Bull. Astr. Soc. India (2007) **35**, 419–426

Signatures of large flares on photospheric magnetic and velocity fields

Ashok Ambastha*
Udaipur Solar Observatory, Udaipur 313 001, India

Abstract. We have analysed the spatial and temporal evolution of photospheric magnetic and doppler velocities in active regions, particularly in the superactive region NOAA 10486, to detect pre- and post-flare changes. These findings have been compared with recent reports by other workers, and significance of these results has been discussed. Helioseismic response of large flares, and the role of sub-photospheric flows in flare-productive as compared to that in less flare-productive active regions are presented.

Keywords : Sun : flares – Sun : oscillations – Sun : magnetic fields

1. Introduction

It is generally believed that a solar flare is the result of a magnetohydrodynamic (MHD) catastrophe in the corona, which leads to the reconnection of magnetic field lines in the corona giving rise to a wealth of pre- and post-flare phenomena (c.f., Priest & Forbes 2002). Photospheric flux motions may stress the coronal magnetic field configuration to non-potential states. As a result, active regions could store adequate free magnetic energy; a fraction of which may eventually be released in flares (Ambastha & Bhatnagar 1988). As flares derive their energy from the stressed magnetic fields, they are expected to be associated with observable changes from the pre- to post-flare state. Giovanelli (1939) was perhaps the first to suggest to look for flare-associated magnetic field changes, and the search was revived after magnetographs became operational. However, the early magnetograph observations were unreliable because of poor sensitivity, spatial resolution, cadence, and coverage (Rust 1974). Efforts to detect changes in magnetic parameters

*e-mail:ambastha@prl.res.in

during flares continued in the 80's and 90's(Ambastha et al. 1993; Chen et al. 1994), but the results were mostly contradictory or unclear (Sakurai & Hiei 1996).

There has been a recent spate of high quality observations providing the evidence of abrupt and permanent changes in photospheric magnetic fields during solar flares. Of particular interest are the superflares of NOAA 10486, observed during October-November 2003, which included the record-setting X28 flare of November 4, 2003; later re-classified as X45±5 flare based on its ionospheric response (Thomson et al. 2004). But its X17/4B event of October 28, 2003 had a larger geomagnetic effect, and the total solar irradiance (TSI) measurement recorded an unprecedented increase by 360 mWm^{-2} due to this flare (Woods et al. 2004). These superflares are potential candidates for the detection of flare-related changes in the photospheric velocity, magnetic flux, and helioseismic effects, as the most detectable changes are expected for the most energetic flares. The active region was favorably located near the disk-center when the X17/4B flare occurred, thus minimizing the projection effects. Therefore, it was better suited for detecting the flare-related signatures, and has been extensively studied by several workers. We review here some recent results on the physical conditions leading to the onset of the flare, changes associated with this superflare and its helioseismic signatures.

2. Observational requirements and the data

Previous studies of magnetic field changes during solar flares have established that the timescale for abrupt and persistent changes are of the order of several minutes. However, it is cautioned that the observed changes could be affected by flare-induced line profile changes (Patterson 1984; Harvey 1986; Qiu & Gary 2003, Abramenko & Baranovsky 2004), which are expected to last over a few minutes during the impulsive phase of the flare. The active region magnetic field can also evolve at a rate of a few gauss per minute. Therefore, a few hour long high resolution magnetic field data taken at high cadence, high sensitivity is needed to distinguish between normal evolution and the abrupt changes associated with flares. GONG and SOHO-MDI provided magnetograms and dopplergrams with such spatial and temporal coverage for the study of NOAA10486. In addition, we used high spatial and temporal resolution H_α filtergrams obtained from the island observatory (USO) at Udaipur, India (73.71E 24.58N) for the flare, and the NASA-MSFC daily vector magnetograms for identifying nonpotential structures.

