Mem. S.A.It. Vol. 82, 149

Memorie della

Magnetic reconnection signatures in the solar atmosphere: results from multi-wavelength observations

F. Zuccarello[1], S. L. Guglielmino[1], and P. Romano[2]

[1] Dipartimento di Fisica e Astronomia – Sezione Astrofisica, Via S. Sofia 78, I-95123 Catania, Italy
[2] Istituto Nazionale di Astrofisica – Osservatorio Astrofisico di Catania, Via S. Sofia 78, I-95123 Catania, Italy e-mail: fzu@oact.inaf.it

Abstract. In the solar atmosphere magnetic reconnection is invoked as the main mechanism causing very energetic events (10^{28} – 10^{32} erg), like flares and coronal mass ejections, as well as other less energetic phenomena, like microflares, X-ray jets and chromospheric surges. In the last decade, thanks to high spatial resolution, multi-wavelength observations carried out by both ground-based telescopes (THEMIS, SST, VTT, DST) and space-born satellites (SOHO, TRACE, RHESSI, HINODE), it has been possible to study these phenomena and several signatures of the occurrence of magnetic reconnection have been singled out. In this paper, we describe some results obtained from the analysis of multi-wavelength observations carried out in the last years, with special emphasis on those events that were characterized by plasma outflows from the reconnection site. The events here discussed are relevant to some active regions observed on the Sun, characterized by the interaction of different bundles of magnetic flux tubes, as a consequence of phenomena of emergence of new magnetic flux from the subphotospheric layers and/or of cancellation of magnetic fragments. We report on these phenomena in order to give a contribution to the possibility to find a similarity with jets observed in AGNs.

Key words. Sun: magnetic fields – Sun: atmosphere

1. Introduction

The processes of current sheet formation and magnetic reconnection are nowadays believed to be at the basis of eruptive solar phenomena, like active prominences, flares and coronal mass ejections. Magnetic reconnection is a topological rearrangement of the magnetic field that occurs when a current sheet forms between differently directed magnetic fields. Here the field lines, brought by plasma flows with velocities lower than the Alfvén velocity, due to the effect of finite resistivity, are cut and finally reconnect (Priest & Forbes 2000). During this process, magnetic energy is converted, by Joule dissipation, into kinetic and thermal plasma energy. The increase of the plasma temperature can cause its emission in different wavelength ranges.

One of the consequences of magnetic reconnection is the outflow of collimated beams

Send offprint requests to: F. Zuccarello

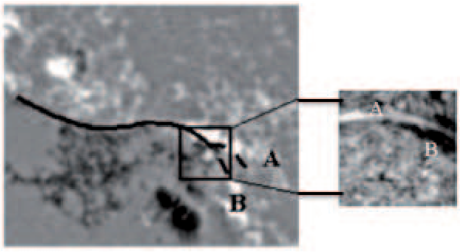


Fig. 1. BBSO high-resolution magnetogram of NOAA 9445 obtained on 5 May 2001, at 16:11 UT. The field of view is 200 × 120 Mm^2. A and B indicate the bifurcate shape of the filament and the location of its threads. The insert, with a field-of-view of 24.5 × 24.5 Mm^2, shows a line-of-sight velocity map, obtained by subtracting a THEMIS blue-shifted image from a red-shifted one, at 17:13 UT. White (black) areas indicate regions where upward (downward) motions are present.

of plasma from the current sheet extremities. In the Sun, observations have shown the presence of plasma jets in sites where magnetic reconnection had likely occurred. These appear as X-ray jets, with speed of about 300 km s^{-1} (Shibata et al. 1992), as well as cooler Hα surges, ejections of plasma with a filamentary structure, characterized by a temperature of about 10^4 K and extending up to 10^5 km, with speed of about 50 km s^{-1} (Kurokawa & Kawai 1993).

Recently, non-stationary plasma jets, observed in AGN environments, have been interpreted in terms of processes of magnetic reconnection (Sikora et al. 2005, 2009). It appears therefore interesting to describe the jets and surges observed in the Sun consequently to reconnection phenomena, to provide some information on these phenomena that might be applicable to the case of the AGNs.

2. Observations of plasma flows and surges in the solar atmosphere

Here we report on three different case-studies concerning some magnetic-related events, observed on the Sun by means of high spatial resolution instruments. During these events many observational findings allowed us to have a confirmation that magnetic reconnection occurred. In particular, plasma jets, more specifically chromospheric surges, have been detected and have been interpreted as a consequence of the reconnection process.

