Observations of Active Region Dynamics: Preflare Flows and Field Observations

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**Abstract.** We have measured flows and magnetic fields at different heights in several active regions. Quantities derived from the measurements include horizontal and vertical velocity fields, intensity fluctuations in the photosphere, temperature minimum region, and low chromosphere, and the magnetic field in the photosphere. The observed regions typically flared one or more times during our observations. Primary observations were made with the Sacramento Peak Vacuum Tower Telescope (VTT) in combination with a narrow band (\(\sim 20\) m\(\AA\)), tunable filter. Many of the observations have simultaneous vector magnetograms obtained with the JHU/APL vector magnetograph (VMG) at the Hilltop complex at Sacramento Peak and were targets for the *Yohkoh* soft x-ray imager. Here, we discuss the relationship between flow fields, magnetic shear and flare kernels in two of the observed active regions. We find evidence that the location of flare kernels correspond to locations showing shear in the vertical and convergence in the horizontal photospheric flows.

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1. Introduction

Observations of dynamical conditions in active regions are essential to understanding the energy build-up and trigger mechanisms responsible for solar activity (Neidig et al. 1978, Neidig et al. 1986). During the maximum activity phase of Solar Cycle 22, we observed the evolution of many different active regions over periods spanning several days. The goal was to observe the dynamics before, during and after the occurrence of activity. When possible, we observed active regions that were targets of the Flare 22 and MAX '91 campaigns as well as prime Yohkoh targets. However, our main operating criteria was to follow an individual active region as long as possible. Often we continued observing a region even when the other campaigns switched regions. This contributed to a high rate of success in obtaining data on many activity events. Several instruments at NSO/Sacramento Peak were used to measure the evolution of the active region, including the VTT, VMG and a spectroheliograph.

A major goal is to determine observational signatures of active region energy storage and processes that trigger magnetic events. Harvey and Harvey (1976) observed strong horizontal velocity shearing along polarity reversal lines in flaring active regions. They conclude that horizontal shearing motion may be an important factor in flare production. Henoux and Somov (1987) cite several indicators that organized flow determines active region evolution and flare production. They also point out the dominance of horizontal over vertical velocities in active regions. Martres et al. (1973, 1982) link vorticity-polarity rules to flare productivity. They speculate that there is active generation of electric current systems by photospheric motion. Skumanich and Lites (1991) report evidence for pre-flare motion of neutral lines due to velocity gradients with the resulting motions occurring towards neighboring spots. However, it is not established that the flows drive the activity. It is possible that the emergence and structure of the magnetic field is the driving force and the flow fields in the photosphere simply respond to changes in the field. For example, Anwar et al. (1993) point out a case in which the flare caused observed footpoint motions, dragging the footpoints of the field lines entering sunspots toward the neutral line.

We provide direct quantitative evidence that shear in the velocity is associated with the location and perhaps triggering of flares. These observations have been made at very high spatial, spectral and temporal resolution at multiple heights in the solar atmosphere, using techniques of bi-dimensional spectroscopy. We want to test the hypothesis that mechanical flux residing in shearing velocity motions observed in the vicinity of the flares could contribute to the build-up of energy released during the flare. Velocities observed at the photospheric level appear correlated with the onset of small C-class flares.

We describe the instrument (Sec 2.1), the method of observations (Sec. 2.2), and provide a list of all the active regions observed to promote collaborative studies with other data sets. In Section 3 we describe our data reduction procedures and in Section 4 we present results from our analysis of two events as examples of the type of data available.
2. Observations

2.1. Instrument

The primary observations for this study were obtained with a narrow-band filter system installed at the VTT. Bonaccini et al. (1989) and Bonaccini and Stauffer (1990) describe the development of this instrument. Keil et al. (1989) discuss velocity measurements made with a preliminary version of the filter. Their results demonstrate that the narrow band filter is well suited for making nearly simultaneous high resolution velocity and intensity maps at multiple heights in the solar photosphere. Bonaccini et al. (1991) report on using the filter for spectro-polarimetry. They demonstrate the ability of the filter to obtain magnetic, velocity and intensity maps at several atmospheric heights in a time short compared to the evolution of granules (30 s).