3. Changes before and after solar flares

Flare theories generally concentrate on the activity in the low-β coronal plasma, treating the photosphere only as a source of energy to drive coronal currents. The pre-flare conditions are set by topological changes, such as, increasing magnetic shear (or twist) and sudden emergence of magnetic flux in the neighbourhood (Wang et al. 2004a & b). It is known that horizontal motions of photospheric magnetic fluxes generate electric current

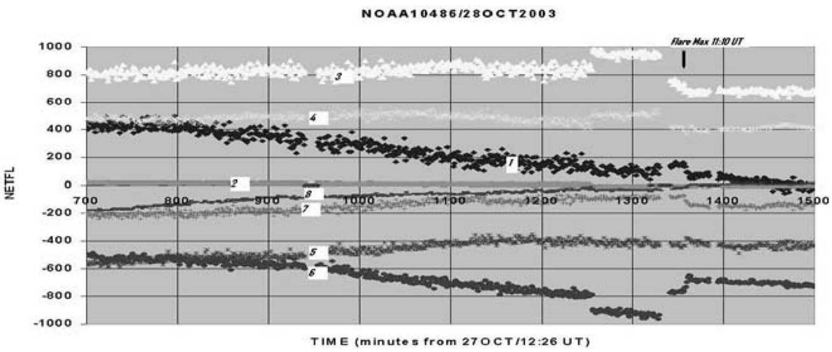

Figure 1. Temporal variations of net area-averaged magnetic fluxes in selected areas-of-interest during October 27-28, 2003 in NOAA10486 using GONG magnetograms (c.f., Ambastha 2006).

systems (Martres et al. 1982; Fontenla et al. 1995), and lead to energy storage of the order of $10^{32} - 10^{33}$ ergs (Ambastha & Bhatnagar 1988; Bilenko et al. 2002) The twisting of magnetic loops may result into kink instability and eventual release of 35-50% of the free magnetic energy (Gerrard et al. 2002). Magnetic modelling of flares has revealed onset of flare due to reconnection of emerging flux in a sheared magnetic field (Berlicki et al. 2004; Brooks et al. 2003).

Some "tracer" observations have indicated structural relaxation from a non-potential configuration towards the potential state of lower energy after a large flare; for example, an Yohkoh X-ray flare event (Shimizu 1996), and H_α arcade evolution during a flare (Debi Prasad et al. 1999). However, it is to note that photospheric magnetic shear does not necessarily decrease after large flares (Ambastha et al. 1993; Wang 1997). Also, changes in magnetic twist were statistically found to be insufficient to discriminate between flaring and nonflaring active regions (Leka & Barnes 2003). These are probably the consequences of attempting to discern the 3-D geometry of reconnecting magnetic fields from only the available 2-D data. Nevertheless, several recent observations have reported permanent increase/decrease of magnetic flux within timescales of 10-100 minute around flares, suggesting it to be a common phenomenon (Kosovichev & Zharkova 2001; Wang et al. 2002a&b; Spirock, Yurchyshyn & Wang 2002; Liu et al. 2003; Meunier & Kosovichev 2003; Wang et al. 2004b; Yurchyshyn et al. 2004; Sudol & Harvey 2005; Deng et al. 2005; Li et al. 2005). Ambastha (2006) report changes with the October 28, 2003 superflare in NOAA 10486 (Fig. 1), along with slow evolutionary variation due to the horizontal motions and emergence/submergence of fluxes. Lara et al. (2000) have reported such magnetic flux changes with CME eruptions also.

The GONG and MDI magnetograms showed an interesting feature moving rapidly away from the superflare site during 10:56-11:15 UT, i.e., around the time of flare's maximum phase, on October 28, 2003 (Fig. 2). Velocity of this feature was estimated to be around 40 km/s, i.e., much larger compared to the usual separation speed of two-