2.1. Bi-directional plasma flows during a filament eruption

The first case-study concerns a filament eruption observed in the Hα line by the Télescope Héliographique pour l'Étude de Magnétisme et des Instabilités Solaires (THEMIS) and by the Big Bear Solar Observatory (BBSO) in active region NOAA 9445 on 5 May, 2001. Moreover, we used line-of-sight magnetograms provided by MDI/SOHO and by BBSO to study the photospheric magnetic field configuration of the active region, as well as TRACE 171 Å images to obtain information on the coronal configuration of the site hosting the filament.

The comparison of MDI and BBSO magnetograms with the Hα images showed that a magnetic fragment emerged laterally to a filament, which later split into two parts. The bifurcation site coincided with the magnetic fragment location. The part of the filament that split was later destabilized and a flare occurred.

The magnetic flux variations in the magnetic fragment and in the surrounding area were analyzed and, considering their trends and other observational signatures (Hα brightenings and associated bi-directional plasma motions, see Fig. 1), we could infer that the magnetic fragment was part of a canceling magnetic feature (CMF).

We determined some geometrical parameters of the CMF (magnetic flux variation, cancellation time, cancellation speed) and by comparing them with those of the low-lying reconnection current sheet given in the model of Litvinenko (1999), we found a good agreement between observed and theoretical values. We concluded that the filament activation and the associated plasma jets observed in the CMF site were triggered by a low-lying magnetic reconnection process (Contarino et al. 2003, 2004).

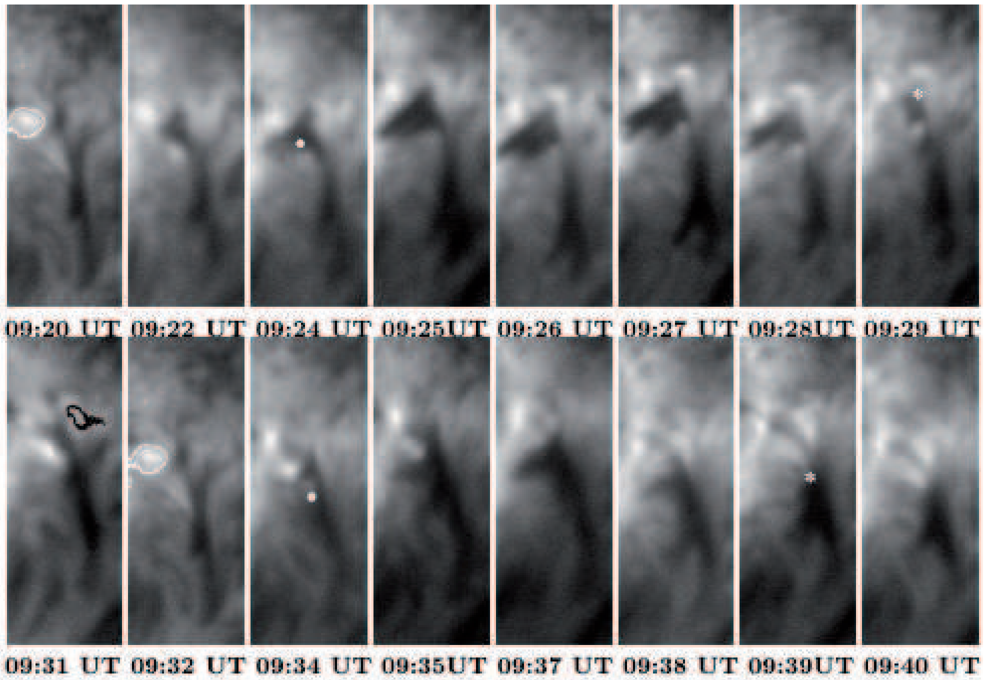
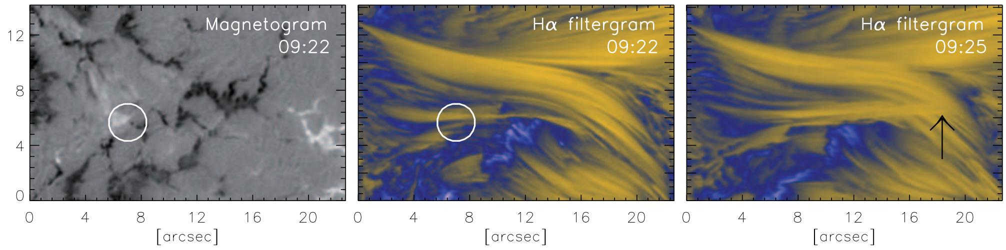


