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Evolution of Magnetic and Velocity Fields in Super-active Region NOAA10486 and the Large 4B/X17.2 Flare of October 28, 2003

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We have used high cadence GONG + photospheric magnetograms, dopplergrams and Udaipur Solar Observatory (USO) chromospheric Hα-filtergrams to study the spatial and temporal evolution of the active region NOAA 10486 in relation to the X17.2/4B flare of October 28, 2003. New flux emergences, large proper motions and development of steady velocity flows have been identified around the flare site. In addition, filament activation and eruption leading to fast CMEs were noticed. During the flare, NOAA 10486 was located near the disk-center; well suited for the ring diagram analysis. Therefore, we have obtained the 3-D power spectra to search for helioseismic response of the large flare on the amplitude, frequency and width of the p-modes. Power enhancement was found during the post-flare phase, and NOAA 10486 possessed steep gradient in the meridional velocity as compared to the less flare-productive active regions.

Introduction

Super-active region NOAA AR 10486 produced several extremely energetic flares, such as, X5.4/1B, X17.2/4B, X10/2B X8.3/2B and the record-setting X28/3B, during October 22 – November 04, 2003. Most of these energetic flares were associated with fast moving CMEs, which continued to occur even as the active region rotated off the west-limb. The X28 flare of November 4, 2003, which saturated the GOES X-ray detectors, was later re-classified as an X45±5 flare based on the ionospheric response. However, the X17.2/4B flare event of October 28, 2003, and associated proton storm and coronal mass ejection (CME) had a larger geomagnetic effect as this event occurred when the AR was located near disk-center, whereas the other larger event occurred on the solar limb. The total solar irradiance (TSI) measurement recorded an increase by 360 mWm^{-2} due to this flare; the first such unambiguous detection of a flare since 1978 when routine TSI measurements started [1]. Two other large regions, NOAA 10484 and 10488, were also observed during around this period, although their flare productivity did not match up with that of NOAA 10486. From the major flares which occurred during October 25 – November 07, 2003, we have selected the X17.2/4B flare for detailed analysis of its photospheric and chromospheric signatures due to the favorable location of the active region near the CMP which minimizes the projection effects. We attempt to identify the conditions leading to flare trigger, viz., flux emergence, and development of *LOS* velocity flows at the flare site along with filament activation and eruption. We also investigate for any flare related changes in *LOS* velocity, magnetic flux and helioseismic parameters.

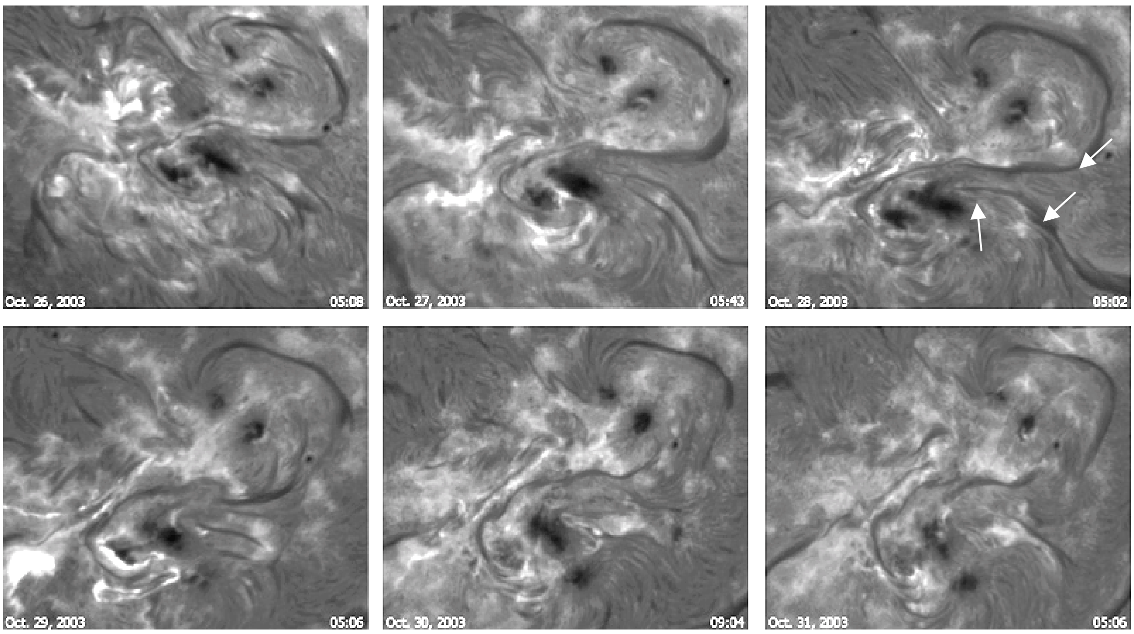

Fig.1. Chromospheric evolution of NOAA 10486 during October 27-30, 2003. Note the filament structural changes in the active region, particularly in areas marked by arrows (USO Hα).