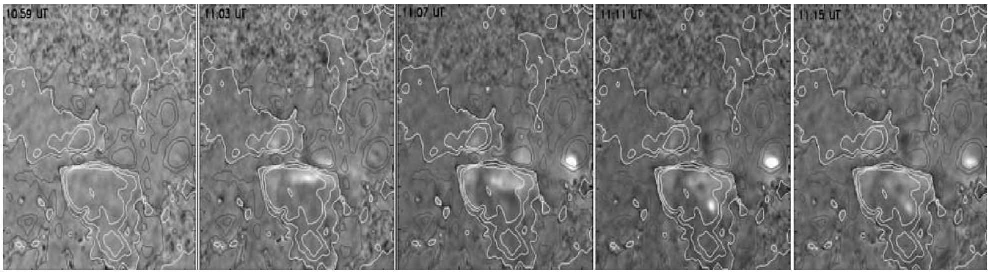

Figure 2. The moving feature observed in GONG difference magnetograms around the flare-maximum phase on October 28, 2003 (reference magnetogram taken at 10:55 UT).

ribbon flares, but comparable to the velocity of seismic waves reported by Kosovichev & Zharkova(1998). If the moving feature was caused due to line profile changes, it is expected to show a relationship with the slower separation speed of flare ribbons. Also, it does not appear to be instrumental artifact either, as both the GONG and MDI images exhibit this feature. The exact nature of the moving feature requires further investigation.

In a location of twisted rope-like structure observed from the USO H_α filtergrams during the superflare's onset time, rapidly evolving blue shift events were seen. These are indicators of upflow from reconnection events that are more frequent before eruptive flares than in noneruptive flares (DesJardins & Canfield 2003). Meunier & Kosovichev (2003) have also found evidence of persistent, supersonic downflows and shear flows in flaring active regions. Upflows in the range of 40-80 km s^{-1} have been detected during the preflare phase (Brosius & Phillips 2004). Keil et al. (1994) found that flare kernels are locations of shear in vertical photospheric flows and of convergence in horizontal photospheric flows.

Increase in magnetic field gradient has also been found to lead to flare onset in some events. Mathew & Ambastha (2000) studied NOAA 8038/May 12, 1997 having weak magnetic field and low shear where new emerging positive fluxes moved with velocities in the range 300–800 m s^{-1} towards the pre-existing negative polarity network fluxes. At the interface of the oppositely moving fluxes, magnetic gradient increased and flux cancellation occurred, followed by a small flare. Wang (2006) have also reported increase and/or decrease of magnetic gradients along magnetic neutral lines, at the onset time of several flares. The MSFC vector-magnetograms show strong magnetic gradient along the neutral lines, which persisted even after the X17/4B flare of October 28, 2003 (Fig. 3). It is also evident that the gradients gradually decreased from October 28 to October 30, 2003, and the orientation of transverse fields changed in some localized areas (marked by "circles"). Su et al. (2006) has recently tried to determine the relationship between the timing of the impulsive phase of the flare and the magnetic shear change in the flaring region. TRACE EUV observations showed a decrease in the shear of the flare footpoints during the flare.

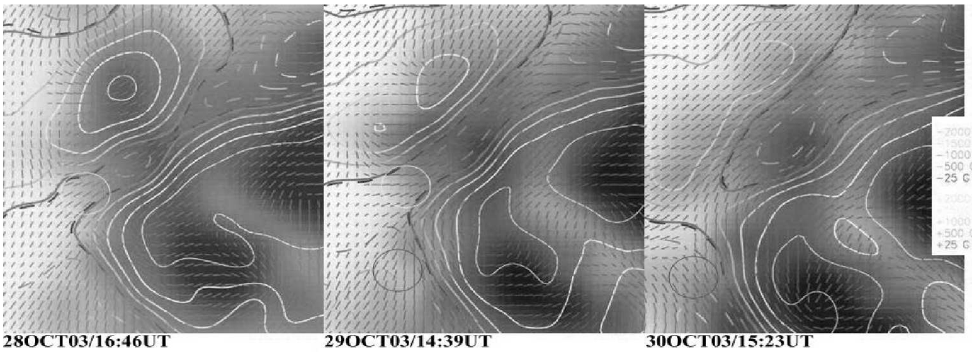

Figure 3. Daily MSFC vector magnetograms for NOAA 10486 during October 28-30, 2003, showing the locations of large magnetic gradients, and shear. The changes are marked by *circles.*

