

Sunspot Rotation, Flare Energetics and Flux Rope Helicity: The Halloween Flare on 2003 October 28

Maria D. Kazachenko¹, Richard C. Canfield¹, Dana W. Longcope¹, Jiong Qiu¹

kazachenko@physics.montana.edu

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¹Montana State University, Bozeman, MT 59715.

ABSTRACT

We use Michelson Doppler Imager observations of photospheric magnetic and velocity fields and TRACE images of photospheric and coronal structures in NOAA 10486 to build a three-dimensional coronal magnetic field model leading up to the X17 eruptive flare on 2003 October 28. The most dramatic feature of this active region is the 123° rotation of a large positive sunspot over 46 hr prior to the event. We apply a method for including such rotation in the framework of the minimum current corona model (MCC, Longcope (1996)) of the buildup of energy and helicity due to the observed motions. We find that the sunspot rotation increases the total active region helicity by 50%. However the free energy and flux rope helicity of the flare itself increase by only 10%. We conclude that in spite of the fast rotation, shearing motions alone store sufficient energy and helicity to account for the flare energetics and ICME helicity content within their observational uncertainties. Our analysis demonstrates that the relative importance of shearing and rotation in this flare depends critically on its location within the parent active region topology.

Subject headings: Sun: magnetic field, Sun: flares, Sun: sunspots

1. Introduction

In this work we study preflare storage of energy and helicity and its release through magnetic reconnection in the Halloween flare of 2003 October 28. This X17 flare took place in AR10486, an active region of complex magnetic structure that had for several days undergone both shearing and rotational motions. Figure 1 (top panel) shows the GOES 1 – 8Å X-ray flux curve from October 26 to October 28, 2003. On the day of the flare the X-ray flux started growing at 9:51 UT and peaked at X17 level at 11:10 UT. About 40 minutes before the X17 flare the observed phenomena included a filament eruption seen in EUV, TRACE and H_α images (Su et al. 2006). Even though this filament eruption and the X17 flare involved the same magnetic inversion line, it is not clear whether they were related to each other, because of the time difference. In this paper, we focus on the X17 event alone.

The Halloween flare has been interesting to many authors (see e.g. Pick et al. (2005); Hurford et al. (2006); Mandrini et al. (2006); Schmieder et al. (2006); Su et al. (2006); Li et al. (2007); Trottet et al. (2008); Zhang et al. (2006); Zuccarello et al. (2009)). Our unique contribution to this large amount of work is the *quantitative* modeling of the storage of energy and helicity due to motions of photospheric magnetic fields, including the effects of *both* shearing and sunspot rotation.

The key to this quantitative modeling is the *Minimum Current Corona* model (Longcope (1996, 2001)). The MCC is a non-potential self-consistent analytical model of the quasi-static evolution of the three-dimensional coronal field due to photospheric motions. It characterizes the coronal field purely in terms of how it interconnects photospheric unipolar magnetic source regions, called *partitions*. The amount of the total potential flux interconnecting regions \mathcal{R}_a and \mathcal{R}_b , called the *domain flux* $\psi_{a/b}^{(v)}$, can be computed from the magnetogram divided into partitions. Replacing each partition with a single magnetic point

charge located at the centroid of the partition, as we choose to do, results in values of $\psi_{a/b}^{(v)}$ that are only slightly different from the actual domain flux (Longcope et al. 2009). As the magnetic charges move they will be interconnected by various values of the domain fluxes, $\psi_{a/b}^{(v)}(t)$. The MCC assumes that the field evolves through a sequence of flux-constrained equilibria (FCE) defined as the states of minimum magnetic energy subject to constraints on all its domain fluxes. Each FCE field includes currents only on the intersections between its separatrices, called separators. These are the only locations at which current is required by the constraints. Under the assumption that no reconnection, flux emergence or cancellation occur during the magnetogram sequence, the domain fluxes could not have changed and the field could not have remained in a potential state. In this way the lack of reconnection leads to storage of free magnetic energy, energy above that of the potential field, which could then be released by reconnection. To achieve the maximum energy release, the field inside the flaring domains would need to relax to its potential state. Our working hypothesis is that the transfer of this flux through reconnection is responsible for the flare. The physical picture of the MCC is that stress is built up on the active region’s coronal magnetic separators due to the observed motions of the photospheric magnetic field and is removed by reconnection in eruptive flare events. The stress starts building up right after the end of a large flare, when the magnetic field becomes fully relaxed, thus to model the stress released in the flare we must pick an active region which had a previous flare before the flare of study. The MCC model allows us to quantify the energetic and topological consequences of changes of connectivity by reconnection and the helicity transfer between magnetic domains.

