

## The May 13, 2005 Eruption: Observations, Data Analysis and Interpretation

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**Abstract.** In this study we present detailed description and analysis of the May 13, 2005 eruption, the corresponding coronal mass ejection (CME) and intense geomagnetic storm observed near the Earth on May 15, 2005. This isolated two-ribbon M8.0 flare and the very fast CME occurred in a relatively simple magnetic configuration during a quiet period of solar activity, which enabled us to reliably associate the solar surface event with its counterpart observed in the Earth magnetosphere. In our study we utilized i) various tools to analyze a multi-wavelength data set that includes ground (BBSO vector magnetograms, H<sub>α</sub>) and space (SOHO, TRACE, RHESSI and ACE) based data; ii) linear force free modeling to reconstruct the coronal field above the active region and iii) erupting flux rope (EFR) model to simulate a near Sun halo CME and a near Earth interplanetary CME (ICME). Our findings indicate that persisting converging and shearing motions near the main neutral line could lead to the formation of twisted core fields and eventually their eruption via reconnection. In the discussed scenario the in-situ formed erupting loop can be observed as a magnetic cloud (MC) when it reaches the Earth. The EFR model was able to produce both a model halo CME and ICME providing a good global match to the overall timing and components of the magnetic field in the observed MC. The orientation of the model ICME and the sense of the twist, inferred from the EFR model, agree well with the orientation and the magnetic helicity found in the source active region.

### Introduction

Shortly after coronal mass ejections (CME) were discovered (Tousey 1973; MacQueen et al., 1974; Gosling et al., 1974), it was found that Earth directed ejecta are related to the occurrence of geomagnetic storms (Burlaga et al., 1981; Wilson and Hildner, 1984). The primary cause of these intense storms are disturbances in the solar wind which are observed as long intervals of strong southwardly directed interplanetary magnetic field (IMF) supplied by CMEs (Rostoker and Fälthammar, 1967; Russell et al., 1974; Tsurutani et al., 1992).

In this paper we present detailed description and analysis of the May 13, 2005 eruption in NOAA AR 0759 and associated coronal and interplanetary phenomena. Because the solar and heliospheric

background conditions were relatively simple for this event, it was possible to unambiguously relate the solar surface event and the associated interplanetary disturbance that caused a strong geomagnetic storm (KYOTO provisional Dst<sub>min</sub> index = -263nT). In our study we utilized i) a multi-wavelength data set that includes ground (BBSO vector magnetograms, H<sub>α</sub>) and space (SOHO, TRACE, RHESSI and ACE) based data; ii) linear force free modeling to reconstruct the coronal fields above the active region and iii) emerging flux rope model to simulate a near Sun halo CME and near Earth interplanetary CME as well as to compare the simulations to the overall timing of the event and to the various field components as observed by ACE satellite.

## Solar Data and Analysis

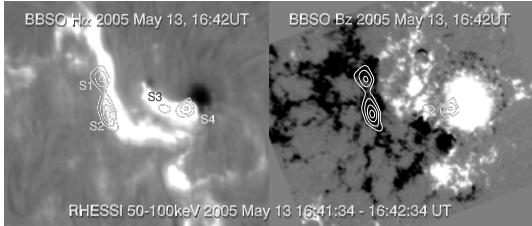


Fig. 1. Partial frame of BBSO full disk H $\alpha$  image (left) and a line of sight magnetogram (right) taken at 16:42 UT. Contours show RHESSI hard X-ray emission in 50-100keV energy band accumulated from 16:41:34 to 16:42:34 UT. Field of view is 230x95 arcsec. North is up, west is to the right.

The eruption that began at 16:03 UT on May 13, 2005 in AR NOAA 0759 was associated with a fast halo CME and an intense geomagnetic storm ( $D_{st\min} = -263$ nT) that commenced on early May 15th. In Figure 1 we show BBSO H $\alpha$  image of the flare and a line of sight magnetogram taken at 16:42 UT during the impulsive phase. The images indicate that this was a typical two ribbon flare that developed in a bi-polar magnetic configuration. The east ribbon was located in an area of negative magnetic fields (black), while the west ribbon was largely associated with the main sunspot of positive polarity. This sunspot displayed a spiral structure with left-handed twist, indicating negative helicity. According to H $\alpha$  data, the extended north-south oriented FN filament seen in the upper part of Figure 3 (right), did activate about 30 min prior the eruption and it became darker and bigger. With the onset of strong flare emission at 16:31 UT the filament mostly ceased to be observed in H $\alpha$  spectral line, however, faint traces of it could be seen throughout the entire length of the flare (see also Fig. 3 in Qiu and Yurchyshyn (2005)). This H $\alpha$  filament restored its shape and appearance before the flare was over. As to the FS filament, it did not exhibit any significant signs of activation

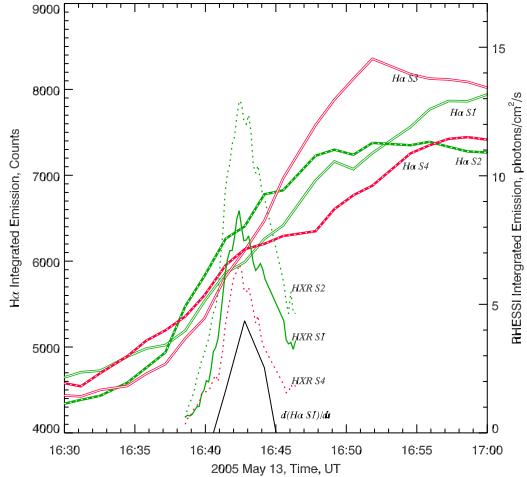


Fig. 2. Light curves for the M8.0 May 13, 2005 flare. Thick lines, denoted with "H $\alpha$ ", represent H $\alpha$  light curves (left axis) determined in the areas covered by RHESSI HXR sources S1-S4 (see Fig. 1). RHESSI light curves (right axis) are shown with thin lines denoted with "HXR". Black solid line is the time derivative of the light curve from H $\alpha$  source S1. For display purposes the true values of the derivative were divided by 2.3

prior to the event, however after the flare peak it became obvious that the shape of the filament has changed: its southern extreme was now curved toward west, pointing to the main sunspot (see dashed line in Figure 3 (right) and compare panels *a* and *c* in Figure 3 in Qiu and Yurchyshyn (2005)).