We modified the original filter system to improve image stabilization and to include a video record. The optical configuration of the instruments is shown in Fig. 1. A field-stop at the focal plane of the VTT, where the image scale is 3.67 mm per arcsecond, limits the field of view (FOV) to one square arcminute. This optimizes the spectral resolution by matching the FOV to the limited FOV of the Fabry-Perot etalon.

Light from the field-stop reflects off of a fast tracker mirror (Rimmele et al. 1991) and is sent to a beam-splitter (BS1). A second beam splitter (BS2) separates the light reflected from BS1 (C1) into components C1-1 and C1-2. The C1-1 component is imaged through a 60 Å interference filter onto a RCA-504 CCD (290x244 pixels) to produce white-light images. The C1-2 component hits a pellicle beam splitter (PBS); light reflected from the PBS is imaged on a video camera and the resulting broad-band white-light video images are recorded on VHS tape, giving a high speed record of the visual quality of the seeing as well as tracking, clouds and changes in the active region structure. The light transmitted through the PBS is imaged either onto a 32x32 pixel correlation tracker (Rimmele et al. 1991) or onto a quad-cell image motion compensator. The signal from the tracker or compensator was used to drive the fast mirror and remove gross motions (image tilt) caused by seeing.

The primary beam, C2, transmitted by BS1, passes through a 0.125 Å tunable universal birefringent filter (UBF) and is then reimaged as a slow (f/120) telecentric beam onto a Queensgate Fabry-Perot etalon (pass band ~ 20 mÅ FWHM at 5500 Å). The light transmitted by the Fabry-Perot etalon is then imaged onto another RCA-504 CCD camera (290x244 pixels) to form a spectral image. We shall refer to the combined UBF+Fabry-Perot system as the narrow band filter (NBF).

Calibration of the NBF uses three diodes. A small percentage of the C1-1 beam is imaged onto a reference diode. The UBF is calibrated by sliding a retractable mirror into the beam just behind the UBF and imaging the diverted light onto a second silicon diode while the UBF is scanned through a reference line (Bonaccini and Stauffer 1990). With the first retractable mirror out of the beam, a second mirror is placed into the beam just behind the Fabry-Perot etalon, feeding a third diode. This allows calibration of the NBF as a unit.

The white-light and the spectral CCD camera have the same one square arcminute FOV. The pixel sizes on the RCA 504 CCD are 16 x 20 microns,
corresponding to an image pixel size of $0.22 \times 0.27$ arcseconds$^2$. To infer the line-of-sight component of the magnetic field, the circular polarization in a given spectral line is analyzed by introducing an achromatic quarter-wave plate in the light beam, just before BS1. The entrance polarizer to the UBF serves as a linear polarizer. The two circular states of polarization are measured by rotating the fast axis of the waveplate to angles of $\pm 45^\circ$ to the polarization axis of the UBF entrance polarizer.

In addition to the NBF observations, vector magnetograms of the regions are made using the JHU/APL vector magnetograph located in the Hilltop facility at Sacramento Peak. This instrument is described by Rust and O'Byrne (1991). The VMG makes a complete vector magnetogram in approximately one minute, however, 10 to 15 magnetograms are averaged to reduce the noise level to less than 50 G. The VMG is typically operated throughout the day, stopping for calibrations at approximately one-hour intervals. We also obtained H$\alpha$ and Ca K-line spectroheliograms using the spectroheliograph at the Sacramento Peak Evans facility.