4. Helioseismic response of large flares

Locally excited acoustic modes interact with local variations in sound speed, flow fields, and magnetic activity which alter their propagation characteristics. A careful analysis of the acoustic waves in a localized patch of the solar photosphere can potentially reveal a great deal about the subsurface dynamics. Local helioseismology investigates small-wavelength acoustic waves that are confined principally to the near-surface layers, i.e. $r \leq 0.97R_{\odot}$. There are several local helioseismology techniques in use, *viz.*, ring-diagrams (Hill 1988), time-distance method (Kosovichev, Duvall & Scherrer 2000), and acoustic holography (Lindsey & Braun 2000). These have helped in the mapping of horizontal flows in sub-photospheric layers, revealing the meridional and zonal circulation patterns, or solar subsurface weather (SSW), and in the far side imaging of active regions (c.f., Gizon & Birch 2005, for a review).

It is generally accepted that acoustic modes, always present on the Sun, are excited by turbulence in the convection zone (Goldreich & Kumar 1988). Energetic transient phenomena, such as, flares and CMEs are expected to contribute additional energy to these modes. Wolff (1972) first suggested that flares could excite solar oscillations as a result of the mechanical impulse produced by the thermal expansion towards the solar interior. On the global scale, however, only a mild anti-correlation is found between the low-ℓ p-mode power and the disk-integrated flare-index (or CME-index) (Ambastha & Antia 2006). It would be interesting to ask whether flares or CMEs may have any detectable effects on the p-modes over the smaller spatial scale of active regions. Earlier attempts to detect flare-associated effects were mostly contradictory and inconclusive (Haber et al. 1988; Braun & Duvall 1990). The difficulty in detecting any flare-related change is caused by the absorption of mode power by large sunspots which can absorb as much as 70% of the power of the incident high-degree modes. Therefore, any excitation induced by the shorter-lived flares has to essentially compete with the effects of absorption due to strong magnetic field of sunspots.

Evidence of flare-associated variation in various mode characteristics, such as, frequency, width, power and asymmetry has been found in several active regions using ring diagram analysis (Ambastha, Basu & Antia 2003), including that in NOAA 10486 after the X17/4B flare (Ambastha et al. 2004). Some recent studies have also shown that subsurface flows may lead to p-mode characteristics variations (Zhao & Kosovichev 2004; Haber et al. 2004). As opposed to the standing waves which constitute normal modes of solar oscillations, traveling wave, or solar quake, emanating from the site of a large flare of July 9, 1996 was reported by Kosovichev & Zharkova (1998, 1999). Such seismic waves have recently been reported for the superflares of NOAA 10486 (Kosovichev 2006). Using helioseismic holography, Donea & Lindsey (2005) have detected compact sources of seismic waves at the sites of the powerful solar flares of this active region. Traditionally, traveling waves, or *Moreton waves*, have been observed to originate from some flaring sites in the chromosphere.

There have been some attempts to search for subsurface signatures of large flares. Ambastha et al.(2004) compared the meridional and zonal velocity profiles with depth under flare-productive and flare-inactive regions, and found steep gradients in meridional velocity below a depth of around 5 Mm in flare-active regions. The velocity gradient vanished after flares in some active regions, while the flare-inactive regions did not exhibit any gradients. Komm et al. (2005) have found strong kinetic helicity signal at the location of NOAA10486 during the epoch when the flares occurred. The sign of the kinetic helicity remained the same at depths greater than about 5 Mm, while closer to the surface, the sign changed with depth indicating a more complicated behavior. Haber et al. (2004) found horizontal flows surrounding NOAA10486 and variation with depth in the upper 14 Mm of the convection zone. They reported large scale shear flows that may contribute to conditions conducive to intense flaring activity.

5. Conclusions

The most important conclusion from a large number of reports on flare-associated variations is that abrupt and persistent photospheric changes are common during large flares. If this is indeed the case, then one of the basic assumptions of modern flare theories that the photosphere does not respond to flares (see, Priest & Forbes 2002), needs to be revised. One could attribute the observed magnetic field changes to emergence (or submergence) of subsurface fluxes and its interaction with the pre-existing structures. However, it would require significant local flux emergence. The most plausible explanation of the observed changes seems to be that the magnetic field changes direction rather than strength, at least in the photospheric layer (Sudol & Harvey 2005).