### Time profiles of H $\alpha$ and RHESSI flare emission

The May 13 flare was associated with strong H $\alpha$  emission from two flare ribbons (Figure 1, left) as well as four RHESSI hard X-ray (HXR) sources that could be detected in a broad 25-100 keV energy band (noted in Figure 1 as S1, S2, S3 and S4). Contours in Figure 1 show RHESSI HXR emission integrated between 16:41:34 and 16:42:34 UT. S1 and S2 sources were located inside the eastern flare ribbon and relatively strong (-200...-350 G) negative polarity fields, while

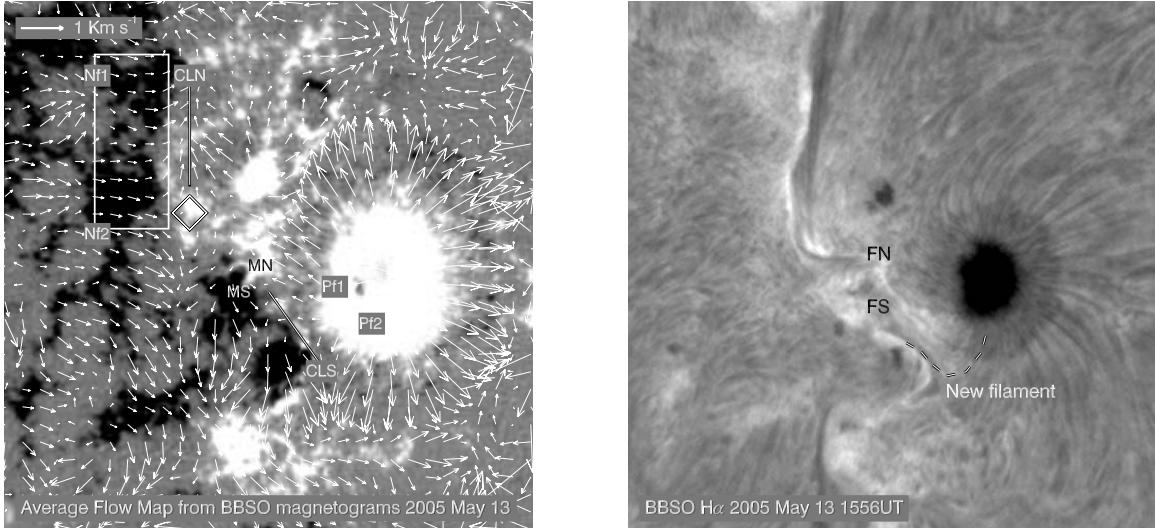


Fig. 3. Left: Averaged flow map calculated from 107 BBSO line of sight magnetograms recorded between 15:43 and 19:44 UT on May 13, 2005. The maximum velocity in the sunspot moat just north the main sunspot is approximately  $1 \text{ km s}^{-1}$ , r.m.s.= $300 \text{ m s}^{-1}$ . The rectangle indicates the position of RHESSI HXR sources S1 and S2, CLN and CLS are lines of converging horizontal flows, the diamond indicates the stagnation point and MN and MS mark the areas where the northern and southern filaments are rooted (see right panel). Right: BBSO H $\alpha$  image taken at 15:56 UT prior the flare onset. The flare ribbons developed along the northern (FN) and southern (FS) filaments. The dashed curve indicates the new location of the FS filament (see text).

S3 and S4 were within the positive polarity ( $300\ldots450\text{G}$ ) penumbra of the main sunspot. Figure 2 shows time profiles of H $\alpha$  emission (H $\alpha$  S1-S4, thick double lines) calculated over the areas covered by the RHESSI sources. The three overlaid curves that peak at 16:42:30 UT (thin lines) correspond to the HXR time profiles from S1, S2 and S4 sources. Emission from S3 was relatively weak and is not shown in this graph. Cleaned RHESSI images with a 10 s cadence (integrated over 60s period) and  $9.8''$  FWHM resolution (using grids 3-9) were used to generate the image sequence and to derive the light curves of the HXR emission. The graph shows that the impulsive phase of the H $\alpha$  flare started at about 16:31 UT and the time profiles from all four H $\alpha$  areas are similar. The lower curve shows the time derivative,  $d(\text{H}\alpha\text{S1})/dt$ , calculated from H $\alpha$ S1 light curve, which corresponds very well to the HXR time profiles implying that chromospheric plasma heating and subsequent H $\alpha$  emission was caused by fast electrons accelerated at the reconnection site

(Neupert, 1968; Dennis and Zarro, 1993). We note, that in order to make this graph less busy we do not plot here time derivatives from the other 3 H $\alpha$  sources, which are similar to that shown in Figure 2. The simple structure of the flare emission, similarity between all four H $\alpha$  and RHESSI time profiles, as well as the fact that the time derivative of H $\alpha$  emission coincides in time with the position of the HXR peaks, all indicate that this flare could be caused by reconnection between two independent magnetic flux systems, as opposed to reconnection between multiple flux systems suggested, e.g., in the break-out model (Antiochos 1998; Antiochos et al., 1999). Examples of complex flare emission can be found in Yurchyshyn et al., (2004; 2006).