2.2. Regions Observed

Table 1 lists days on which we observed with the VTT and narrow-band filter, the type of events that occurred and the NOAA active region number. A "*" by the NOAA number indicates that VMG measurements where also obtained. Spectroheliograms exist for almost every event. Multiple C-class flares are listed as Cs. A "?" means there was some uncertainty in the NOAA report for that (those) event(s). We observed a total of 27 active regions between 1991 March and 1993 June. Over 40 flares, ranging from B and M class to simple SFs, occurred, with the bulk of the flares in the C-class. For this preliminary report we have analyzed the data from active region NOAA 7016 obtained on 1992 January 24 and from NOAA 7420 obtained on 1993 February 6. For NOAA 7420 we have simultaneous vector magnetograms.
### Table 1. Observed Active Regions

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<tr>
<th>NOAA</th>
<th>DATE</th>
<th>FLARES</th>
<th>NOAA</th>
<th>DATE</th>
<th>FLARES</th>
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### 2.3. Observational Sequences

The VTT/NBF observations consisted of time sequences of monochromatic spectral images that spanned several spectral lines. Two different observational sequences were used; one measured velocity fields at multiple heights and the other measured magnetic fields. We measured velocity in FeI 5434 Å ($g_{eff} = 0$), MgII b-line (5172 Å), and Hα (6563 Å) to obtain the velocity in the mid- to high-photosphere, the temperature minimum and in the chromosphere, respectively. Table 2 gives the wavelengths used for the velocity measurements. We measured the magnetic field in FeI 5250 Å ($g_{eff} = 3.0$) and Fe 5247 Å ($g_{eff} = 2.0$). The magnetic sequences rapidly recorded first a left and then a right circularly polarized image at each wavelength in Table 3. The continuum intensity was measured in a spectral position close to the line for each spectral scan. Images were recorded at a 3.6 s rate, limited by the tape write time. Exposures varied from 90 ms in the continuum to 200 ms in the core of Hα. Velocity sequences required 85 s to complete, and magnetic sequences required 115 s. The NBF wavelength scale was calibrated by scanning FeI 5576 Å and comparing to a profile from the Liege atlas (Debouille et al. 1973). A white-light image was recorded simultaneously with each spectral image.

Flat fields were made in a quiet region near disk center. Fifteen images were made at each wavelength listed in Tables 2 and 3 while rapidly moving a defocused solar image in a random fashion to smear out residual solar features. These 15 images were averaged to produce a flat field image which is used along with dark current measurements to generate gain and dark corrections. Another sequence of images, made with a standard target in the beam, recorded image displacements between the white-light and spectral images due to moving optical components in the UBF and quarter-wave plate.
Table 2. List of spectral lines used for velocity measurements.

<table>
<thead>
<tr>
<th>Im.</th>
<th>Pol.</th>
<th>$\lambda$ [Å]</th>
<th>Notes</th>
<th>Im.</th>
<th>Pol.</th>
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Table 3. List of spectral lines used for magnetic measurements.

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2.4. Observations of 1992 January 24 and 1993 February 6

On 1992 January 24, NBF observations of AR 7016 began at 15:24 UT. This region was near disk center at coordinates N1.7° E1.6° and a small Hα flare was just beginning. GOES reported a C2.4 x-ray flare starting at 15:35 UT. SEON and Big Bear also reported a multiple-kernel optical flare of importance SF, which lasted for 43 minutes. We selected our 1 arcminute FOV based on VTT Hα images, magnetograms from the previous day, the NOAA activity forecast, and the compactness of the bright Hα kernel seen through the narrow-band filter. Fig. 3 shows the active region in white-light and Hα at the beginning of the flare. We obtained 18 velocity scans, followed by 4 magnetic scans, followed by an additional 12 velocity scans before stopping to make flat fields. Subsequently, an additional 18 velocity scans, 5 magnetic scans and 31 more velocity scans were obtained. In this paper, we discuss the 30 velocity and 4 magnetic scans made before the flat fields. These 34 scans produced 848 white-light images spanning 90 minutes.

On 1993 February 6, we observed active region NOAA 7420, located at S7° E59°. It was a very active magnetic bipolar region and during the observations it produced several C-class and an M1.0 flare. Observations began with 4 magnetic scans of the region between 15:31 UT and 15:37 UT, followed by 175 velocity scans. The magnetic scans and 65 velocity scans between 15:48 UT and 17:13 UT have been reduced. A set of 1716 white-light images accompany the spectral images. An optical SF flare occurred at 16:05, an M1.0 flare between 16:43–16:54, a C3.5 at 17:38, and two optical SF flares at 18:22 and 18:43.