Significant increase in power of the accoustic modes has been found during large flares, well beyond the normal value expected from the influence of magnetic fields. Solar quakes and compact acoustic sources of seismic waves have also been found. In addition, meridional velocity in flare-active regions is found to possess steep gradient below a depth of around 5 Mm compared to that for less flare-active regions. This is an important finding, having a role in the understanding of flare mechanism, and may help in the prediction of large flares and space weather.

The suggestion that the observed field changes are consequences, rather than triggers of the flares, does not mean that surface or subsurface events cannot be the trigger. There is increasing evidence for a close association between specific subsurface motions and flare productivity, therefore comprehensive flare theories may need to extend from the corona to well beneath the photosphere.

References

Abramenko, V.I., & Baranovsky, E.A., 2004, SoPh, 220, 81
Ambastha, A., & Bhatnagar, A., 1988, JAA, 9, 137
Ambastha, A., Hagyard, M.J., & West, E., 1993, SoPh, 148, 277
Ambastha, A., Basu, S., & Antia, H. M., 2003, SoPh, 218, 151
Ambastha, A., Basu, S., Antia, H., & Bogart, R., 2004, in Proc.SOHO 14/GONG 2004 Workshop, ESA SP-559, p. 293
Ambastha, A., 2006, JAA, 27, 255
Ambastha, A., & Antia, H.M., 2006, SoPh, 238, 219
Basu, S., Antia, H.M., & Bogart, R.S., 2004, ApJ, 610, 1157
Berlicki, A., Schmieder, B., Vilmer, N., Aulanier, G., Del Zanna, G.et al. 2004, A&A, 423, 1119
Bilenko, I.A., Podgorny, A.I., & Podgorny, I.M., 2002, SoPh, 207, 323
Braun, D.C., & Duvall., T.L. Jr., 1990, SoPh, 129, 83
Brooks, D. H., Kurokawa, H., Yoshimura, K., Kozu, H., & Berger, T. E. 2003, A&A, 411, 273
Brosius, J.W., & Phillips, K.J.H., 2004, ApJ, 613, 580
Chen, J., Wang, H., Zirin, H., & Ai, G. 1994, SoPh, 154, 261
Debi Prasad, C., Gary, G.A., & Ambastha, A., 1999, in High Resolution Solar Physics: Theory, Observations & Techniques, eds T.R. Rimmele, et al., APS Conf. Ser., 183, 523–530
Deng, N., Liu, C., Yang, G., Wang, H., & Denker, C., 2005, ApJ, 623, 1195
Deng, N., Xu, Y., Yang, G., Cao, W., Liu, C., Rimmele, T.R., Wang, H., & Denker, C., 2006, ApJ, 644, 1278
DesJardins, A.C., & Canfield, R.C., 2003, ApJ, 598, 678
Donea, A.-C., & Lindsey, C., 2005, ApJ, 630, 1168
Fontenla, J.M., Ambastha, A., Kalman, B., & Csepura, Gy. 1995, ApJ, 440, 894
Gerrard, C.L., Arber, T.D., & Hood, A.W., 2002, A&A, 387, 687
Giovanelli, R. G., 1939, ApJ, 89, 555
Gizon, L., & Birch, A.C., 2005, Living Rev. Solar Phys., 6: http://www.livingreviews.org/lrsp-2005-6
Goldreich, & Kumar, 1988, ApJ, 326, 462
Haber, D.A., Hindman, B.W., Toomre, J., Bogart, R.S., Thomson, M.J., & LohCo Team, 2004, A&AS, 204, 02.11
Haber, D.A., Toomre, J., Hill, F., & Gough, D. O., 1988, Seismology of the Sun and Sun-Like Stars, edited by V. Domingo & E. J. Rolfe, ESA SP-286, p. 301
Harvey, J., 1986, Small-Scale Magnetic Flux Concentrations in the Solar Photosphere, eds W. Deinzer et al. Gottingen: Vandenhoeck & Ruprecht, 25
Hill, F., 1988, ApJ, 333, 996