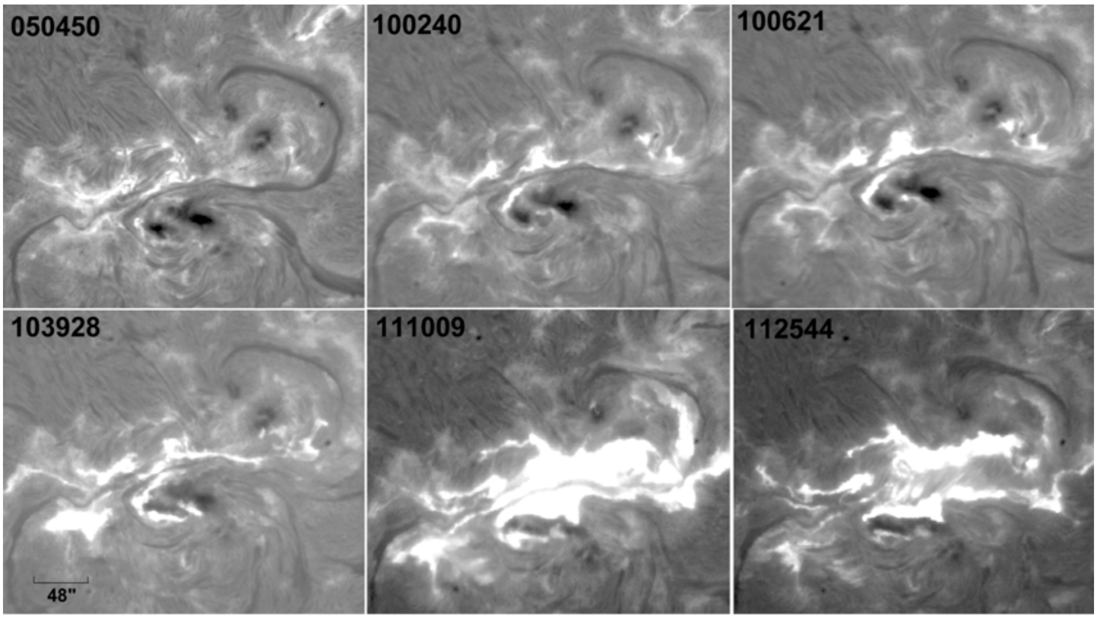

Fig.2. Chromospheric changes observed in Hα during the 4B flare observed in NOAA 10486 on October 28, 2003 (USO Hα).

The Observational Data

High cadence Hα –filtergrams were obtained from USO providing extensive coverage of the active regions NOAA 10484, 10486 and 10488 during the period of October 18 – November 5, 2003. In addition, line-of-sight (*LOS*) magnetograms and dopplergrams were also obtained at a cadence of 1 *mine* by the GONG+ instrument operated at USO. Using movies made from these observations, we attempt to identify the sites of chromospheric restructuring, and corresponding changes in magnetic flux and Doppler velocity in the active region, particularly at the site of flare onset.

Evolution of NOAA10486 and the 4B/X17.2 Flare

Fig.1 shows the daily evolution of chromospheric structures of NOAA 10486 using USO Hα -filtergrams for the period October 26-31, 2003. A long curved filament was seen passing through the middle of the active region on October 26, 2003 with several smaller filaments over the AR. This system of filaments went through a major structural change on October 27, 2003 forming a “channel” of opposite polarity region between them. Ref. [2] reported a strong shear flows along the magnetic neutral line marked by the filament. Ref. [3] had earlier discovered such magnetic “channel” structures of elongated mixed polarity regions with strong shear flows along them. This appears to be a common feature of all superactive regions. As seen from the filtergrams of October 28, 2003, the channel gradually became narrower as a result of significant spatial changes taking place in the active region. Interestingly, this channel was the site of the onset of the 4B/X17.2 superflare of October 28, 2003. Before this flare, several smaller events occurred in the neighboring locations. Chromospheric structural changes associated with the filaments were also observed subsequent to the superflare (cf. Fig.1: October 29 frame).