3. Data Reduction

Analysis of the data requires great care in removing seeing effects. Although the spot tracker removes gross image motion, differential seeing effects must be carefully removed to obtain velocities and magnetic fields. After performing flat field corrections, considerable effort was devoted to aligning the white-light and spectral images.

3.1. Data Alignment

We remove large-scale image motion (over the entire FOV) by correlating each white-light image to the previous one and storing the shifts required to maximize the cross correlation. Since the images had been tracked in real-time, these shifts were generally small compared to one pixel (~ 0.25 arcsecond) and were removed from both the white-light images and the simultaneous spectral images.

A modified version of the local cross-correlation technique developed by November (1986) was used to remove differential seeing effects and to obtain horizontal flows. Each white-light image is divided into sub-areas chosen to correspond to the prevailing isoplanatic patch. Typical sub-areas used varied between 12x10 pixels to 6x6 pixels. Each sub-area from an image is correlated with the previous image to find where it best correlates. This produces a displacement in two orthogonal directions for obtaining the maximum correlation. A running total of the displacements for each sub-area with respect to the first white-light image gives the absolute offset of that sub-area at any given...
time. For the 1992 January 24 data this gives curves with 848 points for each sub-area and for the 1993 February 6 data 1716 points. Fig. 2 shows the drift of these shifts for an arbitrary sub-area chosen from the 1992 January 24 data set in the two orthogonal directions corresponding to rows (x) and columns (y) of the CCD pixels.

![Figure 2](image_url)

**Figure 2.** Accumulated drifts in x and y are shown for an arbitrary sub-area. The upper curve refers to the x axis and the lower curve to the y. The accumulated drift in x of about 40 pixels in 48 minutes corresponds to an average velocity in x of about 2.5 km s\(^{-1}\).

The drift curves show both a high frequency and low frequency component. The high frequency component is principally due to shifts introduced by seeing. The low frequency, slowly varying components correspond to proper motions in the solar photosphere and are used to measure the horizontal flow field in the low photosphere. In order to separate the two components, we computed smoothed curves using various methods, including running means, weighted running means, and Fourier smoothing. Since there is a clear distinction between the two frequency components, the results do not depend strongly on the method selected. The resultant smoothed curves correspond to the low frequency variations, and the difference between smoothed and non-smoothed curves represents the high frequency variations induced by seeing. The x and y displacements for each sub-area of an image obtained from the high frequency component form a displacement map for that image. These displacement maps are used to interpolate a “distortion free”, destretched, white-light image at each time step. The resultant sequence of white-light images is extremely stable and granular evolution is very easy to observe, masked only by a weak intensity fluctuation generated by the 5 minute oscillations.

Next, we apply these displacement maps to the spectral images. However, since the spectral images pass through a different optical path, which depends on wavelength, an additional instrumentally induced distortion can be present in the spectral images. Shifts between the spectral images and between the spectral
images and the white-light images result from the introduction of different pre-
filters at the entrance of the UBF, rotation of the eight elements in the UBF to
tune through the different spectral lines, and the rotation of the quarter-wave
plate for magnetic scans. These shifts have a large fixed component and a much
smaller time-dependent component. Applying cross-correlation algorithms to
images obtained through the standard target, we computed shifts between the
spectral and white-light images to find the fixed component. After removing
the fixed component of the optical distortions, a time varying component may
still exist due to environmental changes in the observing room (temperature,
pressure). Since each spectral line scan begins with a continuum image, we
correlate this continuum image with the corresponding white-light image. The
resultant displacements are added to those generated from the white-light time
sequence and then applied to the spectral images. The corrected spectral images
can then be used to measure Doppler or Zeeman line shifts at each point in the
2-D spatial image at each time step. Since the spectral scan of each line takes
from 15-20 s, depending on the number of wavelengths measured (Tables 2 and
3), the velocities we obtain will contain solar induced errors (for example, a
granular up-flow may change to a down-flow between measuring the red-wing of
the line and the blue-wing). However, since we are primarily interested in long
term flows (see below), these errors will appear as noise on our signal and will
average out over extended time periods (several granular lifetimes).