#### Horizontal Plasma Flow

Figure 3 shows an average flow map calculated from BBSO line-of-sight magnetograms that cover an extended period of time (15:43 - 19:44 UT). This period includes both pre and post flare evolution. The final map was generated by averaging

106 individual flow maps produced by local correlation tracking technique (November and Simon, 1988) with the FWHM of the tracking window of  $6 \times 6$  arcsec and a 1 min correlation interval. This averaged flow map therefore represents large scale and persisting plasma flows.

The white rectangle in the figure marks the location of RHESSI HXR sources S1 and S2 that were associated with negative polarity magnetic fields Nf1 and Nf2. Pf1 and Pf2 indicate the location of S3 and S4 sources and refer to the positive magnetic polarity associated with them. The two dark filaments FN and FS, seen in the pre-flare H $\alpha$  image (Figure 3), had one of their foot points anchored in the vicinity of MN and MS magnetic concentrations (Figure 3, left panel). These polarities are connected by a system of dark arches, which indicates that MN and MS most probably composed one magnetic dipole. This dipole was observed on the day prior to the flare and therefore can not be considered as a rapidly emerging flux.

The most intense horizontal flows were observed in the moat that surrounds the sunspot penumbra. The moat outflow reached speeds of about  $1 \text{ km s}^{-1}$ , while elsewhere the intensity of the flow varied in the range of  $100 - 300 \text{ m s}^{-1}$ . The flow pattern in the vicinity of the major neutral line (NL) has two components: converging and shearing flows. Segments of double black lines in Figure 3 indicate two convergence lines, CLN and CLS, where oppositely directed flows, associated with the negative polarity fields and the main sunspot, merge. The converging flows at the CLS line are not as evident as at the CLN line due insufficient spatial resolution of the flow map and complex pattern of small scale motions. The radial moat outflow from the main sunspot in the SE direction stops at the negative field concentration, which was moving perpendicular (in the SW direction) to this radial outflow. Although this flow interaction does not exhibit the classical

converging pattern it, nevertheless, promotes magnetic field cancellation and magnetic stress build up. The converging lines are separated by a stagnation point in the flow pattern (diamond) and a dipole MN-MS. CLN line is slightly displaced from the main NL and has a shear component directed northward, while CLS has a southward component. The converging and shearing motions that are seen at two different converging lines may be indicative that two independent systems of helical magnetic fields could form above the CLN and CLS neutral lines due to the cancellation process as suggested by van Ballegooijen and Martens (1989) and further explored by Linker et al. (2005) and Welsch (2006).

### **Vector Magnetograms and Electric Currents**

BBSO Digital Vector Magnetograph (DMG) fully covered the event and produced a set of 1 min cadence vector magnetograms with 0.6 arcsec pixel size. Figure 4 shows an example of DMG data taken before the flare onset at 15:43 UT. In general, the active region had a relatively simple magnetic configuration with smooth variations of the transverse field. The main spot was uniformly twisted counter clockwise (negative helicity). Due to insufficient sensitivity of the instrument, magnetic field measurements within the sunspot umbra are not reliable. The 180 degree ambiguity was resolved by applying a potential field method (Abramenko 1986). Recent study in the framework of SDO/HMI-CSAC Azimuth Ambiguity Resolution Workshop (Metcalf et al., 2006) showed that this method can correctly resolve ambiguity for about 90% of strong transverse magnetic fields, which makes it quite applicable in cases of simple magnetic configurations . Vector magnetogram data were used to calculate density distribution of vertical electric currents in the active region. Thus, Figure 5 shows that highest current density was associated with two small negative

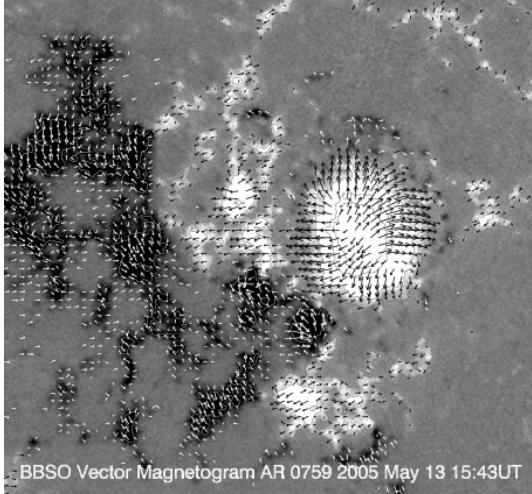


Fig. 4. 15:43 UT BBSO vector magnetogram resolved for 180 deg ambiguity.

polarity magnetic concentrations just SE of the main sunspot. This area was also the location of strong converging flows at the CLS line (Figure 3). Note that the "O"-shaped structure in the center of the sunspot is an artifact caused by the insufficient counts inside the very dark umbra. Contours, plotted over the current density map, show the location of RHESSI HXR emission and it appears that these HXR sources were not co-located with strong electric current densities, which agrees with earlier reports (de La Beaujardiere, Canfield, and Leka, 1993; Leka et al., 1993).

