Dynamical Motions as Precursors to Activity

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Abstract. We have observed the evolution of several active regions prior to flares, Hα brightening, and CMEs. The observations include full-disk Hα images taken at a 10 second cadence with the NSO/SP flare patrol and high-resolution images of the selected active regions taken with the NSO/SP Dunn Solar Telescope. The high-resolution data includes 30 second cadence Doppler-grams and magnetograms and 5 second cadence Hα and G-band images. Using local correlation tracking techniques, we derive horizontal surface flows reflecting photospheric and chromospheric heights. These are compared with the line-of-sight magnetic flux and velocity field and with structures seen in the Hα and G-band images. We investigate these data for pre-activity signatures.

Our preliminary analysis of flares on 1997 April 7 and 1998 May 5 indicates that strong vortices in the surface flow often precede strong Hα brightening and filament eruptions. The full-disk Hα campaigns are being conducted to develop activity prediction techniques in anticipation of the high cadence imaging that will be provided by the Air Force’s Improved Observing Optical Network (ISOON).

1. Introduction

The evolution of solar active regions prior to activity events such as flares and mass ejection has been intensely studied in hopes of finding observational signatures leading to activity prediction. Several predictors have been suggested including active region complexity, magnetic shear, intense Hα fibril activation, surface velocities, and pre-flare brightening. However, statistical studies (Neidig, 1990) show that even when taken together, prediction using these factors have been of limited accuracy and usefulness.

Longcope and Cowley (1996) demonstrated that stresses applied by photospheric motions can lead to current ribbons and Longcope (1996) showed these ribbons can store magnetic energy and facilitate flares. Recent work has shown that flux can emerge from the sun in pre-stressed states (Leka et al., 1996)
that flux can emerge from the sun in pre-stressed states (Leka et al., 1996) and that surface flows are not necessary to have twisted field lines. However, the emergence of twisted field may induce twisting motions in the atmospheric plasma and Hα fibrils. In some cases, twisting motions have been clearly seen before the occurrence of a flare (e.g. Keil et al., 1994, Paper I). Although flare energy release is primarily a coronal phenomena, the source of energy is surely in the lower atmosphere or sub-atmospheric layers. The magnetic field lines involved in solar activity are deeply rooted through the photosphere into the convective zone. Thus, one expects to find observable manifestations in the photosphere and intervening chromosphere of the phenomena driving the active region toward instability.

Magnetic shear is important for flares, but several authors have shown that shear alone is not sufficient to predict the location, timing or frequency of flares (e.g. Ambasta, 1998, Choudhary, Ambasta and AI, 1998). Emergent flux and rapid motion of the field also play a role. Zirin and Wang (1990), have reported seeing motions associated with pre-flare sunspot regions and emerging flux.

In Paper I we discussed the roles of vertical and horizontal flows in flares that occurred on 1992 Jan 24 in NOAA 7016 and on 1993 Feb 6 in NOAA 7420. In both cases, strong vorticity in the horizontal flow and shear in the vertical flow were seen at the locations of the primary flare kernels as seen in Hα. In both cases only a small amount of data was obtained before the flare began, and it was not possible to say if the velocity shear and vorticity could serve as a predictor. In a second paper (Balasubramaniam, Milano, & Keil, 1998, Paper II) we used the 1-minute cadence Hα patrol at NSO/SP to investigate horizontal motions in the chromosphere prior to the 1997 Apr 7 flare in NOAA 8027. By tracking horizontal motions in Hα we can follow filament activations as well as net flows in the chromosphere. Strong vorticity were seen in association with the Hα flare kernels. Similar twisting motions have been reported by Canfield et. al. (1996) in connections with Hα surges and associated x-ray jets. Shimojo, Shibata, & Harvey (1998) show that the x-ray jets occur in region of rapidly changing flux and converging bipoles.

In this paper we report a preliminary attempt to improve the results of Papers I & II by increasing both the observational cadence and the length of time observed before the flare. Section 2 describes the observations and the following sections give results for flares observed in active regions NOAA 8210 and 8214 on 1998 May 5.