Such slow energy storage is often inferred observationally using the time-rate-of-change of relative helicity flux as a proxy (Berger and Field 1984; van Driel-Gesztelyi et al. 2003). The time-rate-of-change of relative helicity due to photospheric motions is given by a surface integral involving velocity and magnetic field. For brevity we hereinafter refer to

this total integral as the *helicity flux*, recognizing that there is no spatially resolved density capable of revealing the local distribution of helicity changes (Pariat et al. 2005). The helicity flux integral can be decomposed into a sum of terms corresponding to distinct types of photospheric motion and modes of energy storage. A term involving vertical velocity corresponds to the injection of helicity and energy by emergence of current-carrying flux. Terms involving the horizontal velocity are further separated into *braiding* and *spinning* contributions (Welsch and Longcope 2003; Longcope et al. 2007). The braiding term captures energy and helicity injected as photospheric magnetic features move relative to one another, while the spinning term captures energization when they rotate.

This is the third in a series of studies we have carried out on specific large eruptive flares, analyzing observations of the structure and evolution of photospheric magnetic fields to quantitatively estimate the amount of coronal helicity and energy released by reconnection.

In Paper 1, Longcope et al. (2007) applied the MCC model to the X2 flare of 2004 November 7, in NOAA AR 10696. They partitioned a 40-hour sequence of magnetograms to create a model of the evolving AR photospheric magnetic field as moving point flux elements. Because the magnetogram sequence showed only shear motions, and no sunspot rotation (Longcope et al. 2007), all flux elements could be represented by magnetic point charges. Longcope et al. (2007) quantified the evolution of the coronal fluxes in the flux domains interconnecting these flux elements, related them to the magnetic separators of the 3D topological skeleton of the AR, and applied the MCC model to estimate the stored energy and helicity. They found that the amount of flux that would need to be reconnected during the flare in order to release the stored energy compared favorably with the flux swept up by the flare ribbons measured using TRACE 1600 Å images. Full details of the separator reconnection sequence and the application of the MCC model to this event are

given in Paper 1.

In Paper 2, Kazachenko et al. (2009) applied the MCC model to the M8.0 flare event of 2005 May 13, in NOAA AR 10759. The preflare evolution of the photospheric magnetic field of this AR differed from that studied in Paper 1 in one important respect: it showed obvious sunspot rotation. These authors therefore incorporated rotation into the MCC by using a three-point (quadrupolar) representation of the partition that corresponded to the rotating sunspot, rather than a single point. They found that the rotation of the sunspot produced three times more energy and magnetic helicity than the non-rotating case, and the inclusion of sunspot rotation in the analysis brought the model into substantial agreement with observations. Discussion of previous work on sunspot rotation and details of the incorporation of the quadrupolar representation into the MCC are given in Paper 2.

In this work we apply the analysis methods developed in Papers 1 and 2 to the Halloween flare. Using the MCC model and a quadrupolar representation of the large rotating sunspot, we calculate the amount of flux, energy, and helicity transferred by reconnection. Interestingly, in contrast to Paper 2, we find that the rotation of the large sunspot does not significantly change the total flare thermal energy and flux rope magnetic helicity compared to the non-rotating case.

This paper is organized as follows. In Section 2 we present the magnetogram sequence and partitioning used in the study. In Section 3 we discuss the helicity injected by the photospheric motions, the rotation of the large positive sunspot, and the way we incorporate it in our model. In Section 4 we calculate the reconnection flux from the model and compare it with the measured flux from the flare observations. Section 5 lists properties of the separators found in the coronal topology at the time of the flare. In Section 6 we evaluate the role of sunspot rotation. Finally, we summarize our results in Section 7.