Keil, S.L., Balasubramaniam, K.S., Bernasconi, P., Smaldone, L.A., & Cauzzi, G., 1994, ASP Conf. Ser., 68, 265
Komm, R., Howe, R., Hill, F., Gonzalez Hernandez, I., & Toner, C., 2005, ApJ, 631, 636
Kosovichev, A.G., & Zharkova, V.V. 1998, Nature, 393, 317
Kosovichev, A.G., & Zharkova, V.V., 1999, SoPh, 190, 459
Kosovichev, A. G., Duvall, T. L. Jr., & Scherrer, P. H., 2000, SoPh, 192, 159–176
Kosovichev, A.G., & Zharkova, V.V., 2001, ApJ, 550, L105
Kosovichev, G., 2006, SoPh, 238, 1
Lara, A., Gopalswamy, N., & Deforest, C., 2000, GeoRL, 27, 1435
Leka, K.D., & Barnes, G., 2003a ApJ, 595, 1277; 1296
Li, J., Mickey, D. L., & LaBonte, B. J., 2005, ApJ, 620, 1092
Lindsey, C., & Braun, D. C., 2000, SoPh, 192, 261
Liu, C., Deng, N., Liu, Y., Falconer, D., Goode, P. R., Denker, C., & Wang, H., 2005, ApJ, 622, 722
Liu, Y., Jiang, Y., Ji, H., Zhang, H., & Wang, H., 2003, ApJ, 593, L137
Martres, M.J. et al., 1982, PASJ, 34, 299
Mathew, S.K., & Ambastha, A., 2000, SoPh, 197, 75
Meunier, N., & Kosovichev, A., 2003, A&A, 412, 541
Patterson, A., 1984, ApJ, 280, 884
Priest, E., R., & Forbes, T.G. 2002, A&AR, 10, 313
Qiu, J., & Gary, D. E., 2003, ApJ, 599, 615
Rust, D. M., 1974, Flare Related Magnetic Field Dynamics, ed. Y. Nakagawa & D. M. Rust (Boulder: HAO/NCAR), 243
Sakurai, T., & Hiei, E., 1996, AdSpR, 17, 91
Shimizu, T., 1996, Yohkoh Views the Sun – The First Five Years, Institute of Space and Astronautical Science, National Astronomical Observatory, Japan
Spirock, T.J., Yurchyshyn, V.B., & Wang, H., 2002, ApJ, 572, 1072
Su, Y.N., Golub, L., Van Ballegooijen, A.A., & Gros, M., 2006, SoPh, 236, 325
Sudol, J.J., & Harvey, J.W., 2005, ApJ, 635, 647
Thomson, N.R., Rodger, C.J., & Dowden, R.L., 2004, GeoRL, 31, L06803
Wang, H., 1997, SoPh, 176, 163
Wang, H., Spirock, T. J., Qiu, J., Ji, H., Yurchyshyn, V., Moon, Y.-J., Denker, C., & Goode, P. R. 2002a, ApJ, 576, 497
Wang, H., Ji, H., Schmahl, E. J., Qiu, J., Liu, C., & Deng, N. 2002b, ApJ, 580, L177
Wang, H., Liu, C., Qiu, J., Deng, N., Goode, P. R., & Denker, C. 2004a, ApJ, 601, L195
Wang, H., Qiu, J., Jing, J., Spirock, T. J., Yurchyshyn, V., Abramenko, V., Ji, H., & Goode, P. R., 2004b, ApJ, 605, 931
Wang, H., Liu, C., Deng, Y., & Zhang, H., 2005, ApJ, 627, 1031
Wang, H., 2006, ApJ, 649, 490
Wolff, C.L., 1972, ApJ, 176, 833
Woods, T.N., Eparvier, F.G., Fontenla, J., et al., 2004, GeoRL, 31, L10802
Yurchyshyn, V.B., Wang, H., Abramenko, V., Spirock, T. J., & Krucker, S., 2004, ApJ, 605, 546
Zhao, J., & Kosovichev, A.G., 2004, ApJ, 603, 776