Earlier, Abramenko, Gopasik, and Ogor (1991; 1993) reported that the intensity and the lifetime of H $\alpha$  and HXR flare emission, associated with upward currents, were found to be higher than those associated with downward currents. Authors suggested that upward currents could contribute to the acceleration of electrons traveling downward to the photosphere and thus enhance flare emission in those places. In this context, we calculated the net current over the area covered by HXR sources S1, S2, S3 and S4. Thus, electric current imbalance inside the combined area S1+S2 was about 20% and the upwardly directed net current was about  $2.5 \times 10^{11}$  A. The current imbalance in the area S3+S4 was -4%

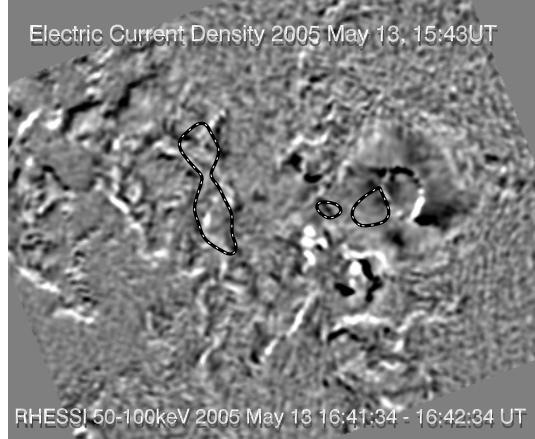


Fig. 5. Distribution of electric current density calculated from the 15:43 UT vector magnetogram. Black/white corresponds to  $9000$  Am $^2$ . Positive (white) currents are upward. Contour lines show RHESSI hard X-ray emission in the 50-100keV energy band accumulated from 16:41:34 to 16:42:34 UT. Field of view is 230x195 arcsec. Solar north is up, east is to the left.

and the downward net current was about  $-4.3 \times 10^4$  A. Note, that S1 and S2 sources were the most intense (see Figure 2) and that the net current associated with them was upward. These results, therefore, support the earlier idea that strong upward electric currents could supply additional energy to the downward moving electrons thus causing asymmetry of the X-ray flare emission at the foot points of the flare loops.

### Structure of Magnetic Fields

Figure 6 shows coronal magnetic fields above the active region as seen in the pre-flare TRACE 171Å image taken at 12:58UT. Here, positive and negative magnetic fields associated with RHESSI HXR sources S1 - S4 are marked by Pf1, Pf2, Nf1, Nf2. Three main features can be distinguished in this image (see also the inset): i) rising, bright, reverse "S" shaped fields, indicated by the black and white dotted curve and located above the dark FN H $\alpha$  filament (Figure 3); ii) two bright loop systems rooted at Pf1-Nf1 and Pf2-Nf2 and iii) two low density voids encompassed by the loop systems Pf1--Nf1 and Pf2--Nf2. We thus speculate that these

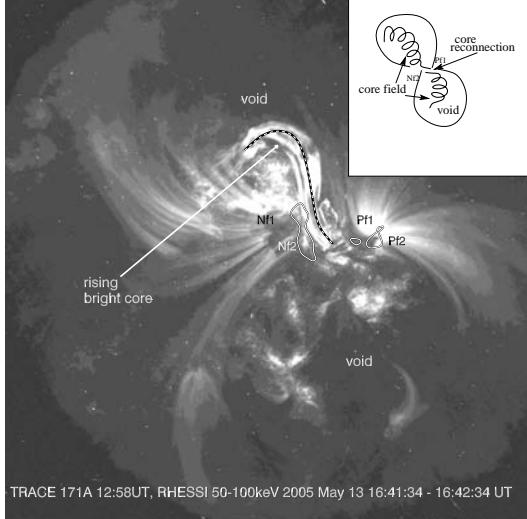


Fig. 6. 12:58UT TRACE 171Å image. Contours show RHESSI hard X-ray emission in 50-100keV energy band accumulated from 16:41:34 to 16:42:34 UT. The black and white curve traces the reverse “S” shaped rising bright core. Inset shows that this magnetic configuration could contain flux ropes suspended above neutral lines and surrounded by large-scale coronal fields. Please, note that the number of turns in the core fields is exaggerated.

structures in the TRACE 171Å image are indicative of a flux rope(s) present in the active region.

We used a linear force free method (Abramenko and Yurchyshyn 1996) to model the coronal field above the active region. A 16:03 UT full disk MDI magnetogram (Figure 7, background) was used as a photospheric boundary condition and we further assumed that the magnetic field was in the potential state everywhere on non-photospheric boundaries of a 3D volume. The numerical solution was obtained for a volume of size 156x204x243 arcsec with the size of a grid cell of 1.98x1.98x2.79 arcsec. The best fit between the field-line features in the TRACE image and the model field lines was obtained with the parameter  $\alpha = -0.025 \text{arcsec}^{-1}$ .

In Figure 7 we show modeled force lines that originate within the SE part of the sunspot (locations of HXR sources S3 and S4 and the west flare ribbon) and divided into

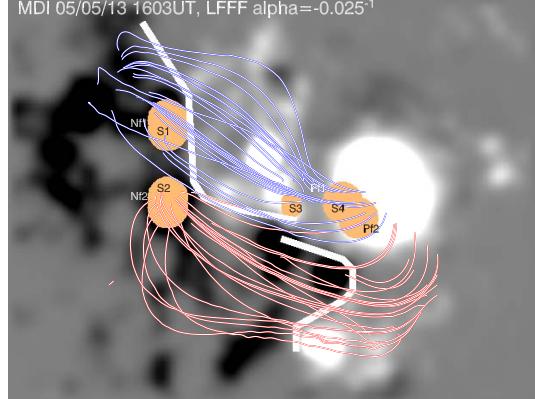


Fig. 7. Background: A partial frame of an MDI full disk magnetogram of AR NOAA 0759 recorded at 16:03 UT. Over-plotted force lines are calculated from a linear force free model with parameter  $\alpha = -0.025 \text{arcsec}^{-1}$ . Filled areas mark the location of RHESSI HXR sources S1-S4 (see also Fig. 1). Two thick white lines indicate the location of H $\alpha$  filaments FN and FS. The blue cylinder in the upper right corner shows directions of the axial and azimuthal fields in a model MC derived from the erupting flux rope model (see Section 3.2).