2. The Magnetogram Sequence

Our magnetic field data consist of a sequence of SOI/MDI full-disk magnetograms (2'', level 1.8, Scherrer et al. (1995)). As the start time of the sequence we take $t_0 = 2003$ October 26 12:00 UT, after the X1.2 flare, which occurred in AR10486 on October 26 05:57 UT. As the end time of the sequence we take $t_{flare} = 2003$ October 28 10:00 UT, one hour before the X17 flare peak time. We chose t_{flare} and t_0 so that the magnetic field measurements do not contain artifacts associated with the onset of the flare brightening (Schrijver et al. 2006; Qiu and Gary 2003). As a result, we form an hourly sequence of 45 low-noise magnetograms, which covers 46 hours of the stress build-up removed by X17 flare on October 28 11:10 UT.

To estimate the amount of flux topologically changed during the X17 flare, we must divide the pre-flare photospheric field into a set of evolving unipolar partitions. Firstly, for all successive pairs of magnetograms we use a Gaussian apodizing window of 7'' to derive a local correlation tracking (LCT) velocity (November and Simon 1988). We then take a magnetogram at t_{flare} and group pixels, exceeding a threshold $B_{thr} = 60$ Gauss downhill from each local maximum, into individual partitions (Barnes et al. 2005). We combine partitions by eliminating any boundary whose saddle point is less than 700 Gauss below either maximum it separates. Each partition is assigned a unique label which it maintains through the sequence. To accomplish this we generate a reference partitioning by advecting the previous partitions to the present time using LCT velocity pattern, and assigning a partition the label of reference partition which it most overlaps. We find that performing the process in reverse chronological order backward from t_{flare} provides the most stable partitioning. Figure 2, shows the spatial distribution of these partitions at t_{flare} .

Each magnetic partition a is represented by a magnetic point charge (or magnetic point source) with centroid, \mathbf{x}_a , and magnetic flux, Φ_a . The magnetic point charges found in this

way exhibit so little variation in flux from one magnetogram to the next in the sequence, that we use what we call the *reduced model*, in which all individual partition fluxes are held strictly constant and equal to the fluxes at t_{flare} .

The overall evolution of the active region can be characterized by the flux of relative helicity into the corona, \dot{H}_{LCT} . This can be calculated from the LCT velocity \mathbf{u} (Berger and Field 1984; Chae 2001; Démoulin and Berger 2003) from the integral

$$\dot{H}_{LCT} = -2 \int_{z=0} [\mathbf{u} \cdot \mathbf{A}_P] B_z d^2x, \quad (1)$$

over the magnetogram, where \mathbf{A}_P is the vector potential field for the curl-free (potential) magnetic field matching $B_z(x, y)$. The motions of the magnetic point charges alone contribute a *braiding helicity flux* (Berger and Field 1984; Welsch and Longcope 2003; Longcope et al. 2007),

$$\dot{H}_{br} = -\frac{1}{2\pi} \sum_a \sum_{b \neq a} \Phi_a \Phi_b \frac{d\theta_{ab}}{dt} \quad (2)$$

where θ_{ab} is the polar angle of the separation vector, $\mathbf{x}_a - \mathbf{x}_b$, connecting two magnetic point charges a and b . H_{br} quantifies the amount of helicity added to the coronal field as its footpoints are moved about one another. Integrating each of these expressions from t_0 to t_{flare} shows a steady flux of negative helicity until it reaches maximum value at approximately t_{flare} (see Figure 1, bottom panel). The braiding helicity fluxes of the point charges with observed fluxes ($H_{br,obs}$, diamonds) and of the reduced model ($H_{br,red}$, dashed curve) closely match the actual helicity flux (H_{LCT} , solid line). This gives some confidence that the centroid motions of our source regions capture the likely driver for the flare: helicity injection.

3. Sunspot Rotation.

3.1. Observations of rotation.

Observations of the large, positive sunspots P02 and P01 in MDI full-disk intensity images show them to be rotating around their umbral centers during 2003 October 25-30 (Zhang et al. 2006). To find the rotation rate Zhang et al. (2006) measure the angular displacement of the sunspots between two successive days and look at the fluctuations of the umbra profile on the MDI intensitygrams. MDI magnetograms of the same temporal and spatial resolution are not useful for rotation measurements since they exhibit lower contrast of the features in the penumbra than intensitygrams. Using rotation rates from Zhang et al. (2006) we find that in 46 hours between t_0 and t_{flare} P02 rotated by 123° , whereas the southern part of P01 rotated by only 12° .