2. Observations & Reduction

The observations were obtained with the Richard B. Dunn Solar Telescope (DST) and the Hα flare patrol at Hilltop Facility at NSO/Sacramento Peak. Three camera’s were used in the DST. A 403x256 pixel RCA 504 CCD was placed behind the Universal Birefringent Filter (UBF) resulting in a 2’ x 1’ field-of-view (FOV) with 0.3”x0.23” pixels. The UBF was used in 1/8th angstrom mode and tuned to two wavelengths in the blue wing of Ca I 6122 separated by 20 mÅ where Stokes I+V and I-V were recorded and then to the red and blue wing of Fe I 5434 Å to obtain a Doppler pair. All six measurements were obtained every 30 seconds. A 1024 x 1024 pixel Thomson camera was placed
behind a 10 Å G-band filter at 4305 Å with a 3’x3’ FOV. A second 1024 x 1024 Thomson camera was placed behind a 200 mÅ Zeiss Hα filter which was tuned on-band. The pixel size is 0.16”x0.16” on both Thomson cameras and they were operated at a 5-second cadence.

At the Hilltop Facility, the standard Hα film camera was replaced with a 2K x 2K Xedar CCD camera. The Hα patrol uses a 10 cm lens, stopped down to 6 cm to feed a 0.25 Å tunable Halle Hα filter. The resultant pixel size is 1.3”x1.3”. In its standard patrol mode the filter is tuned to line center, Hα ± 0.5 Å, over exposed at line center for prominence, and to white light near Hα. For our observations, we only tuned to line center, permitting us to run at a 10-second cadence. The observations are summarized in Table 1.

Clouds permitting, we started observations near sunrise at both facilities and observed all day. The DST was pointed at the active region which seemed most likely to produce activity. Flat fields and dark calibrations were made periodically throughout the day.

<table>
<thead>
<tr>
<th>Filter</th>
<th>CCD</th>
<th>λ [Å]</th>
<th>Pol.</th>
<th>Cadence</th>
<th>FOV</th>
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<td>30</td>
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</table>

On 1998 May 5, 3918 images were obtained with the full disk Hα imager between UT 13:35 and 00:24. These were gain and dark corrected, circularized and rotated so heliospheric north was up. Fig. 1 shows a typical image and the location of the two active regions used in this study. After correcting each image for limb darkening, we selected an area containing NOAA 8210 (S12W50) and 8214 (N26W18) respectively and made a separate time sequence for each region from the full disk images. Foreshortening was removed to obtain a disk-center view, and each region was tracked to remove image motion. The corrected images were then divided into sub-images and local correlation tracking techniques (Keil et al. 1994) were applied to track the drift of these sub-images. For NOAA 8210, which is close to the limb, the sub-image size in the corrected images was 13”x13” and for NOAA 8214 the sub-image size was 9”x9”. Rapidly varying displacements of sub-images due to seeing changes between images were separated.
from slowly varying displacements due to actual motion of features on the sun using a low-pass filter. We then computed the derivative of the slowly varying component to obtain a horizontal surface velocity at each 10s time step.

For NOAA 8210, simultaneous observations were obtained with the DST. All DST images were first gain and dark corrected. The four polarization images in Ca I 6122 Å and the two Doppler in images in Fe 5434 Å from each UBF spectral scan were registered by destretching them with respect to the first Ca I image. The Ca I polarization pairs were then subtracted to obtain the Stokes V signal at each wavelength. The slope of the Ca I line was determined from the two wing wavelengths and the weak field approximation was used to compute the magnetic flux. The Fe I 5434 Å Doppler pairs were used to obtain an estimate of the line-of-sight velocity. Thus for each 30 s interval needed to scan the UBF through 6 wavelengths, we produce one magnetogram and one Doppler-gram. These were then corrected for foreshortening. After gain and dark correction, the G-band and Hα images were also corrected for foreshortening. Fig. 2 shows a G-band image along with a magnetogram and a Doppler-gram with foreshortening removed. As with the full disk Hα images, we then used local correlation tracking to obtain the time-dependence of the horizontal flow field for each set of images. Tracking was done on 5″x5″ sub-images.
Figure 2. DST images of NOAA 8210 corrected for foreshortening. From left to right the images are a G-band image, a magnetogram, and a Doppler-gram from the DST time sequence at 22:15 UT. The magnetogram saturates in the sunspot umbra and the flux was set to a constant value. Positive flux is white in the magnetogram and redshift is white in the Dopplergram. The G-band images covers 281″x162″ on the sun. The magnetogram and Doppler-gram cover a slightly smaller FOV (231″x118″).