3.2. Determination of Physical Parameters

Investigation of the interaction between flows and magnetic fields requires ex-
traction of velocity and magnetic maps from the measured spectral lines. When
observing in the velocity mode, we obtain a line-of-sight velocity map every 85
s in each of the three spectral lines. We obtain a transverse flow map every
3.6 s from the white-light sequence. The vertical component of the individual
velocity maps contains contributions from 5 minute oscillations and solar gran-
ulation while the horizontal component contains noise caused by the difficulty
of tracking solar features in the presence of seeing effects. We study the long
lived component of these flows since they affect the magnetic field in the active
region (Simon and Leighton 1964, Simon et al. 1988, Zappala and Zuccarello
1989). Zappala and Zuccarello looked at a wide variety of motions on the Sun
and concluded that the motions must not have a stochastic behavior in order to
be efficient in heating magnetic loops and in producing shear in the magnetic
field.

3.2.1 Longitudinal Magnetic Field

The VTT circular polarization scans give only the line-of-sight component of the
magnetic field. To obtain accurate line-of-sight maps, we tested several methods
of recovering the magnetic field from these measurements. We introduced arti-
ficial magnetic fields into a model of the solar atmosphere and used a spectral
line synthesis code to produce artificial spectral lines. These artificial lines were
convolved with the filter profile and used to compute the magnetic field with
the same algorithms applied to the data. The computed field was compared
with the artificial field we had added to the atmosphere. We found that sev-
eral methods were needed to make the magnetic maps, depending on the field

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strength in the observed regions. However, the center of mass method worked well for a broad range of field strengths (Cauzzi et al. 1993), and we adopted it for this paper. The center-of-gravity method is based on the determination of the center-of-gravity separation of the circular polarized components \( I_+ = I + V \) and \( I_- = I - V \), and is defined as:

\[
\lambda_\pm = \frac{\int (I_c - I_\pm(\lambda)) \lambda \, d\lambda}{\int (I_c - I_\pm(\lambda)) \, d\lambda}
\]  

(1)

where \( I_c \) is the continuum intensity for the right or left circular polarization components. The longitudinal magnetic field \( B_{\|} \) is (Rees et al. 1979):

\[
B_{\|} = \frac{\lambda_+ - \lambda_-}{2} \cdot \frac{1}{4.667 \times 10^{-13} \lambda_0^2 \, g_{eff}}
\]  

(2)

where \( \lambda_0 \) is the central wavelength of the spectral line being measured, with \( B_{\|} \) in G and \( \lambda \) in Å.

### 3.2.2 Longitudinal Velocity Field

We computed the line-of-sight velocities using the center-of-gravity method. For the velocity mode lines, FeI 5434, MgII 5172, and Hα, we measured the total intensity and computed the center-of-mass wavelength from equation 1, substituting \( I(\lambda) \) from the unpolarized measurements for \( I_\pm(\lambda) \). For the magnetic lines, where we had measured the two states of circular polarization, we computed the mean wavelength between \( \lambda_+ \) and \( \lambda_- \) obtained from equation 1. The center of mass velocity was then obtained from:

\[
v = c \cdot \frac{\lambda_c - \lambda_0}{\lambda_0}
\]  

(3)

where \( c \) is the light speed, \( \lambda_0 \) the wavelength of the line core at rest, and \( \lambda_c \) the center-of-mass wavelength of the measured line profile. Determining the rest position of the unshifted line, \( \lambda_0 \), was a problem. We fixed \( \lambda_0 \) by requiring zero net flow in quiet regions (after removal of the convective blue shift). For MgII 5172 and Hα, we only measured the line at five points (Table 2). This under-sampling introduced a systematic error in the amplitude of the measured velocity. We obtained a correction factor by taking the equivalent line from the Liege Atlas (Debouille et al. 1973) and systematically Doppler shifting it for velocities of increasing amplitude. We then used our velocity algorithm to measure the resultant shift. This gave a velocity dependent correction function which was applied to the measured velocities.