two groups depending on where these field lines end. Thus, the model indicates that source S4 could be located in a region which was common to the foot points for two otherwise-independent magnetic flux systems, while their other foot points were separated and associated with S1 and S2 sources. This inference is supported by Figure 6 which shows that the two different TRACE loop systems, described above, are rooted at Pf1 and Pf2 and share one common RHESSI source S4 (contour), while their other foot points, anchored at Nf1 and Nf2, were associated with S1 and S2.

We further speculate that converging and shearing flows could, according to the cancellation model (van Ballegooijen and Martens 1989), lead to formation of these two systems of independent magnetic loops and to the build up of free magnetic energy in the coronal field (Welsch 2006). As the flux strengthens due to continuous inflows it may slowly expand and rise above the

photosphere due to loss of stability and transition to a neighboring state of equilibrium. Note that the time scale of flux injection into a flux rope via cancellation process is rather large and thus allows the magnetic configuration to "absorb" the new flux without catastrophic eruptions. Thus, the pre-flare TRACE image shows that the bright dense core, which is seen suspended above the neutral line in the 12:58 UT TRACE 171Å frame became active and started its slow ascent as early as 12:00 UT. The persistent converging flows could drive the magnetic configuration to a critical state when gradual changes at the photospheric magnetic boundary could no longer be accommodated by quasi-steady evolution of coronal fields.

Therefore we suggest that the May 13 eruption proceeded according to the tether-cutting model (Moore and LaBonte 1980) where the eruption between the two independent sheared flux systems was initiated due to reconnection process in the core field, which gradually involved large scale fields enveloping the core field. The four RHESSI HXR sources could then be caused by magnetic reconnection between two sheared loop systems Pf1-Nf1 and Pf2-Nf2 that occurred high in the corona.

The outcome of this reconnection process will be one large scale magnetic system that would directly connect the leading and following part of the active region. In the discussed scenario erupted magnetic fields should be co-aligned with the large-scale structure of the active region, i.e. the foot points of the erupted loop (CME) could be rooted in the leading positive and following negative fields. The orientation of the CME is then expected to follow the orientation of the major NL that runs approximately along the SW-NE line and its predominant twist should be the same as that of the active region (negative helicity). This suggestion can be tested by analyzing interplanetary magnetic field data obtained from the ACE spacecraft.

## Interplanetary Manifestation

### *Erupting Flux Rope Model*

Krall et al. (2006) showed that the erupting flux rope (EFR) model (Chen and Garren 1993; Chen 1996; Krall, Chen, and Santoro 2000) was able to reproduce many details of the CME/ICME event on October 28-30, 2003. These results present another evidence of a strong correlation between the magnetic field in an active region and that in the corresponding ICME (Bothmer and Schwenn 1994; Rust 1994; Marubashi 1997; Zhao and Hoeksema 1998; Crooker 2000; McAllister and Martin 2000; Yurchyshyn et al., 2001; Nindos, Zhang, and Zhang 2003; Ruzmaikin, Martin and Hu 2003; Hu et al., 2005; Luoni et al., 2005; Mandrini et al., 2005; Rust et al., 2005; Yurchyshyn, Hu, and Abramenko 2005). Here we further investigate the relationship between solar magnetic fields in the May 13, 2005 event and the associated ICME at 1 AU. In modeling the May 15, 2005 ICME event, we endeavor to reproduce the near-Sun CME morphology and dynamics, as observed in LASCO coronagraph.

The erupting flux rope model (Chen and Garren 1993; Chen 1996; Krall et al. 2000) follows the motion of the apex of a three-dimensional flux rope that has foot points rooted below the photosphere. In the model calculation, all flux rope plasma and field quantities are functions of the distance from the Sun,  $Z$ , and flux rope minor radius,  $a$  (see Fig. 2 in Krall et al., 2001) and are evaluated at each time step. The version of the code that was used in this study is that of the Krall et al. (2006) with the elliptical flux rope shape instead of the circular shape (the appendix in Krall et al. (2006) describes the model updates).

We would like to emphasize that because the model focuses on the dynamics of a pre-existing solar flux rope, the process of flux-rope formation is not addressed. Moreover, in this study the EFR model is exclusively used as a magnetic cloud fitting

tool without discussing the model driver mechanism and the propagation of the flux rope in interplanetary media.

The driving forces that generate the outward motion of the flux rope are:  $J \times B$  hoop force, the pressure force, the inward directed “tension” due to the toroidal field, gravity forces, drag, and the radial  $J_t \times B_c$  force, where  $J_t$  is the component of the current flowing parallel to the flux rope axis and  $B_c$  is the component of the background coronal field that is perpendicular to both the flux rope axis and its direction of motion. That is,  $B_c$  represents overlying field that the flux rope must push aside as it expands outwards. In this model, the drag term accounts for specific physical processes such as momentum coupling between the flux rope and the solar wind through which it passes and the resulting MHD wave and shock generation.

The model flux rope is initially in an equilibrium state and is driven to eruption by an increase in the helicity via a specified increase in the poloidal flux versus time. The interpretation of this helicity increase, which could result from either macroscopic reconnection or from a process that drives a current along the length of the flux rope, has been discussed elsewhere (Krall et al. 2001; Chen and Krall 2003).

