ABSTRACT

Multi-instrument data sets of NOAA AR10938 on 2007 January 16 (e.g., Hinode, STEREO, GOES, MLSO, and ISOON Ha) are utilized to study the fine structure and evolution of a magnetic loop system exhibiting multiple crossing threads, whose arrangement and individual shapes are very suggestive of individual field lines in a flux rope. The footpoints of the magnetic threads are closely rooted into pores and plage areas. A C-class flare recorded by GOES at approximately 2:35 UT near one of the footpoints of the multi-thread system (along with a wisp of loop material shown by EUV data) led to the brightening of the magnetic structure revealing its fine structure with several threads that indicate a high degree of linking (suggesting a left-handed helical pattern as shown by the filament structure formed later on). EUV observations by Hinode/EIS of hot spectral lines at 2:46 UT show a complex structure of coronal loops. The same features were observed about 20 minutes later in X-ray images from Hinode/XRT and about 30 minutes further in EUV images of STEREO/SECCHI/EUVI with much better resolution. Ha and 304 Å images revealed the presence of several filament fibrils in the same area. They evolved a few hours later into a denser structure seemingly showing a helical pattern, which persisted or several days forming a segment of a larger-scale filament. The present observations provide an important indication for a flux rope as a precursor of a solar filament.

Key words: methods; data analysis – Sun: activity – Sun: corona – Sun: magnetic fields – Sun: UV radiation – Sun: X-rays, gamma rays

1. INTRODUCTION

Most solar atmospheric features with varying degrees of complexity (i.e., active regions, prominences, filaments, loops, etc) are thought to be shaped by magnetic fields emerging from the solar interior due to buoyancy instability (Parker 1984). The complex topologies (twist, writhe, linking, and shear) of emerging flux tubes are key ingredients for numerous theoretical studies of solar eruptions resulting from magnetic reconnection (prominences, filaments, flares; see Linton et al. 1998, 2001). In fact, highly twisted flux tubes store magnetic energy that is necessary for the heating and acceleration of the plasma in the erupting structures. X-ray observations have shown that the majority of the active regions leading to coronal mass ejections (CMEs) have an S-shaped structure (Canfield et al. 1999). Amari et al. (2000) studied the crucial role played by twisted flux tubes in the formation of topologically complex flux ropes and their evolution into solar eruptive phenomena, such as CMEs.

Simulations of flux emergence from the convective zone into the upper atmosphere showed that untwisted flux tubes suffer convective stresses leading to their fragmentation and impeding their emergence to the upper atmosphere (Schüssler 1979; Longcope et al. 1996). It has been found that some degree of twist in rising flux tubes is needed to avoid the conversion of the tube into vortex pairs (Moreno-Insertis & Emont 1996). It has also been reported that the flux reaching the upper atmosphere depends on both the field strength at the bottom of the convective zone (simulation box) and the degree of twist of the rising flux tube (Martinez-Sykora et al. 2008).

Different mechanisms have been invoked to be at the origin of the twist of rising flux tubes: (1) helical turbulent motions (Longcope et al. 1998); (2) Coriolis force (Fan & Gong 2000); (3) differential rotation (Devore 2000); (4) helicity generation by the solar dynamo (Seeber et al. 2003); (5) turbulent diffusion of wrapped poloidal flux into the rising flux tube (Chatterjee et al. 2006). Measurements of the magnetic field vector in sunspots have shown that the magnetic field has a preferential helicity sign in both hemispheres (negative in the north and positive in the south; see Seeber 1999; Pevtsov et al. 1995, 2001). Lites et al. (1995) studied the topology of the emerging flux tube in a δ-sunspot, and found a rather simple structure at the start with increasing topological complexity. Leka et al. (1996) found that proper motions imply that flux bundles are twisted before they emerge. In the last few decades particular attention has been paid to coronal filaments and prominences, which can erupt into CMEs. At the chromospheric level, they are characterized by a channel of fibrils with the filament spine, if present, lying above. An EUV or X-ray arcade of loops forms a “transverse” dome relative to the filament spine with a cavity separating both structures (see Martin 1998 for a review). Numerous studies were dedicated to characterize the formation and evolution of these structures. Resolving the fine structure of these structures is important to understand the mechanisms leading to their eruption and to constrain models. Li et al. (1998) studied the fine structure of filaments through the interpretation of spectroscopic observations. They found evidence for the presence of two dynamically different threads with different thermodynamic properties. Pojoga et al. (1998) compared prominence spectra to models taking into account the radiative transfer effect. They found different structures with different optic opacity along the line of sight. Although resolving observationally the fine structure of filaments and prominences proved to be difficult to achieve, Chae (2000) used EUV observations to study qualitatively the chirality of filaments through the crossing topology of bright and dark threads.