New active filaments formed later during October 30-31, 2003, indicating significant magnetic field restructuring. The active region retained its large magnetic complexity, and contained sufficient energy even after the superflare of October 28, 2003; evident from the fact that a large 2B/X10 white light flare followed at 20:37 UT on October 29, 2003. NOAA 10486 was estimated to possess an order of magnitude greater free energy than that in the two other active regions NOAA 10484 and NOAA 10488 on October 29, 2003 [4].

Fig. 2 shows the spatial and temporal evolution of the 4B/X17.2 super-flare observed in Hα. After the preflare activation seen in 10:39:28 UT frame, the flare erupted impulsively, reaching a maximum phase at 11:10 UT. The flare-ribbons separated away rapidly; a typical property of two-ribbon flares. Post-flare loops, generally observed during the decay phase, appeared as seen in the 11:25:44 UT frame, while the flare lasted over much longer. Notably, the Hα filtergrams showed formation of a twisted rope-like structure in the magnetic channel, rising upwards and eventual eruption of the filament.

Evolutionary and Flare-Associated Changes in Magnetic Flux and Velocity

Major flares such as this superflare are known to occur near the polarity reversal or neutral lines at location of strong magnetic gradients and/or magnetic shear. Several attempts have been made in the past to monitor the changes in magnetic flux, shear and electric currents before, during and after flares [5-8]. More recently, [9] have found a decrease in magnetic flux using high resolution MDI magnetograms for the “Bastille Day Flare”' of July 14, 2000. Ref. [10] carried out a similar flux analysis for the large X20 flare of April 2, 2001, and reported an increase by 6×10^{20} *Mx* in the leading polarity and no clear change in the following polarity. Ref. [11] showed similar flux variation for six other X-class flares. However, the changes in the magnetic field twist parameter were found statistically insufficient to distinguish between flaring and non-flaring active regions [12].

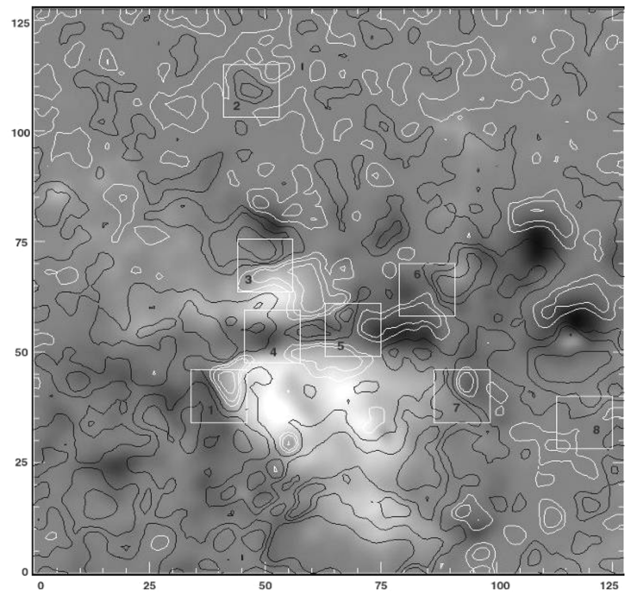

Fig.3. Overlay of GONG+ LOS magnetograms (grey level) and Doppler velocity (contours) observed in NOAA 10486. Also marked are the 12x12 pixel boxes enclosing areas of interest.

Movies of GONG+ velocity and line-of-sight magnetic field maps obtained during October 28, 2003, showed significant evolutionary changes at several locations along the magnetic channel and in the vicinity of the elongated filament. Fig.3 shows overlay of a typical GONG+ line-of-sight magnetogram (grey level) and dopplergram taken on October 28, 2003/11:10 UT, with boxes marking eight areas-of-interest. Development of an increasing upward flow was seen in box "7", around which the filament was destabilized. Increasing upward directed flow was also observed in box "6", where a positive polarity flux emerged. In box "5", which covers location of the Hα twisted rope structure, moving blue shift events were observed. These evolved considerably during the time of the flare onset. Such events are indicators of upflow from reconnection events that are found to be 5 times more frequent before eruptive flares than in non-eruptive flares [13], and upflows in the range of 40-80 *km/s* have been detected during the preflare phase [14]. Ref. [15] found that flare kernels are locations of shear in vertical photospheric flows and locations of convergence in horizontal photospheric flows. Ref. [16] has also found evidence of persistent, supersonic downflows and shear flows in flaring active regions.

