus no opportunity for a
significant energy build-up to produce a large flare. As we have indicated above,
unless the energy is released in situ it is likely to be transported by energetic
charged particles. The particles travel along the loops, increase the pressure at
the footpoints where they interact with the dense chromospheric material and
produce the chromospheric brightenings. The pressure pulse initiates surges visible
in H$\alpha$ if the magnetic configuration allows it, i.e., in an open magnetic field line
configuration. This is because the plasma expands rapidly into such a structure,
thereby cooling it such that it is visible in H$\alpha$. In a small, closed structure any
material motion upwards will be visible as a high temperature upflow as there will
be less expansion and therefore less cooling.

Steinolfson, Schmahl, and Wu (1979) have been relatively successful in mod-
elling the surge as the atmospheric response to a chromospheric pressure pulse in a
low-$\beta$ situation. They found no need to consider magnetohydrodynamics, but this
does not preclude the magnetic field from playing a role in the ejection. The delay
of 5 to 10 min after the pressure pulse before the H$\alpha$ material reaches significant
heights that they found is consistent with our observations (Section 5.2).

In any case, the relative timing of X-rays, UV emission and Hα events may be the key to understanding the mechanisms which trigger surges and flares. YOHKOH may give interesting data for such studies.

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