The active region NOAA AR10938 is the area of interest for the present study. On 2007 January 16, it was located approximately at N02E30. Multi-instrument observations, mainly from the Hinode (Kosugi et al. 2007) and the Solar Terrestrial Relations Observatory (STEREO: Kaiser et al. 2008)
missions, are utilized to study the formation and evolution of a loop system that is highly suggestive of a flux rope.

2. OBSERVATIONS

The Hinode Extreme UV Imaging Spectrometer (EIS: Culhane et al. 2007) carried out three raster sequences of AR10938 on 2007 January 16, at 1:54 UT, 2:20 UT, and 2:46 UT with a 1″ slit. The observations were acquired in a number of spectral lines whose formation temperatures span a range from \( \sim 0.08 \) to \( \sim 15 \) MK.

The Hinode Solar Optical Telescope (SOT: Tsuneta et al. 2008) filtergram (hereafter SOT-FG) and X-Ray Telescope (XRT: Golub et al. 2007) were observing the active region jointly, within the same time intervals and with comparable temporal cadence, on 2007 January 15–16. High-resolution LOS-magnetograms from SOT-FG are utilized to study the photospheric evolution of magnetic flux (emergence and dynamics). The data are recorded on 2007 January 15 10:57–15:51 UT and 22:18 UT until 2007 January 16 5:59 UT with a temporal cadence of approximately 1 minute. XRT observations (Al-poly filter: \( \log T \approx 5.5 - 8.0 \), with maximum around 6.9) along with STEREO/SECCHI/EUVI (Howard et al. 2008, hereafter EUVI) data provide a proxy of the topology of the different coronal loop systems.

EUVI-A was recording with a time cadence of 10 minutes in both 171 Å and 195 Å, while EUVI-B was observing hourly. Since these observations were recorded soon after the STEREO launch, the angular separation of the two satellites was very small and three-dimensional reconstruction of the observed structures is not possible. Thus, we limit ourselves to EUVI-A observations. EUVI-A 304 Å images, which are taken with a lower time cadence, are also used to study cool counterpart structures in relation to X-ray and EUV ones.

Additional data from other instruments (GOES, SOHO/EIT, ISOON) are also utilized to acquire complementary information on the activity level of AR10938. They are, however, not presented here.

3. RESULTS

Figure 1 displays a LOS-photospheric magnetogram from SOT-FG of AR10938. The triangles depict the footpoints’ locations of the different threads forming the magnetic structure suggesting the presence of the twisted coronal flux rope. The different threads are rooted in pores and plage areas at both ends. The middle panel shows a difference map of the unsigned of magnetic flux between 3:10 UT and 3:00 UT 2007 January 16. It is clear that significant changes occur in the regions near the loops’ footpoints. For instance, the large changes occur within the positive and negative polarity regions in the left-central area and toward the bottom-right corner of the map, respectively. Flux changes elsewhere in the map are not as important. This trend persisted for several hours. The bottom panel exhibits the temporal evolution of the magnetic flux. Similar variations are obtained for the areas where the important changes occurred. The flux fluctuations are indicative of changes in the magnetic field topology, in particular in the areas where the threaded magnetic structure is rooted. Starting from 23:00 UT, an overall increase in the total flux (and also that of both polarities) is found until approximately 1:30 UT when a significant decrease coincided with increasing coronal activity.

GOES recorded 12 X-ray bursts that occurred in AR10938 between 14:00 UT 2007 January 15 and 16:00 UT 2007 January 16. The most prominent one (a C-class flare) occurred on January 16 at approximately 2:35 UT. White light coronagraphs STEREO/SECCHI/COR1 & COR2 Howard et al. (2008) and SOHO/LASCO Brueckner et al. (1995) did not detect any CME material in relation to the C-class flare. On the other hand, EUVI images show a material wisp, very likely in conjunction with the flare.

EIS raster sequence performed at 2:46 UT reveals enhanced emissions in hot lines (Fe xxiv 255.1 Å: \( \log T = 7.2 \); Ca xvii 192.82 Å: \( \log T = 6.7 \); Fe xvi 262.98 Å: \( \log T = 6.4 \); and Fe xv 284.16 Å: \( \log T = 6.3 \)). These emissions show a relatively complex system of loops with northeast–southwest direction (footpoint locations are indicated in Figure 1).
The X-ray data recorded simultaneously with the SOT-FG photospheric magnetograms show rapidly evolving coronal loop structures. The top panels of Figure 2 display snapshots illustrating the development of the active region AR10938. The bottom panels show the same structures with enhanced contrast after application of wavelet filtering as described by Stenborg & Cobelli (2003). Different loop systems are expanding rapidly in the corona with relatively simple topology, i.e., loops toward the bottom of the different panels of Figure 2. However, the bright loop system within the white box in Figure 2(b) is of particular interest. It had an apparent simpler topology shown by X-ray data recorded earlier (10:57 UT–15:51 UT 2007 January 15). The occurrence of the structure within the white box (Figure 2(b)), that is extending from northeast (−585″,120″) into southwest (−515″,80″), preceded the brightening of several other loops (see Figure 2(c)) forming a rather complex pattern. The features of the X-ray system compare relatively well to those observed in hot line emissions observed by EIS.