For FeI 5434 several wavelengths were measured and it was possible to reconstruct a line profile by using interpolation schemes. We compared Fourier interpolation and cubic splines and obtained velocity signals that differed by a few meters per second; cubic splines were adopted for this paper. From the resultant spectral line fit, we measured the core position of the line and the position of several bisector points at various intensity levels in the line. The position of the line core obtained in this manner refers to a higher level in the atmosphere than the center of mass velocities, while the chosen bisector levels
refer to deeper layers in the atmosphere relative to the line core. Because of limited spectral sampling of the line, only 3 or 4 independent bisector positions can be found. As with the center-of-mass, determining a zero level for velocities measured in the core or the bisectors was also a problem. Zero levels for the bisector velocities were also set by requiring zero net flow in a quiet region, after removal of the convective blue shift.

Contributions to the vertical flow from the solar granulation and five minute oscillations in the photosphere and three minute oscillations in the chromosphere were removed by applying filters in the spatial wavenumber and temporal frequency domain. We thus isolated these short period velocities from the longer lasting flows which may have lasting effects on the magnetic field.

3.2.3 Horizontal Velocities
Transverse velocities deep in the photosphere, at an optical depth near unity at 5500 Å corresponding to our white-light images, are obtained from the low frequency component of the drift curves discussed in Section 3.1. The transverse velocity field is computed from the first derivative of the smoothed drifts. From the two orthogonal surface velocities we obtain \( V_x \) and \( V_y \) at each time step corresponding to a white-light image. While the individual measurements of \( V_x \) and \( V_y \) are noisy (rms values of \( \sim 250 \) m s\(^{-1}\)), averages over several granular lifetimes are stable for the length of our observing runs.

3.3. Time Sequences and Correlations
The final step in the reduction was to assemble the data into time sequences of velocity, intensity and magnetic field fluctuations, to generate mean flow fields over extended time intervals and to compute correlations between magnetic fields, brightness structures and velocities. Maps giving the divergence and curl of the flow fields were computed as functions of time and correlated with the location of magnetic structures and flare kernels observed in H\( \alpha \). The mean horizontal flow was used to generate cork movies showing how a test particle dropped into the solar atmosphere would move over extended periods of time. Cork movies make it easy to see where flows are converging and diverging.

4. Analysis and Results
Using the velocity and magnetic field measurements obtained above, we investigate the links between dynamical processes and flares in the two observed active regions. Results are presented below for each region separately and then a few general conclusions are discussed in Section 5.

4.1. NOAA 7016 - 1992 January 24
The C2.4 flare that occurred in this region started at UT 15:35 as observed in the GOES x-ray measurements. Fig. 3 shows how the region looked at UT 15:24 in both white-light and H\( \alpha \). The first flare kernel to appear is already visible near the center of the H\( \alpha \) image. The flare spreads horizontally from this kernel into the other bright H\( \alpha \) regions. Chromospheric brightenings in H\( \alpha \) proceed the coronal (GOES x-ray) onset by 11 minutes. There is a large sunspot just out of the FOV in the upper right quadrant of the figure.
Fig. 4 shows the magnetic field and the mean vertical velocity obtained by averaging the first 30 minutes of individual velocity maps (15:24-15:54). The background is the Hα image taken near the beginning of the flare. Because the region was near disk center, the observed line-of-sight velocity is the vertical flow and the transverse velocity is the horizontal flow. The vertical flow is highly sheared at the location of the first flare kernel. The amount of shear in this region is $\sim 200\,\text{m}\,\text{s}^{-1}$ between up and down flow.

![Figure 3](image)

**Figure 3.** Active Region NOAA 7016 is shown in white-light and Hα. There is a sunspot just out of the field of view in the upper right quadrant. Several magnetic pores (dark spots) can be seen in the white-light image and the beginning of the flare can be seen in the Hα image.