3.2. Representation Using Point Charges.

Since P02 is one of the largest and fastest rotating partitions in the AR, a large fraction of the total helicity flux, and possibly the energy storage, is associated with it. Clearly it is not possible to model the helicity injected by a spinning partition with a single point charge. In order to model helicity and energy storage due to such motion we represent P02 with three separate point sources P02a, P02b, and P02c, of equal flux. Rather than constraining connection to P02 as a whole we constrain connections to each source separately. Following Paper 2, we locate the three point sources about an ellipse (see Figure 3) so as to match the first three terms of the multipole expansion that matches the true field of P02. To model rotation we move the triad of point charges about the ellipse injecting braiding helicity flux into P02 beyond what the single-charge model would yield. The internal braiding helicity can be used to account for observed spin helicity from P02 using the method described in

Paper 2.

Although we find that the helicity injected by the rotation of the largest partition P01 is negligible, we nevertheless chose to represent P01 with three rather than one point sources. We do this since multipole expansion improves the accuracy of coronal extrapolation and enables a more in-depth analysis of the photospheric magnetic field changes. We neglect the rotation of P01 for two reasons. Firstly, P01’s rotation rate is more than 10 times smaller than the one of P02. Secondly, the rotation is observed only in the southern part of P01, which lies further from the part of the polarity inversion line where the flare occurs. We find that the neglect of the rotation of P01 leads to an error of maximum 6% in the total braiding helicity flux ΔH_{br} .

Figure 3 shows the motions of the point charges through the sequence which lead to helicity accumulation. Note the representation of P01 with three poles which do not rotate and P02 with three poles that do. The importance of the plotted P02 rotation as a source of helicity injection into the whole active region is demonstrated by comparing the braiding helicity flux from two different models. In the first, P02a, P02b and P02c *do not rotate* and move only so as to reproduce the centroid motion of P02 alone; the time-integrated braiding helicity flux (Equation 2) of the whole active region is

$$\Delta H_{br} = -9.0 \times 10^{43} \text{ Mx}^2. \quad (3)$$

In the second, P02a, P02b and P02c *rotate* reproducing the rotation rate derived from MDI intensitygrams ($2.67^\circ \text{ hr}^{-1}$); the time-integrated braiding helicity flux is

$$\Delta H_{br} = -14 \times 10^{43} \text{ Mx}^2. \quad (4)$$

Evidently, rapid motion of the three poles of P02 relative to the other poles injects almost twice as much helicity as the case where the three poles do not rotate. Clearly for meaningful helicity calculations of the whole active region, we must take rotation into

account. However, we show below that for the helicity of the event itself rotation is not important.

4. Reconnection Flux: Model Versus Observations.

To find the theoretical estimate of the amount of flux reconnected in the flare we must first determine the domains where the flare occurred, the so-called *flaring domains*. Figure 4 shows a superposition of the elements of the topological skeleton at t_{flare} onto the TRACE 1600Å flare ribbon image at 11:15 UT. The topological skeleton (poles, null points, spines etc) describes the potential field geometry found for the observed magnetic charge distribution. The spines (solid lines) that are associated with ribbons form the footprint of a combination of separatrices which overlay the flaring domains. The overlay suggests that the southern ribbon is associated with the spines connecting flaring point sources (poles) P02a, P02b, P02c, P01a, P01b, P01c, P05, P09 and P03; and the northern ribbon is associated with the spines connecting N07, N05, N03, N02, N01, N18, N19 and N15. Field lines connecting the pairs of opposite sources listed above represent flaring domains; the nulls which lie between those sources we call flaring nulls. The calculated geometry of spines is close to the observed ribbon location except for the spine which goes through N02. However, if we look at the evolution of the ribbon position during the decaying stage of the flare (after 12:30 UT), the location of the northern ribbon goes through the southern part of region N02.