Fig. 2. Successive chromospheric flag-shaped surges ejected from a filament, as observed by the THEMIS telescope in the center of the Hα line during the time interval 9:20 – 9:40 UT on 14 July 2003. North is at the top, West is at right. The flag-shaped surge appears at the northern extremity of the filament at 9:22 UT: it increases its extension in the following images, until it disappears at 9:29 UT. Between 9:35 and 9:38 UT, in the same location observed previously, there is a second flag-shaped surge. These surges occurred as a consequence of a magnetic cancellation event. The circle and the asterisk indicate the points of the maximum upward and downward velocity, respectively. The white (black) contours in the images acquired at 9.20 and 9:32 (9:31) UT indicate a bright area associated with an upward (downward) plasma motion. The field of view is $\sim 10 \times 24$ Mm^2.

2.2. Consecutive surges in an active region filament

The second case-study concerns an active filament that formed in active region NOAA 10407 on 14 July 2003, and the phenomena responsible for its destabilization and short lifetime ($\sim$ 12 h). The sequence of chromospheric images acquired by THEMIS along the Hα profile showed two dark, flag-shaped surges occurring sequentially in the northern part of the filament. In the same area two bright Hα patches were also located (see Fig. 2). From the analysis of the photospheric MDI/SOHO magnetograms, we noticed that a magnetic flux cancellation had occurred in this area. The coronal magnetic field configuration deduced from a linear force-free field extrapolation of the line-of-sight MDI magnetograms, the presence of a CMF in the same area where the dark Hα surges occurred, the temporal behavior of the velocity fields in the surges, and the presence of bright Hα patches in the CMF area, suggest a scenario characterized by a coronal arcade initially sustaining the filament, that later underwent consecutive reconnection processes. From the concurrence of these events with the filament activation and successive disappearance, we deduced that the arcade field lines, after the reconnection events, changed their connectivity, so that the plasma filament was no longer confined in the arcade: this led to its destabilization and disappearance (Zuccarello et al. 2007).



(a) **(b)** **(c)**

Fig. 3. (a): Fe I magnetogram acquired at SST, showing the magnetic field configuration of the region where the emerging flux region (EFR) appeared: white (black) areas indicate positive (negative) fields. The circle indicates the positive polarity of the EFR approaching a network element of opposite polarity. (b) - (c) Sequence showing the evolution of the Hα surge associated with the EFR. The circle in the central (b) image shows the location of the Y-shaped structure. The black arrow in the right (c) image indicates the extent of the surge.

2.3. Chromospheric surge in an Arch Filament System

In a third case-study we analyzed the temporal evolution of an emerging flux region (EFR) appeared in active region NOAA 10971 on 30 September 2007 (Guglielmino et al. 2008, 2010), observed at high spatial resolution with both SST (Swedish Solar Tower) and Hinode. The emergence of the EFR led to the appearance of a chromospheric surge visible in the Hα images acquired at SST (see Fig. 3).

The Hα filtergrams displayed in Fig. 3 show a Y-shaped jet, which originates where the positive emerging magnetic field is pushed against a small network element of opposite polarity. The horizontal velocity of the surge is of the order of 25 km s^{-1}, with a peak of 50 km s^{-1} in the impulsive phase. The cross-point of the surge coincides with a brightening seen in the Ca II H line and in a number of EUV lines. As the extent of the brightness enhancement decreases with increasing formation temperature of the lines, the origin of the brightening is genuinely chromospheric.

The analysis of the light curves in the Ca II H, Hα, X-ray wavelengths clarifies the evolution of the reconnection process which gives rise to the jet. The brightness increase is firstly seen in the low chromosphere, i.e. in the Ca II H line: roughly at the same time the surge sets up (9:20 UT). Then the higher chromosphere is involved (increase in the Hα line) and finally the low corona is excited, as indicated by the presence of a soft X-ray loop with enhanced emission. The X-ray peak appears to be simultaneous with the strongest Ca II H and Hα brightenings, as a further indication of the common origin of the underlying process.

The fact that the onset of the surge is observed during the rising phase of the positive emerging flux in the upper photosphere suggests that the magnetic reconnections process, that supplies the kinetic energy to the surge, occurs firstly in atmospheric layers higher than the low photosphere. The emergence of flux bundles from the subphotospheric layers triggers the reconnection process as the new flux system forming the EFR interacts with the pre-existing field of the active region, as suggested by recent numerical simulations (Archontis et al. 2004).