Recently, using GONG+ magnetograms, [17] have reported statistically significant changes in magnetic flux related with flares. However, it is important to consider flare-related changes in photospheric spectral lines while deriving such inferences, as this may seriously affect magnetic field calculations [18]. It may be noted that the GONG magnetic field measurements have been found not to be very sensitive to line shape changes, while the velocity estimates do strongly depend on the line variations [19]. Using simulated observations of a flare they found that flare associated magnetic field changes are not due to line shape changes, and the flare time magnetic flux changes are expected to be real.

Using the GONG+ Doppler (line-of-sight) velocity and magnetic data-cubes taken at a cadence of 1 *min*, we have evaluated the net magnetic flux and Doppler velocity during 2003 October 27/12:26 – October 28/16:09 UT for the sub-areas marked by the boxes in Fig.3. Maps of the Doppler and magnetic flux overlays show the temporal and spatial variations before and after the flare (Fig. 4).

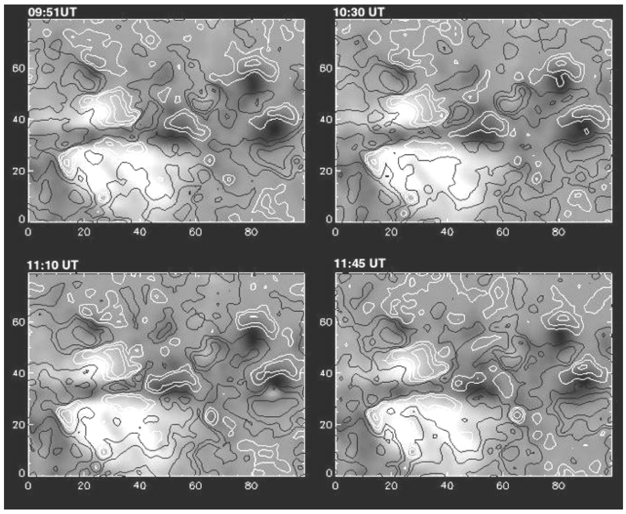

Fig.4. Overlay of GONG+ LOS magnetograms (grey level) and velocity (contours) observed in NOAA 10486 before, during and after the 4B/X17 superflare.

The magnetic flux distributions in the active region are shown by grey levels - positive (white) and negative (dark) - while the velocity are shown by the overlaid contours - upflow (white contours) and downflow (black contours). Time profiles of net magnetic flux obtained over the box of 12×12 pixel for the tracked regions are given in Fig. 5.

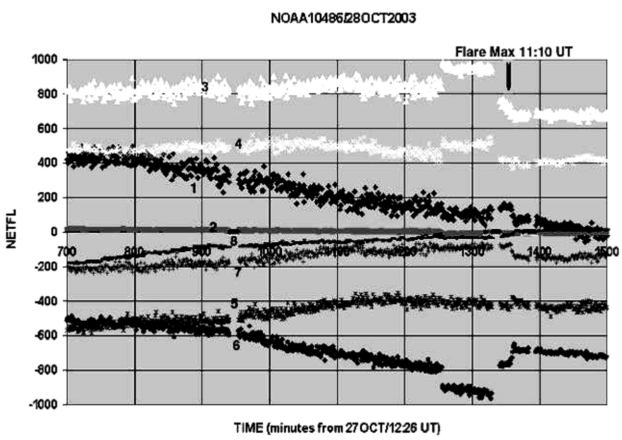

Fig.5. Overlay of GONG+ LOS magnetograms (grey level) and velocity (contours) observed in NOAA 10486.

Both evolutionary and flare associated changes in magnetic fluxes may be inferred in these profiles obtained using GONG+ data. The box “2” was located in a quiet area of low magnetic field, which was used as a reference, showing zero net flux. The boxes “1”, “3” and “4” were located in areas of net positive flux. On the other hand, boxes “5”-“8” were located in areas of net negative flux. The net flux for the boxes "3", "4" and "6" is found to go through a change before and after the flare (maximum phase of the flare is marked by arrow). Although the magnitude of the net (negative) flux in box “7” was comparatively low as compared to the other boxes, it showed an abrupt change after the flare.