Once the set of flaring domains is found we can estimate the amount of flux that the flaring domains exchanged. For this we find domain fluxes in the potential field $\psi_{a/b}^{(v)}(t)$ before and after the energy build-up at t_0 and t_{flare} . To calculate the domain fluxes we use a Monte Carlo method (see Barnes et al. 2005) whereby field lines are initiated from point charges in random directions and followed to their opposite end. Due to magnetic charge

motions some domains gain flux ($\Delta\psi_{a/b}^{(v)} = \psi_{a/b}^{(v)}(t_{flare}) - \psi_{a/b}^{(v)}(t_0) > 0$), while the others lose flux ($\Delta\psi_{a/b}^{(v)} < 0$). Using solid and dashed lines, Figure 3 shows domains with the largest domain flux changes, i.e. $|\Delta\psi_{a/b}^{(v)}| > 0.5 \cdot 10^{21}$ Mx. In other words reconnection transfers flux from flaring domains for which $\Delta\psi_{a/b}^{(v)} < 0$ (solid) and into faring domains for which $\Delta\psi_{a/b}^{(v)} > 0$ (dashed). By summing all the positive and negative domain flux changes in the flaring domains and taking their absolute value we find the net flux transfer which must occur in the two-ribbon flare: $\Delta\Psi_{model} = 15.5(14.8) \times 10^{21}$ Mx. Were it not for connections outside the ribbon set with external sources, these two quantities would exactly match, since one domain's increase comes from another domains' decrease. It is this flux transfer by reconnection which was responsible for the X17 flare.

The model reconnection flux from the connectivity analysis discussed above could be compared with observed reconnection flux derived from the ribbon motion. Two flare ribbons associated with the impulsive phase of the X17 flare were observed by TRACE at 1600Å with 30 s cadence and with a pixel size of 0.5'' between 09:30 and 12:50. The ribbons became visible in 1600Å images at 10:58 UT and peaked at 12:51 UT. To measure the total magnetic flux swept out by ribbon motion, we count all pixels that brightened during any period of the flare and then integrate the unsigned magnetic flux encompassed by the entire area taking into account the height of the ribbon's formation, a 20% correction (Qiu et al. 2007). The total measured reconnection fluxes at 12:51 UT when the reconnection flux rate is close to zero, amount to $\Delta\Psi_{obs,+} = (2.6 \pm 0.5) \times 10^{22}$ Mx, and $\Delta\Psi_{obs,-} = (-1.9 \pm 0.3) \times 10^{22}$ Mx for positive and negative fluxes respectively ($h = 2000$ km, the ribbon-edge cutoff is taken to be 10 times the background intensity). The model reconnection flux ($\Delta\Psi_{model} = 1.5 \times 10^{22}$ Mx) compares favorably with observed reconnection flux derived from TRACE within the uncertainties given.

5. Flare Energy and Flux Rope Helicity: MCC and Observations

We now apply the MCC model, as described in Paper 1 and 2, to the quadrupolar model, where the sunspot rotation is determined from the MDI intensity images. This produces an estimate of the energy and helicity available for the Halloween flare.

From the set of flaring poles and nulls, we found six flaring separators, i.e. separators connecting the flaring nulls (thick lines in Figure 5). The main properties of those separators are listed in Table 1: separator index (i , same as in Figure 5), flaring nulls that the separator connects (nulls), length (L_i), maximum height ($z_{i,max}$), flux ($\Delta\psi_i$), current (I_i), energy (\mathcal{E}_i) and helicity (H_i). Table 1 indicates that the most energetic separators are the shortest separators A19-B07 ($i = 2$, 4.6×10^{31} ergs), A16-B06 ($i = 3$, 3.7×10^{31} ergs) and A16-B07 ($i = 4$, 4.1×10^{31} ergs) where the reconnection happens first. As a flare progresses, the reconnection moves from separator to separator, balancing the flux and reducing the energy state of the global magnetic field (Longcope and Beveridge 2007). In the bottom row of Table 1, the total energy (\mathcal{E}_{MCC}) and helicity (H_{MCC}) of the reconnection sequence are given. The total helicity released on six *flaring* separators $H_{MCC} \simeq -9.5 \times 10^{43} \text{ Mx}^2$ accounts for a large part of the helicity injected by the motions of the model flux sources, shown in Figure 3. The total helicity in the whole active region contributes to current flowing in the other 26 separators, so it is somewhat larger ($\Delta H_{br} = -1.4 \times 10^{44} \text{ Mx}^2$). The total energy released through a sequence of reconnections on all flaring separators is $\mathcal{E}_{MCC} = 1.85 \times 10^{32}$ ergs.