The mean horizontal flow, averaged over the same 30 minutes of data, is shown in Fig. 5. The length of the vectors is proportional to the amplitude of the flow. The longest vectors are $\sim 1\,\text{km}\,\text{s}^{-1}$. The mean horizontal flow converges strongly from the left and upper quadrants of the image toward the region containing the first flare kernel with a mean velocity of $\sim 500\,\text{m}\,\text{s}^{-1}$. This flow is transporting negative magnetic flux toward a region of positive flux in the lower right quadrant. Although we cannot make a precise calculation of the energetics in this active region, we can form a rough estimate of energy available from the horizontal flow. The kinetic energy carried by the flow can be estimated from $\sim \frac{1}{2} \rho V^2$. Using $500\,\text{m}\,\text{s}^{-1}$ for the mean flow and a density at optical depth unity of $\rho = 3.2 \times 10^{-7} \,\text{g}\,\text{cm}^{-3}$, the flow has a kinetic energy of $\sim 400\,\text{erg}\,\text{cm}^{-3}$. Since the amplitude of the vertical flow is $\leq 200\,\text{m}\,\text{s}^{-1}$, it can carry away $\leq 1/6$ of this energy. If we assume, as suggested by Fig. 5, that the flow over a quadrant of our FOV is moving into the region of the flare, we can estimate how much kinetic energy arrives in one hour. The amount of energy will depend on the depth of the flow. Since the contribution function for our white-light continuum window spans the low photosphere, we will assume the flow exists in a layer 100 km thick. An estimate of the energy arriving per hour
Figure 4. Magnetic contours (left image) and vertical velocity contours (right image) are shown superimposed on the Hα image from Fig. 3. Magnetic fields of -100, -200, and -400 G are shown as solid black contours and +100 G as a solid white contour. Down-flows of 50, 100, and 200 m s\(^{-1}\) are shown as solid black contours and up-flows of -50, -100, and -200 m s\(^{-1}\) are shown as solid white contours.

Figure 5. The left image shows vectors of the horizontal flow superimposed on the Hα image from Fig. 3. The average horizontal flow is about 500 m s\(^{-1}\). The image on the right shows positions to which corks (see text) placed in the horizontal flow field would propagate after 6 hr.
per unit depth is given by \( W_k = 400 \times \frac{1}{4} \pi r^2 \), where \( r \) is the furthest distance from which the flow can arrive in one hour which is 1800 km at 500 m s\(^{-1}\). Thus \( W_k \approx 10^{19} \text{ erg cm}^{-1} \text{ hr}^{-1} \) or, over a depth of 100 km, \( W_k \approx 10^{26} \text{ erg hr}^{-1} \). While this is much less than the energy released in the C2.4 flare, such a flow persisting for several tens of hours could be a contributor to development of the flare, even though the main source of energy must lie elsewhere.

The horizontal flows shown in Fig. 5 were used to make a cork movie. Test particles, initially distributed uniformly in the flow, are moved at the local velocity for one time step. They are then given the new local velocity for the next time step. After several hours, many of the corks converged toward the first flare kernel and toward a line where subsequent flare kernels erupted (Fig. 5). The vertical velocity field observed in H\(\alpha\), which reflects conditions in the chromosphere above the velocity and white-light images shown in Figs. 3, 4, and 5, also shows a strongly sheared flow along the magnetic filament connecting the flare kernels.

4.2. NOAA 7420 - 93 February 6

The pre-flare behavior observed in active region NOAA 7420 on 93 February 6 is similar to that observed in NOAA 7016. The major difference is that 7420 flared several times, including a much stronger M-class flare. NOAA 7420 is more complex in structure than 7016 and we observed it closer to the solar limb, so projection effects must be accounted for. Fig. 6 shows white-light and H\(\alpha\) images taken just before the M-class flare. Fig. 7 shows the line-of-sight magnetic field and vertical velocity averaged over 30 minutes while Fig. 8 shows the mean horizontal flow. The flare begins near the center of our FOV and spreads towards the sunspots on the right and left. Strongly convergent horizontal flows are observed in the regions of the flare kernels and shear in the vertical flow was observed both in the photosphere and in H\(\alpha\) (chromosphere). A magnetic filament connecting the flare kernel in the lower left corner in Fig. 7 with the flare kernel near the center of the image showed what is apparently helical or twisted velocity field in the chromosphere and a steady horizontal flow underneath it in the photosphere. The flow was directed outward from the center of the filament toward the two flare kernels. Corks placed in the mean horizontal flow and permitted to propagate for several hours, converged toward these two flare kernels and are shown in Fig. 8. All of the prominent H\(\alpha\) brightening caused by the flare is located near places where the corks converge.