As mentioned earlier, these changes in magnetic flux measurement are expected to be unaffected by the spectral line profile changes. Net flux for the box "1", shows only a gradual decreasing trend of flux evolution, while boxes “5” and “8” showed an opposite trend of flux increase. These three boxes were relatively free from any flare related effects. The profiles of net Doppler velocity obtained for these boxes show larger scatter, and any flare-related changes are not obvious from the corresponding profiles. Using MDI magnetograms for the “Bastille Day Flare” of July 14, 2000, [9] have found a decrease in magnetic flux. However, we find both decrease and increase in net flux for boxes located in different locations in NOAA 10486.

These observed flux changes may occur due to a variety of processes, such as, emergence or submergence of flux and horizontal motions leading to the enhancement or cancellation of fluxes. GONG VMG movie shows such features at several locations during the course of the flare. It is known that photospheric horizontal motions of magnetic fluxes could lead to the accumulation of magnetic energy in a flare current sheet of the order of 1032-1033 ergs [20], and twisting of magnetic loops may result into kink instability and eventual release of 35-50% of the free magnetic energy [21]. Also, magnetic modeling of flares has revealed onset of flare due to reconnection of emerging flux in a sheared magnetic field [22, 23]. Appearance of certain horizontal velocities may lead to changes in local magnetic field structures, and generate electric current systems [24, 25]. The observed motion of fluxes along the filament channel, i.e., magnetic neutral line in NOAA 10486, corresponds to shear flow as found in [2]. The sheared fields could reach a critical stage breaking the equilibrium and settling to a more potential configuration releasing a part of the available free energy as flares and CMEs.

There is another aspect of the observed variations of magnetic field, which needs to be mentioned. The magnetograms may render an artifact due to changes in the thermal structure of the photosphere during large white light flares. This may affect the formation of the Ni I λ 6768 line. It is interesting that the penumbral magnetic signature remains significantly changed long after the white light signature has vanished. However, there is a possibility that the nominal penumbral magnetic signature is contaminated by magnetically insensitive molecular lines, such as TiO, in the neighborhood of NiI λ 6768. If these molecules are destroyed in great numbers by the thermal or radiative enhancement evident in the sunspot photosphere during the white light flare, the magnetic signature could be changed accordingly, and a considerable amount of time may elapse ($\geq$10 *min*) before the molecular composition of the penumbral photosphere recovers to preflare conditions.

Helioseismic Signatures of the Flare

It is interesting to ask whether large flares or CMEs may have any effect on p-modes on the smaller spatial scales of active regions. Although most of the flare energy is released in the chromosphere and corona, the white light flares imply that a part of energy may be deposited in the photosphere, affecting the modes of solar oscillation as reported by [26]. The effect of flares on solar oscillation modes has been further explored for several active regions using the ring diagram technique by obtaining 3-D spectra before, during and after the flares, giving evidence of variation in mode characteristics such as frequency, width, power and asymmetry [27]. At the time of 4B/X17.2 superflare, NOAA 10486 was located ideally at the disk-center and the flare was energetically substantial to look for any flare related effects on the p-mode characteristics. Fig.6 shows that relative difference in mode frequencies, widths and ratio of peak power for NOAA 10486. The frequencies and widths of the modes are not affected significantly during the three day period around the flare, i.e. October 27-29, 2003. However, the mode-amplitude increased substantially after the large flare of October 28, 2003 (Fig.6: left panel). It increased further on October 29, 2003 (Fig.6: right panel), as a result of more flares which occurred after the superflare of October 28, 2003 [28]. Some studies have shown that subsurface flows may also lead to p-mode characteristics variations [29, 30].

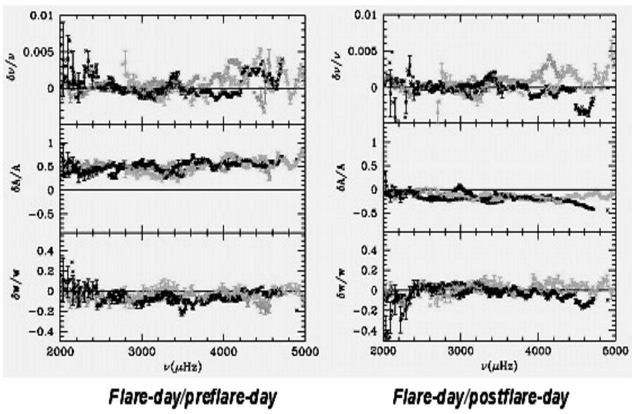

Fig.6. NOAA 10484, 10486 and 10488 at different stages of evolution. The lines show the results obtained by RLS inversions while points mark those obtained by OLA [33].