In the MCC currents are driven along separators to offset changes in the potential flux of the domains lying under these separators. The domains which lie under the flaring separators are P01a-N03, P01b-N03, P01c-N03, P01b-N02, P02b-N03. Out of the whole set of domains those are the only ones that determine the flux and energy content of the flux rope. It is interesting that P02b-N03 is the only P02-domain, i.e. a domain influenced

by rotation; it takes part in the energetics of only one A16-B04 flaring separator ($i = 6$, 3.5×10^{31} ergs) which contains 18% of the total energy.

We may test the model by comparing the energy value to three observations. First, the total radiative energy output of the flare can be estimated from the GOES observations. Using GOES analysis software in SolarSoft, the observed fluxes in the two channels (1–8 Å and 0.5–4 Å) of the GOES instrument give the plasma temperature, emission measure, and radiated power during the interval of elevated X-ray flux (Thomas et al. 1985). Integrating the radiated power over this time period gives a total radiated energy of $\mathcal{E}_{obs} = 5.5 \times 10^{31}$ ergs. This energy value is about three times smaller than the model value $\mathcal{E}_{MCC} = 1.85 \times 10^{32}$ ergs. Second, Régnier et al. (2005) calculated the free energy of the active region as a whole using non-linear force free and potential extrapolations of vector magnetograms $\mathcal{E}_{free} = \mathcal{E}_{nlff} - \mathcal{E}_{pot} = 5 \times 10^{32}$ ergs. This estimate is two and a half times larger than our theoretical energy estimate. Third, Metcalf et al. (2005) estimated the free energy based on the magnetic virial theorem the next day after the flare of our study: $(5.7 \pm 1.9) \times 10^{33}$ ergs (Metcalf et al. 2005). One must keep in mind that there are many uncertainties involved in the energy calculations. Firstly, the model used in GOES assumes a fully filled isothermal plasma. Secondly, the MCC model provides lower bound on the stored energy since it assumes the ideal quasi-static evolution and applies a small number of constraints rather than point-for-point line-tying. Finally, there are uncertainties in the measurements of the rotation rate from MDI intensitygrams.

An interplanetary coronal mass ejection (ICME) was observed near Earth on October 29 11:30UT. From in situ magnetic field observations with Advanced Composition Explorer (ACE) spacecraft, it has been found that the interplanetary structure is a magnetic cloud (Hu et al. 2005). Using the Grad-Shafranov method and the ACE observations, the self helicity of the associated with the Halloween flare magnetic cloud is $H_{obs} = -3.0 \times 10^{43} \text{ Mx}^2$

(Hu et al. (2005), for 1 AU) and $H_{obs} = -8.0 \times 10^{43} \text{ Mx}^2$ (Lynch et al. (2005), for 1 AU). However the estimate of helicity using the ACE data with both methods yields a large uncertainty since the spacecraft crossed the edge of the magnetic cloud (Hu (2009), case B in Riley et al. (2004)). Our model value of the flux rope self helicity lies between the two estimates. The liftoff of the flux rope does not remove all of the helicity available in the flux rope (Mackay and van Ballegooijen 2006). For the MHD simulated eruption Gibson and Fan (2008) found that 41% of the helicity is lost with the escaping rope, while 59% remains. For simplicity, we assume that 50% of the total mutual helicity from the MCC model (see Table 1) ends up as self helicity of the flux rope created by reconnection. Then the ejected flux rope would carry $H_{self} = \frac{H_{MCC}}{2} \simeq -4.8 \times 10^{43} \text{ Mx}^2$.

6. The Role of Rotation

We now seek to understand the role of sunspot rotation. For that purpose we compare the rotating case discussed above, where three poles representing P02 rotate uniformly at a rate of $2.67^\circ/hr$ for the 46 hr of build-up, with the non-rotating case, where the three poles P02a-c are kept at the same angle $\bar{\theta}$ as in the magnetogram at t_{flare} (see Appendix A of Paper 2). In the non-rotating case P02a, P02b and P02c do move in order to account for the motion of the centroid of P02, but by keeping $\bar{\theta}$ fixed they do not inject spin helicity: $\dot{H}_{sp, P01} = 0$.