In order to obtain the best fit between the arrival time and the magnetic field intensity given by the model and the observed data at 1AU we vary only four parameters: the amount of poloidal magnetic flux “injected” over a time of 1 hour (final value of  $4.4 \times 10^{22}$  Mx), the intensity of the overlying field near the initial flux rope apex position that stabilizes the flux rope (6G), the interplanetary drag coefficient (1.15), the eccentricity of the flux rope ellipse (0.87), and the initial density of the cold plasma in the prominence ( $2.1 \times 10^8$  cm $^{-3}$ ). The interplanetary solar wind speed in the model was set at 450 km/s to match the pre-event speed at 1 AU. Other parameters, such as initial flux rope

geometry (height and foot point separation) were set to typical values (Krall et al., 2006). The geometry affects the very-near-sun flux-rope acceleration profile, which is not observed in this case. Subsequent dynamics are not sensitive to these parameters.

Once these parameters are set at the beginning of a run they (or any other parameters) they remain constant during calculations. Each run produces a flux rope that is then oriented in space in such a way that the model generated magnetic field profiles match the profiles observed with a satellite. Below we describe this process in more details.

### May 13, 2005 CME/ICME Event

The May 13, 2005 CME first appeared in the LASCO/C2 coronagraph (Brueckner et al. 1995) field of view at 17:22 UT. The only full frame LASCO C3 image (17:42 UT, Figure 8, left) taken during the ejecta shows the CME seen as a “halo” around the occulting disk. According to the CME Catalog, this halo CME was rapidly expanding with the plane of sky speed exceeding 1650 km s $^{-1}$ . The ejecta reached the Earth on May 15, 2005 and caused an intense geomagnetic storm. Figure 9 shows the corresponding solar wind data (solid curves) as measured at 1 AU by the SWEPM (McComas et al., 1998) and MAG (Smith et al., 1998) instruments on board ACE. The associated ICME was a cloud-like structure (its boundaries indicated by vertical lines) with a smoothly-rotating  $B_z$  component and a relatively low density. The MC arrived at about 06:00 UT (day of year 135.25) and it ended at about 19:12UT (day of year 135.8). This ICME featured a velocity of about 900 km sec $^{-1}$  and an interplanetary (IP) shock at its leading edge. This ACE event showed a well defined counter streaming electron flow between 05:30 UT on May 15 and at least 08:00 UT on May 18 (Gosling 2006), which indicates that the flux rope remained connected to the solar photosphere, when it was detected at 1AU.

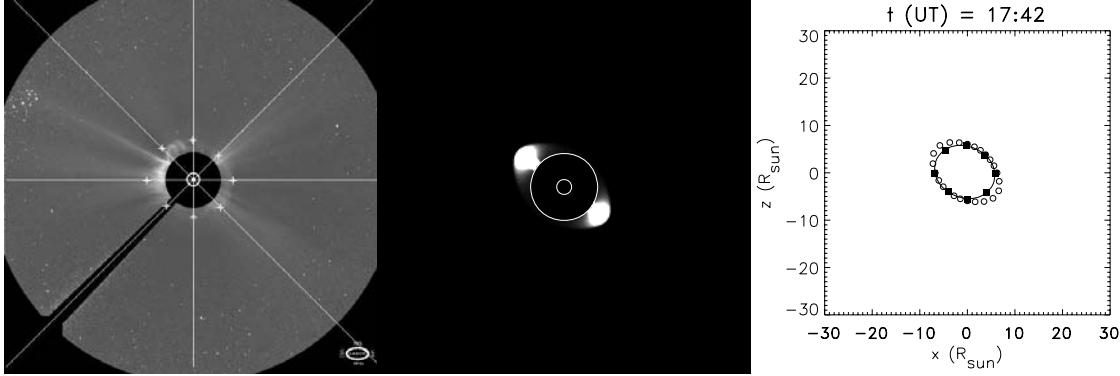


Fig. 8. Left: LASCO/C3 17:42 UT image of the halo CME on May 13, 2005. Eight points (“+”), evenly spaced in position angle (straight lines), were measured along the outer edge of the halo. CME properties such as the size, shape and orientation can be quantified by fitting a model halo CME to the measured points. Middle: A synthetic coronagraph image of the model halo CME. The bright patches on both sides of the occulting disk in this image indicate the legs of the flux rope, which are typically more pronounced in the model than in the data. Right: Model-data comparison corresponding to the 17:42 UT LASCO C3 image. Here the orientation angles are set at fixed values, chosen to provide a “best-fit” to the observed coronagraph image for this event. Open circles show the outline of the model flux rope and dark boxes are measurements from the LASCO C3 image (left).

For the purpose of orienting the 3D flux rope geometry, we define a coordinate system with its origin at Sun center, the  $z$  axis northward, the  $x$ -axis directed towards the west limb and the  $y$ -axis directed along the Earth-Sun line, away from Earth. When orienting the model flux rope, we include five angles: source latitude,  $\lambda_0$ , (for the May 13, 2005 event  $\lambda_0=12N$ ), source longitude ( $\phi_0=11E$ ), a tilt in the direction of latitude,  $\alpha_x$ , a tilt about the direction of motion of the flux rope apex,  $\alpha_y$ , i.e., the orientation of the large axis of the ellipse measured clockwise (CW) from the  $x$ -direction (west), and a tilt in the direction of longitude ( $\alpha_z$ ).