EUVI-A 171 Å (Figure 3) and 195 Å images recorded roughly between 3:00 UT and 4:00 UT show the relatively cooler (∼1 MK) counterpart of the loop system observed by EIS and XRT (see Figure 2). The system developed rapidly within a time interval of about 30 minutes, as shown in Figures 3(b)–(d).

Figure 3(d) shows the fully developed complex topology of the threaded system. A number of the new EUV loops do not correspond necessarily to those observed earlier, as was
the case of the X-rays with respect to the EIS ones. The topology of the different threads indicates a high degree of linking, suggesting the presence of a twisted flux rope (see Figures 3(c)–(d)). Figure 3(c) displays bright loops seemingly with a left-handed helical pattern as suggested by the presence of an inverse S-shaped filament (see Figure 4(e); Rust & Martin 1994). The system evolved further as a number of loops dimmed and disappeared later. Other seemingly higher loop systems brightened later, as shown in Figure 3(f). These show some similarities with X-ray loops that appeared earlier (see Figure 2(d)).

The sequential appearances of the suggested flux rope in hot emission lines (e.g., Fe xxiv 225.1 Å, log T = 7.2), then in X-ray images (a few MK), and finally in EUV 171 Å and 195 Å images (~1 MK) show the gradual cooling of the magnetic structure and display details of its fine structure. A sheared arcade of loops is also seen seemingly crossing from above the indicated flux rope in 171 Å and 195 Å images (Figure 3(f)). A similar arcade was also seen prior to the flare and the appearance of the magnetic thread system.

EUVI-A 304 Å images reveal the presence of fibrils along the path of the magnetic thread structure observed in EUV and X-ray data. These fibrils, also seen in Hα from Mauna Loa Solar Observatory and ISOON-Sac-Peak, were present several hours before the appearance of the multiple crossing thread system. These are probably part of a larger structure forming an inverted S-shape (see Figures 4(a)–(b)) extending along the neutral line across AR10938. This is well developed north to the active region and is of filamentary nature within and south of the same active region. 304 Å data reveal a denser structure along the location of the indicated flux rope that formed few hours later with an apparent helical pattern (see Figure 4(d)). The presence of the filament was more prominent over the next few days, in particular on 2007 January 18 (see Figures 4(e)–(f)). We believe this is a segment of the larger filament structure. Hα images showed also the presence of prominence activity coinciding with the presence of the active region at the west limb on 2007 January 24–26.

4. CONCLUSIONS AND DISCUSSION

Multi-instrument observations of the active region NOAA AR10938 on 2007 January 16 provide evidence for a magnetic thread system with a complex, multiple crossing topology, which is highly suggestive of a flux rope. A C-class flare in the active region AR10938 led to the brightening of the magnetic structure showing its fine structure in an unprecedented manner. The fine structure of the magnetic system is best seen in XRT images at approximately 3:00 UT and with better contrast in EUVI-A 171 Å and 195 Å data at about 3:30 UT. It is very unlikely that the observed complex topology is the result of projection effects. XRT data suggest that the indicated flux rope was present prior to the flare and its appearance is the result of heating processes related to the flare eruption. This led to emissions in hot spectral lines observed by EIS, followed by a cooling phase through X-rays and EUV, and ultimately the gradual disappearance of the system.

Hα and 304 Å data reveal the presence of dark fibrils aligned along the suggested flux rope. These structures were present before the appearance of the magnetic thread system. The X-ray and EUV threads suggest a high degree of linking as shown by the formation of a segment of an inverse S-shaped filament in the same location later on conveying a left-handed helical pattern for the loop system. We believe that the dark fibrils are part of a filament channel and the indicated flux rope
is a segment of the filament. The latter runs along the neutral line across the active region. It is well developed north of AR10938 and of filamentary nature elsewhere. This is supported by the presence of a loop arcade presumably lying above the multi-thread system, which is necessary for the formation of filaments. 304 Å observations show a dark, denser structure that formed about 8 hr after the brightening of the suggested flux rope. This evolved further into a wider feature in the following days, reflecting the formation of the filament which is also supported by the presence of prominences when the active region was near the solar limb.

The present study should be useful for constraining models of filament formation. The role of the magnetic field topology, in terms of twist and shear, is a matter of debate concerning the processes of filament formation. An important aspect is how and when (with respect to the eruptive phase of filaments) the processes of filament formation remain unclear.

It is likely that the flux tube emerged twisted from the convection zone. Photospheric shear motions may also contribute to the twist of the flux tube. However, shear transfer during the flare, which led to the brightening of the thread system, may be more plausible. The shear within the non-eruptive flaring structure should remain within the system. The only plausible way for this to happen is to increase the topological complexity of neighboring magnetic structures. A more detailed study of the dynamics within the active region is needed, and will be carried out in the future.

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