In Table 2, we list the properties of the flaring separators for the non-rotating case, for comparison, with those for the rotating case in Table 1. Since in both cases the topological skeleton at t_{flare} is the same, the geometrical properties of the flaring separators, such as length (L) and maximum height (z_{max}), are also the same. However, since the topology of the magnetic field at t_0 differs in two cases, the changes in the fluxes ($\Delta\psi_i$) of the domains underlying the flaring separators and hence current (I_i), energy (ΔW_i) and helicity (H_i)

also differ. Comparing the bottom rows of Table 1 and Table 2, we see that the total energy and helicity values differ by only 10%: in the rotating case the total energy is $\mathcal{E}_{MCC} = 1.8 \times 10^{32}$ ergs and the helicity is $H_{MCC} \simeq -9.5 \times 10^{43} \text{ Mx}^2$ and in the non-rotating case the energy is $\mathcal{E}_{MCC} = 1.6 \times 10^{32}$ ergs and helicity is $H_{MCC} \simeq -8.7 \times 10^{43} \text{ Mx}^2$. This comparison clearly indicates that rotation is not important in this event.

In fact among the six flaring separators there is only one separator A16-B04 ($i = 6$) which overlies a domain directly influenced by rotation, i.e., the P02b-N03 domain. However since the P02b-N03 domain is small ($\Phi = 0.1 \times 10^{21} \text{ Mx}$) and its flux does not change much with time in either case, we get very similar properties of the separator A16-B04 ($i = 6$) in two cases: its energy is 3.5×10^{31} ergs for the rotating case and 3.1×10^{31} ergs for the non-rotating case; its helicity is $-1.5 \times 10^{43} \text{ Mx}^2$ for the rotating case and $-1.6 \times 10^{43} \text{ Mx}^2$ for the non-rotating case.

The total reconnected flux, i.e., the amount of positive and negative changes in the domain flux of the ribbon domains, is comparable in two cases: the non-rotating case predicts $\Delta\Psi_{model} = 1.2 \times 10^{22} \text{ Mx}$ of reconnected flux and the rotating case predicts $\Delta\Psi_{model} = 1.5 \times 10^{22} \text{ Mx}$; earlier in Section 4, we found $\Delta\Psi_{obs} = 2.6(-1.9) \times 10^{22} \text{ Mx}$ of reconnected flux from observational measurements of the ribbon brightening. Slightly lower predictions in the non-rotating case are related to smaller, slower change in domain flux. However since rotation of P02 happens far from the location where the flare happened, it does not influence domain flux evolution and hence the separator properties enclosing those domains.

From the above comparison, we conclude that braiding motions dominate the flare energy and helicity budget of this flare.

7. Conclusions

This paper follows Paper 1 and Paper 2 in which topological methods were applied to understand the role of sunspot rotation, in comparison to shearing, in storage of energy and helicity prior to two large eruptive flares. In the active region harboring the X2-class November 7 2004 flare, as Longcope et al. (2007) showed, only shearing motions and no rotation have been observed, and that shearing determines the energy budget of the flare. In the M5.8-class May 13 2005 flare both rotation of the large positive sunspot and shearing motions have been observed, and that rotation clearly dominated the flare energetics (Paper 2). In this paper, we analyze the Halloween X17 flare on October 28 2003 in which both rotation of the large positive sunspot and shearing motions have been observed. We show that shearing dominates the flare helicity and energy and rotation is not important.

AR10486 has a large positive sunspot P02 containing 20% (15.7×10^{21} Mx) of the total AR positive flux, which rotated by 123° in 46 hours before the flare. Since the total helicity flux is the sum of the braiding and spinning helicity fluxes, such a significant rotation along with a fact that the spin helicity flux is proportional to the magnetic flux squared might give an idea that rotation of P02 is important for the flare. Indeed the fast rotating partition P02 is important for the helicity budget of the whole active region. We show that the rotation of P02 raises the total helicity flux of the active region by 50% (from -9×10^{43} Mx² to -14×10^{43} Mx²).