To quantify the observed CME morphology, eight points, evenly spaced in position angle, were measured along the outer edge of the ejecta (Figure 8, left). At each angle, the edge of the halo is chosen to be the outermost point on the overall expanding CME structure. In order to visualize the shape, size and orientation of the model halo CME, the 3D flux rope geometry is constructed by computing the positions of a large number of points, which outline the flux rope's exterior surface; to

obtain synthetic coronagraph images, interior points and density values must also be computed. In this model-data comparison the orientation angles are set at fixed values, chosen to provide a best global fit to the only coronagraph image available for this event. Specifically, after each “run” of the model, the orientation angles were adjusted, by trial and error, to obtain the best fit, on average, to the measured halo points while maintaining agreement with the Sun-Earth ICME transit time and the flux-rope field amplitude at 1 AU. Note that the computed flux-rope dynamics are independent of the orientation angles: that is the orientation angles can be adjusted without re-computing the model.

The inferred position of the flux rope for the May 13, 2005 event is shown in Figure 8, where the outline of the projected model-CME halo is indicated by the open dots, while the solid boxes correspond to positions measured in the coronagraph image. We note that the elongation of the halo in the best-fit model solution, which is somewhat more pronounced than the elongation of the actual halo, indicates the

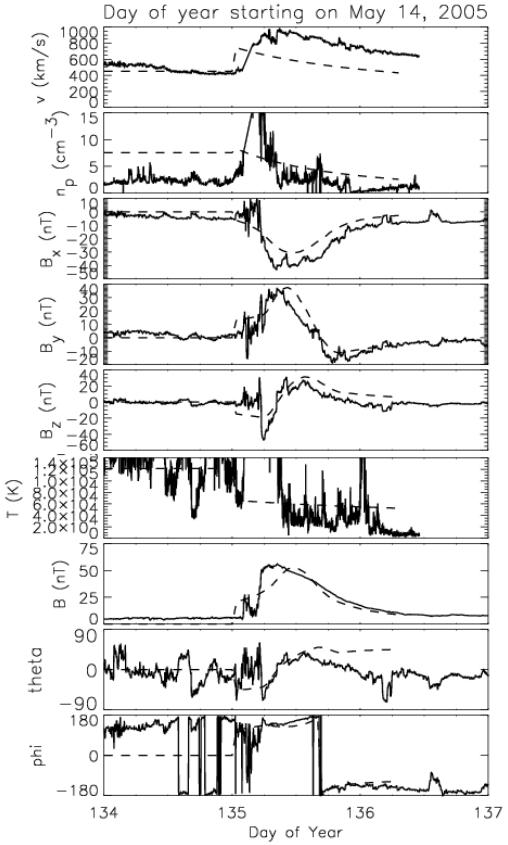


Fig. 9. Data-model comparison for the May 15, 2005 ICME. Solid lines represent ACE measurements in the GSE coordinate system of various parameters of the May 15, 2005 MC taken at 1AU (from top to bottom): solar wind speed, density,  $B_x$ ,  $B_y$  and  $B_z$  components of the magnetic field, temperature, the magnitude of the magnetic field and the cone,  $\theta$ , and clock,  $\phi$ , orientation angles of the magnetic field vector. Dashed lines are the corresponding in situ curves generated from the EFR model.

direction of the flux-rope axis. This can be seen in the synthetic coronagraph image in Figure 8, which shows a top view of an expanding loop. The bright patches on both sides of the occulting disk in this image indicate the legs of the flux rope, which are typically more pronounced in the model than in the data. We shall see that our choice of near-Sun orientation angles is close to the correct orientation for the model ICME fields at 1 AU.

For the EFR model, model-data comparisons in the near-Earth region can be

accomplished by evolving the model flux rope beyond the L1 point at 1 AU and by applying the orientation angles as in the near-Sun comparison. Equivalent in situ curves were then generated by diagnosing the position of Earth within the model flux rope and determining model field, density, velocity, etc., at that point. In order to obtain the directions of ICME field, the handedness of the flux rope and the sign of the leading-edge field must be specified (model dynamical results are independent of these two quantities). These selections were guided by ACE measurements which show that in the May 15, 2005 MC the leading-edge field was negative turning into positive, while the  $B_y$  component was positive. This indicates a left handed MC.

In order to obtain model-data match at 1AU we had to change the orientation angles  $\alpha_x$ ,  $\alpha_y$  and  $\alpha_z$ , while source location angles ( $\lambda_0$  and  $\phi_0$ ) and all other model inputs have been held constant. The orientation angle,  $\alpha_y$ , was increased from 215 to 220 degrees, corresponding to a 5-degree CW rotation of the halo away from the ecliptic plane. The tilt angle,  $\alpha_z$ , was decreased from 11 to 8 degrees, corresponding to a 3-degree deflection towards the solar disc center, relative to the Earth-Sun line, while  $\alpha_x$  was increased by about 3 degree which correspond to deflection of the flux rope toward south pole. In practice, EFR input parameters are adjusted to obtain an optimum match to both the SOHO and ACE data, with only  $\alpha_x$ ,  $\alpha_y$  and  $\alpha_z$  being allowed to vary between the near-Sun and near-Earth solutions.

Figure 8 shows a model-data comparison at 1 AU for the event. The model results (dashed curves) provide a good match to the overall transit time and various field components as observed by ACE satellite (solid curves), however, typical model velocities are lower by 35% relative to concurrent ACE velocities. Because the interplanetary dynamics are so ill-understood at present, it is possible that

the actual interplanetary forces, such as solar wind drag, differ greatly enough from the model to routinely produce a higher velocity (relative to the model), with the same transit time. Because the near-Sun velocity is not well-constrained in this event, both (model and observed) velocities, therefore, may be mismatched, while the average transit velocities and the transit times are correct. More distant possibility that may contribute is that the CME path may be curved along the Parker spiral, while the model assumes a straight path directly from the Sun to the Earth. The shorter path of the model CME allows the same transit time with a smaller velocity.