We have used the regions tracked for 8192 minutes around the central meridian passage, and inverted the frequency differences to calculate sound speed between an active and quiet region for NOAA 10484, 10486, and 10488. An inversion for solar structure is a process to determine solar structural parameters using the observed solar oscillation frequencies. The differences between the structure of the Sun and a reference model are related to the differences in the frequencies of the Sun and the model by kernels. Instead of inverting the differences between the frequencies of a model and those of the Sun, we invert the differences between the frequencies of active and quiet regions to determine the difference in structure between the two. We still need to use a solar model to determine the kernels for the inversion. The use of the differences between two sets of solar frequencies instead of frequency differences between a model and the Sun ensures that we minimize any possible systematic error that may be caused by uncertainties in the solar model. The inverse problem can be solved using a variety of techniques.

This has been carried out by using the two common methods of solving the inversion integral, viz., the Regularized Least Squares (RLS) [31], and Optimally Localized Averages (OLA) [32]. These two inversion methods are complimentary in nature; therefore, one can be more confident if OLA and RLS results are in good agreement [33]. It is found that the sound speed in active regions was lower just below the surface but at depths exceeding 7 *Mm*, the trend reversed. Similarly, the fitted velocities for each mode are inverted to calculate the meridional (*u*) and zonal (*v*) components as a function of depth [28]. A steep gradient in meridional velocity is found to exist below a depth of 4Mm which appears to be correlated with flares (Fig.7) as similar feature was also observed for other major active regions such as NOAA 9026, and 9393 [27].

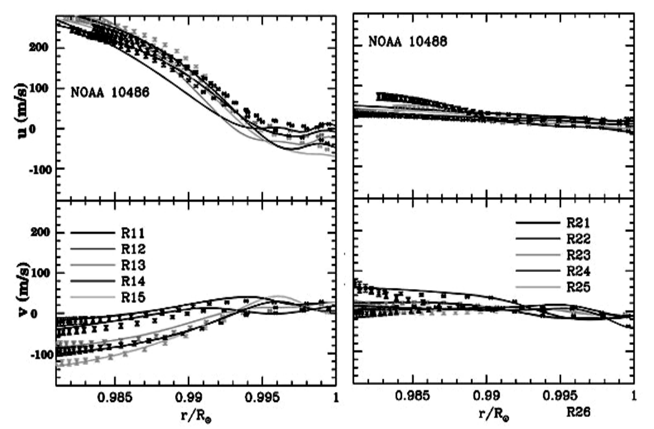

Fig.7. NOAA 10484, 10486 and 10488 at different stages of evolution. The lines show the results obtained by RLS inversions while points mark those obtained by OLA following [33].

Conclusions

Net flux and Doppler velocity have been obtained at several locations in NOAA 10486 using GONG data during October 28-29, 2003. Significant evolutionary and flare time variation in net magnetic flux is found, showing variations before and after the X17.2 flare of October 28, 2003. Large flux motions at several locations before the flare are observed.

The Doppler maps show that upward (and downward) flows developed near the large Hα filament, associated with new emerging fluxes. This process could have destabilized the filament delineating the narrow channel. The magnetic free energy was found adequate to account for the subsequent white light flare of October 29, 2003 even after the release of large energy in the event of the 4B/X17.2 flare.

Recently, emission of seismic waves has been detected from the powerful solar flares that occurred in NOAA 10486 on 2003 October 28 and 29 [34, 35]. The source region locations observed in these reports for the October 28th flare were located in the narrow channel contained near the boxes 4-5 of this work. This was also the site of strong magnetic field gradients and the filament channel observed in the Hα–images.

The filament erupted along with the flare, which perhaps resulted in the fast Earth-ward moving CME. After the flare, the filament was partially restored with significant restructuring and disconnection. Evidence of reconnection was observed at the site of flux emergence.

We found significant increase in power of the acoustic modes during the X17 flare, which was beyond the normal value expected from the influence of magnetic fields. In addition, the meridional velocity in the flaring region was found to have a steep gradient below a depth of 5 *Mm*.

Acknowledgements

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