3. Results

3.1. NOAA 8210

NOAA 8210 was observed from 14:10 to 00:09 UT with the DST. A series of strong Hα brightening and small flares led up to a M2.5 flare at approximately 23:27 UT. From the NSO/KP magnetograms shown in Fig. 1, we see that NOAA 8210 is a complex δ-sunspot region. The spots exhibit strong negative polarity with positive flux intruding from above and below between the large spot on the left and the smaller spot on the right (Fig. 2). The G-band bright features just below the large spot correspond to negative polarity flux that is being transported away from the sunspot. This negative flux collides with the positive flux seen below and to the left of the large sunspot. The time sequence of magnetograms reveals flux disappearing at the interface between the two opposite polarity regions. The Doppler-gram clearly shows the Evershed flow and reveals an area of sheared line-of-sight flow directly below the sunspot.

Fig. 3 shows a sequence of Hα images, corrected for foreshortening. A small Hα brightening occurs at about 23:00 UT in the region to the right of the sunspot. The contours show levels of curl in the horizontal flow as measured by local correlation tracking of the Hα images. White represents positive curl (clockwise) and black negative and each contour level represents a doubling of the curl from the previous level. The curl is seen to increase in the region of the flare approximately one-hour prior to the Hα brightening.

Figs. 4 is similar to Figs 3, but shows the much stronger M-class flare that occurred approximately 30 minutes later. The net curl in the region begins to increase about 30 minutes prior to the flare and peaks about 10 minutes after the flare commences.

Fig. 6 shows the Hα brightness and the absolute value of the curl as functions of time, averaged over the boxes shown in Fig. 5. The net curl more than doubles in the region prior to the flare. The box labeled R-4 is in a region that remained fairly quiet throughout the period of observation. The average curl
Figure 3. Curl Contours superposed on Hα images.

Figure 4. Curl Contours superposed on Hα images.

Figure 5. Absolute value of curl and Hα brightness vs time averaged over the boxes shown on curl image (upper right) and Hα image (lower right)

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Figure 6. Absolute value of curl and Hα brightness vs time averaged over the boxes shown on curl image (upper right) and Hα image (lower right)

is seen to fluctuate by about 30% in this region. The region R-1 contained the small Hα brightening shown in Fig. 3. The curl is seen to reach a peak almost double its nominal value about 1 hour before the flare. R-2 contains the kernel of the much stronger M2.5 flare that began near 23:27 UT. The curl begins to increase about 30 minutes prior to the onset of the flare. R-3 contains some Hα filaments that also become involved in the flare. The filaments become activated before the flare, which is reflected in the curl shown in Fig. 6.

The much longer sequence of full-disk images was also used to investigate NOAA 8210. Fig. 7 shows the region after correction for foreshortening. The region labeled R-1 is above (North) of the FOV of the DST image shown in Fig. 5. The vertical component of the curl was again measured by tracking Hα surface flows. The larger sub-image size (13"x13") used to track the motions tends to smooth over and reduce the curl signals, but they are still clearly visible as was noted in Paper II. Fig. 8 plots the absolute value of the curl and Hα brightness vs time averaged over the four regions shown in Fig. 7. R-2 roughly corresponds to R-1 in Fig. 5 and R-3 corresponds to R-2 and R-3 in Fig. 5. R-4 in Fig. 7 is averaged over the entire active region.