### **Comparison between the Magnetic Fields in the Active Region and in the ICME**

1) In Section 2.4 we found that the coronal magnetic field above the active region can be very well approximated by a linear force free model with  $\alpha = -0.025 \text{arcsec}^{-1}$  implying that negative twist dominated this magnetic region. The same sense of twist was found in the MC, associated with the eruption, by fitting of the observed data with the EFR model.

2) The average angle between the direction of the force-free lines (they are directed from north (white) to south (black) polarity in Figure 7) and the solar west is about 210 degrees. This compares well with the orientation angles of the model CME ( $\alpha_y=215$  deg near the Sun) and ICME ( $\alpha_y=220$  deg near the Earth) as derived from the EFR model. Note that  $\alpha_y$  is the angle measured clockwise from the  $x$ -axis (west, see Section 3.2) to the direction of the axial field in the MC.

3) As determined from the EFR model, the toroidal (axial) flux,  $Ft^{\text{EFR}}$ , confined in the model ICME was found to be about  $2.9 \times 10^{21} \text{Mx}$ , while the corresponding poloidal flux,  $Fp^{\text{EFR}}$ , was about  $4.4 \times 10^{22} \text{Mx}$ . Note that the poloidal flux is the measure of magnetic twist in a flux rope. The model toroidal flux  $Ft^{\text{EFR}}$  is two times lower than

the reconnection flux,  $Fr = 6.2 \times 10^{21} \text{Mx}$ , reported for this event in Qiu and Yurchyshyn (2005). The reconnection flux was derived as integration of the line of sight magnetic field swept by the separating H $\alpha$  flare ribbons (see Qiu et al., 2004 for more details). Hu (2006) has calculated the toroidal (axial) and poloidal (twist) fluxes from a Grad-Shafranov reconstruction technique (Hu and Sonnerup 2002) applied to the May 15 ACE event. For the axial flux, Hu finds  $2.1 \times 10^{21} \text{Mx}$ , which compares well to the EFR result ( $2.9 \times 10^{21} \text{Mx}$ ). For the poloidal flux Hu (2006) reports  $4.2 \times 10^{21} \text{Mx}$ . Computation of the total poloidal flux, however, depends on global flux-rope geometry, which significantly differs in EFR and Grad-Shafranov technique, and therefore the numbers for the poloidal flux can not be directly compared.

### **Conclusions and Summary**

In this study we present ground and space based data on the May 13, 2005 solar eruption, CME and the corresponding interplanetary ejecta observed near the Earth on May 15, 2005. This isolated two ribbon M8.0 flare and the very fast CME occurred in a relatively simple magnetic configuration during a quiet period of solar activity. This enabled us to reliably associate the solar surface event with its counterpart observed in the Earth magnetosphere. Based on the analysis of an extended data set (solar ground and space based data as well as magnetospheric measurements at 1AU) and results from numerical modeling we concluded the following.

- 1) A magnetic configuration in the active region was relatively simple and could be reasonably well approximated with a linear force-free model with negative parameter  $\alpha$  indicating that negative magnetic helicity (left handed twist) dominated in this active region.
- 2) The flow pattern in the vicinity of the convergence lines CLN and CLS, as determined from a series of line of sight

magnetograms, had two components: converging and shearing flows. These motions may be indicative that strong helical magnetic fields could form above the major neutral lines due to the cancellation process as suggested by van Ballegooijen and Martens (1989) and further explored by Linker et al. (2005) and Welsch (2006).

3) RHESSI HXR sources observed in this event did not spatially coincide with strongest electric current concentrations, which agree with earlier reports (de La Beaujardiere et al., 1993; Leka et al., 1993). However, the most intense HXR sources S1 and S2 were associated with upward net electric current of about  $2.5 \times 10^{11} A$ , while less intense S3 and S4 sources were located in the area of downwardly directed net current of  $-4.3 \times 10^4 A$ . This is in accord with earlier suggestions that upward electric currents could provide additional acceleration to the downward moving electrons thus causing the asymmetry of the X-ray emission at the foot points of flare loops.

4) The simple structure of flare emission, similarity between all H $\alpha$  and RHESSI time profiles as well as the fact that the time derivative of H $\alpha$  emission coincides in time with the position of the HXR peaks, suggest that the May 13, 2005 flare could be caused by reconnection between two independent magnetic flux systems.

5) Erupting Flux Rope model was able to produce a model halo CME and an ICME that provided a good match to the overall transit time and to various field components as observed ACE satellite. The orientation of the model ICME (215 deg) and the sense of the twist (left handed), inferred from the EFR model, agree well with the orientation (210 deg) and the magnetic helicity

(negative) found in the active region that spawn this event. We would like to emphasize that in this event, as well as in the Oct 28 2003 event (Krall et al., 2006), the direction in which the observed halo CME is elongated corresponds to the projected orientation of the MC, determined from the EFR model.

Finally, we speculate that persisting converging and shearing motions in the vicinity of the main magnetic neutral line could lead to a formation of strongly sheared and twisted core fields and eventually their eruption as according to the reconnection model (Moore and LaBonte 1980). The product of this reconnection will be one large scale magnetic loop that would directly connect the leading and following part of the active region. In the discussed scenario this newly formed erupting loop can be observed as a magnetic cloud when it reaches the Earth. Since this loops is connected to the Sun we can reasonably expect that the orientation of the CME is more or less preserved as it propagates through interplanetary medium.

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