3. Conclusions

In recent years it has become increasingly clear that the study of physical processes occurring on the Sun can provide useful hints for a better understanding of the phenomena taking place in different astrophysical contexts. Of course, it is important to take into account the differences in the spatial, temporal, and mass scales, but it appears extremely important to have profit from the comparison of solar phenomena with those occurring, e.g., in stellar coronae, in neutron star and black hole X-ray binaries, as well as in supermassive black holes.

Magnetic processes, like the reconnection of field lines, can be deeply investigated on the Sun: the results obtained in these years have indeed indicated that reconnection is the fundamental process for accelerating plasma on the Sun and several authors are trying to extend the results of these studies to the case of binary systems showing activity phenomena (see, e.g., Zhang 2007).

In particular, the physical mechanisms at the basis of collimated jets of plasma in the reconnection sites investigated in the solar context, thanks to high resolution observations carried out in several wavelength bands (Yokoyama & Shibata 1995, Innes et al. 1997), have also been invoked to explain the presence of non-stationary jets of plasma observed in black holes surrounded by accretion disks (Yuan et al. 2009).

In this paper we have highlighted the importance of the interaction of different bundles of magnetic field lines that can give rise to reconnection processes and to jets/surges formation in the Sun. This information might therefore contribute to the interpretation of plasma jets observed in AGNs environments in the framework of the magnetic reconnection scenario.

The interaction between different bundles of magnetic field lines likely occurs *inside* an accretion disk, where magnetic flux tubes are formed, with a mechanism similar to that observed in the solar case.

In AGNs there can be a *further* mechanism able to create current sheets in those systems having an accretion disk: structures like streamers might form between the magnetic field of the disk and that of a central object, when the two bundles of field lines, anchored in the accretion disk and in the central object respectively, are directed in opposite directions (see, e.g., Fig. 11 in de Gouveia Dal Pino 2005).

A quantitative estimate requires further investigations and a comparison between the results of observations and numerical simulations, both in the Sun and in other astrophysical environments of interest.

Acknowledgements. This work was supported by the European Commission through the SOLAIRE Network (MRTN-CT-2006-035484), by the Catania University, by the Istituto Nazionale di Astrofisica (INAF) and by the Agenzia Spaziale Italiana (contract I/035/05/0). The authors wish to thank Dr. M. Massi for helpful discussion.

References

Alissandrakis, C. E. 1981, A&A, 100, 197

Archontis, V., Moreno-Insertis, F., Galsgaard, K., Hood, A., & O'Shea, E. 2004, A&A, 426, 1047

Contarino, L., Romano, P., Yurchyshyn, V. B., Zuccarello, F. 2003, Solar Phys., 216, 173

Contarino, L., Romano, P., Zuccarello, F. 2004, Astron. Nach., 327

de Gouveia Dal Pino, E.M. 2005, Advances in Space Research 35, 908

Guglielmino, S. L., Zuccarello, F., Romano, P. & Bellot Rubio, L. R. 2008, ApJ, 688, L111

Guglielmino, S. L., Bellot Rubio, L. R., Zuccarello, F., Aulanier, G., Vargas Domínguez, S. & Kamio, S. 2010, ApJ, in press

Kurokawa, H. & Kawai, G. 1993, IAU Colloq. 141: The Magnetic and Velocity Fields of Solar Active Regions, 46, 507

Innes, D. E., Inhester, B., Axford, W. I., & Wilhelm, K. 1997, Nature, 386, 811

Litvinenko, Y. E. 1999, ApJ, 515, 435

Priest, E. R. & Forbes, T. G. 2000, Magnetic Reconnection: MHD Theory and Applications, Cambridge Univ. Press

Sikora, M., Begelman, M.C., Madejski, G. M., & Lasota, J.-P. 2005, ApJ, 625, 72

Sikora, M., Stawarz, L., Moderski, R., Nalewajko, K., & Madejski, G. M. 2009, ApJ, 704, 38

Shibata, K., et al. 1992, PASJ, 44, L173

Yokoyama, T. & Shibata, K. 1995, Nature, 375, 42

Yuan, F., Lin, J., Wu, K., & Ho, L. C. 2009, Mon. Not. R. Astron. Soc., 395, 2183

Zhang, S. N. 2006, Highlights of Astronomy, 14, 119

Zuccarello, F., Battiato, V., Contarino, L., Guglielmino, S. L., Romano, P., Spadaro, D. 2007, A&A, 488, 1117