For the region containing the small Hα brightening at 23:00 UT (R-2, Fig. 7) an increase in the curl begins near 21:00 UT and peak at approximately 22:15 UT, about 15 minutes later than the peak seen in the DST data (R-1, Fig. 5 and 6). The apparent time difference between the two data sets probably reflects the difference in spatial resolution. The increase in curl in R-3 (Fig. 7) is less
Figure 7. Hα image showing boxes where the curl was computed. Region R-4 contains the entire active region.

Figure 8. Absolute value of curl and Hα brightness vs time from NOAA 8210.
Figure 9. Hα image showing boxes where the curl was computed. Region R-4 is a quiet region for comparison

pronounced than seen in R-2 and R-3 (Fig. 5), but coincides well in time (about 30 minutes before flare onset). Again, the reduced spatial resolution probably accounts for the reduced curl signal. R-1 (Fig. 7), which also showed a strong flaring component, exhibits a steady increase in curl, peaking 30 minutes prior to the flare. Even when the curl is averaged over the entire active region (R-4, Fig. 7 and 8), an increase, although small, is still apparent before the flares.

3.2. NOAA 8214

NOAA 8214 was only observed with the full disk flare patrol. The data was processed in the same manner as NOAA 8210. The NSO/KP magnetogram shown in Fig. 1 shows that this region also has a weak δ-configuration. Regions labeled R-1 and R-2 in Fig. 9, contain an area that produced two C3.5 flares between 18:00 and 20:00 UT. R-1 contained several filaments and most of the strong Hα brightening took place in this region. The curl begins increasing about 45 minutes prior to the first flare and peaks between the two flares. Hα emission was already elevated in R-2, but it contained very little filamentary structure. A slight increase in the curl was visible before the first flare, but compared to the fluctuations observed in a quiet region (R-4, Fig. 9 and 10) it doesn't appear to be significant. R-3 exhibited several filament eruptions and finally a small flare near the end of the observed period. The curl remained slightly elevated in this region throughout the observing period, with a several fold increase before the flare.

4. Discussion

A wide variety of phenomena have been associated with the occurrence of solar flares. In his review, Wang (1998), lists: (1) strongly curved magnetic neutral lines (‘S’ or reversed ‘S’-shaped), (2) steep gradients of the line-of-sight magnetic field, (3) filament activation, (4) new emerging flux, often being pre-twisted par-
ticularly in δ-sunspot regions, (5) highly sheared transverse field, (6) magnetic flux cancellation, and (7) vertical current concentration. The present work attempts to quantify (3) directly and (4) indirectly. Our primary results are:

- From Figs. 3–4 we see strong pairs of oppositely directed curl form near the location of subsequent flare kernels. In Paper II we speculated that these oppositely directed twists could result from the untwisting of magnetic flux.

- The amount of vorticity in the horizontal flow in flaring regions, as measured by summing the absolute value of the vertical component of the curl, increases up to an hour before the Hα brightening begins, as seen in Figs. 5, 8 and 10.

We have attempted to look closely at flows in the chromosphere associated with flaring regions and filament eruptions. In Paper I, photospheric motions associated with flares were investigated and strong vorticity were seen at the foot points of filaments that erupted during the flare. If these motions are caused by the relaxation of twisted fields, then one might expect to see similar flows in the chromosphere. Since we have only looked at the flows in this paper, we cannot say whether or not they cause or are induced by changes in the magnetic field. Martres et al. (1977) noted changes in the twisted pattern of Hα fibril structures occurring up to an hour before the onset of flares. This work confirms and quantifies their observations.

Canfield and Pevtsov (1998) give a review of magnetic helicity of solar active-region magnetic fields arguing that the twist of active region fields observed in the photosphere and corona originate beneath the visible surface. On the small scale observed here, one expects turbulence below the surface to be a major factor in the local twist. The motions we observe could be due to the
emergence of twisted field into the active region. The emergence of this flux into the pre-existing field of the active region could provide a trigger for the flare or provide the energy for the flare itself through reconnection. In any case, the increase in the vorticity of the surface motions seen in Hα appears to be a good indicator that an eruption is eminent.

We plan to extend our analysis of these regions to include the evolution of the line of sight magnetic field and the associated flows in the G-band images which reflect deeper layers in the photosphere.

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