The vector magnetograms of this region, obtained with the JHU/APL VMG show weak shear along the neutral line associated with the spot on the left. From Fig. 7, we see there is some positive flux emerging near the center of the FOV in a region of negative flux. The vector magnetogram shows some shear associated with this emergence. The emergence is occurring at a location where the vertical flow is highly sheared and the horizontal flow is converging. Whether the presence of the flow field or the emergence of the flux, or both, triggers the flare is not determined.
Figure 6. Active Region NOAA 7420 is shown in white-light and Hα. The region is located at W 60° near the solar equator. The images were taken just at the beginning of an M1 flare. Flare kernels are located along a filament running from the center of the image into the penumbra of the sunspot in the lower left and along the penumbra of the sunspot on the right.

Figure 7. As in Fig. 4 but with different contour levels: magnetic fields of -100, -200, and -400 G are shown as solid black contours, and +100, +200, and +400 G as a solid white contours. Downflows of 200, 500, and 800 m s⁻¹ are shown as solid black contours and upflows of -200, -500, and -800 m s⁻¹ are shown as solid white contours.
Figure 8. Horizontal flow vectors and corks, as in Fig. 5.

5. Conclusion

We have demonstrated that it is possible to carefully map out the dynamics of solar active regions and to relate these dynamical processes to subsequent activity. We find evidence that the locations of flare kernels correspond to locations showing shear in the vertical and convergence in the horizontal flows in the photosphere. The relationship between these flows and the magnetic structure measured in the photosphere provides evidence that at least some, if not all, activity events are related to local dynamics. The fact that Hα brightenings preceeded the x-ray onset measured by GOES supports the idea that the energy source is located lower in the atmosphere. Modeling and further analysis of the observations will determine if the dynamical processes in the atmosphere are transferring energy into the magnetic fields, which then become unstable and erupt or whether the fields are being driven from below and in turn are controlling the dynamics of the atmosphere. In either case, it appears that measuring atmospheric flows should provide a means of assessing the stability of active regions.

We plan to reduce data from all of the active regions observed during our solar maximum campaigns to produce 3-D maps of the active region dynamics. These maps will be used as inputs to develop 3-D, MHD models of active region evolution. The goal of the models will be to predict the magnetic structure of the active region, especially the overlying coronal loop structure where activity appears to be triggered. Soft x-ray images from the Yohkoh satellite as well as observations of subsequent activity obtained from the Sacramento Peak activity patrol instruments and the SEON instruments will be used to verify the model predictions.

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Group Discussion

Ryutova: What is the maximum height at which you observe these velocities, and can you say if more active dynamics is connected with the downflows rather than the upflows?

Keil: We measure the velocity in Hα, however, we only have two points in each wing and one at the line core. For FeI 5434, we measure the flow at several bisector levels in the wings and the core. The core is formed at about 550 Km above the $\tau_{5000} = 1$. The deepest measure the vertical flow is in the wings of FeI 5434 which are formed near 150 Km above the $\tau_{5000} = 1$. The filament activation and flares seem to be located where there is shear between the upflows and downflows.

Schnack: In light of your experience in studying the dynamics of many active regions, what is your opinion of the role of sheared photospheric flow in the onset of flares?

Keil: The three cases we have studied in detail show sheared vertical velocities near the regions (kernels) where the flare originated. They also show converging horizontal flows in the same regions. Whether the flows are determined by the field structures or flare, or whether the flows are driving the flare process, we cannot say from just three events.

Venkatakrishnan: Looking at the line-of-sight velocity maps and the horizontal velocities of the active region, the convergence doesn’t give the usual downdraft, but a downflow on one side of the neutral line and an upflow on the other side.

Keil: We are showing the vertical flow averaged over a 30 minute period. The instantaneous flow in the vicinity of the pore that disappeared during the flare was downward, the centroid of the downflow was slightly offset from the intensity centroid of the pore.