Although the rotation of P02 is important for the whole active region, we conclude that it is not important for the flare. We reach this conclusion by considering the 6 flaring separators, which connect nulls nearest the flare ribbons. Using the Minimum Current Corona model (Longcope 1996) for each separator we find the current, generated by the changes in the underlying domain fluxes, the energy and helicity. Topological analysis reveals that among the domains underlying the flaring separators there is only one P02

domain. This domain is overlaid by only one flaring separator ($i = 6$), which contains less than 15% of the total energy released on all flaring separators. In other words in spite of the fast rotation of the P02, its direct contribution to the flare energetics is small. However since there are other domains which lie under the mentioned separator and influence its energetics, to estimate the role of rotation in the flare more accurately we compare the observed case where P02 rotates (rotating case) with the model case where P02 does not rotate (non-rotating case). We find that in the rotating case the flare energy and flux rope helicity is by only 10% larger than the one in the non-rotating case. We show that the reason for that lies in the topology of the rotation relative to the flare’s location. Since rotation of P02 happens far from the location where the flare happened, it does not affect the flux changes of the domains lying under the most energetic flaring separators and hence the properties of those separators such as current, helicity and energy.

We assume that the flux rope created in a sequence of reconnections would carry away half of the injected helicity, i.e. its self-helicity is $H_{self} = \frac{H_{MCC}}{2} = -4.8 \times 10^{43} \text{ Mx}^2$. The ACE spacecraft made observations of an ICME believed to have been launched during the flare. These measurements show a flux rope with helicity comparable to that in the model ($H_{obs} = -3.0 \times 10^{43} \text{ Mx}^2$ (Hu et al. 2005) and $H_{obs} = -8.0 \times 10^{43} \text{ Mx}^2$ (Lynch et al. 2005)). However the estimate of helicity using the ACE data with both methods yields a large uncertainty since the spacecraft crossed the edge of the magnetic cloud (Hu (2009), case B in Riley et al. (2004)).

Several authors have made energy estimates relevant to AR 10486 and the Halloween flare. Our theoretical estimate for the free magnetic energy ($\mathcal{E}_{MCC} = 1.8 \times 10^{32} \text{ ergs}$) is three times larger than the energy from GOES observations ($\mathcal{E}_{obs} = 5.5 \times 10^{31} \text{ ergs}$). Régnier et al. (2005) and Metcalf et al. (2005) estimated the free magnetic energy accumulated in the whole AR10486 ranging from $5 \times 10^{32} \text{ ergs}$ to $(5.7 \pm 1.9) \times 10^{33} \text{ ergs}$. Comparing the \mathcal{E}_{MCC} to

the \mathcal{E}_{free} estimate by Régnier et al. (2005), it is not surprising that the flare radiates only 16% of that contained in the whole active region. However, one must keep in mind that our energy estimate yields a lower-bound on the free-energy of a line-tied field (Longcope et al. 2001). In summary, lacking a detailed model of how the energy stored as currents on the separators is converted to other forms (thermal, mass motions, accelerated particles), we conclude that the MCC energy budget is consistent with observations and the works of other authors.

Using methods other than point charges, the topology of the AR10486 has been studied by several authors (Mandrini et al. 2006; Zuccarello et al. 2009; Régnier et al. 2005). Even though their topological methods are different from the ones in this paper, the comparison is valuable. Using linear (Mandrini et al. 2006; Zuccarello et al. 2009) and non-linear (Régnier et al. 2005) force free extrapolation of the magnetic field at different times, in all three papers a coronal magnetic null point lying above the negative polarity N07 (between P04 and P02) has been found. The observational evidence for nulls is weaker than for separators: many flares lack null points but none would lack separators (Démoulin et al. 1994; Barnes 2007). While the coronal magnetic null point found by these authors could be relevant (Zuccarello et al. 2009) to the X17 flare onset, or not (Mandrini et al. 2006), we find two flaring separators ($i=5$, $i=6$) which lie close to it.

In addition, from linear force-free extrapolation of the magnetogram at the flare time (11:11UT), Mandrini et al. (2006) found two Quasi-Separatrix Layers (QSL, Démoulin et al. (1996)), i.e. thin coronal volumes where field lines display drastic connectivity gradients. They conclude that quadrupolar reconnection occurred before the X17 flare and related filament eruption at the location where one QSL is the thinnest. Visually comparing our topology with the QSL location we speculate that, in our case, one of the QSLs would be associated with one of the two flaring separators $i = 5$ or $i = 6$. However, the goal of our

analysis is to quantify the properties of the flux rope created during the X17 event itself, not the precursor event.

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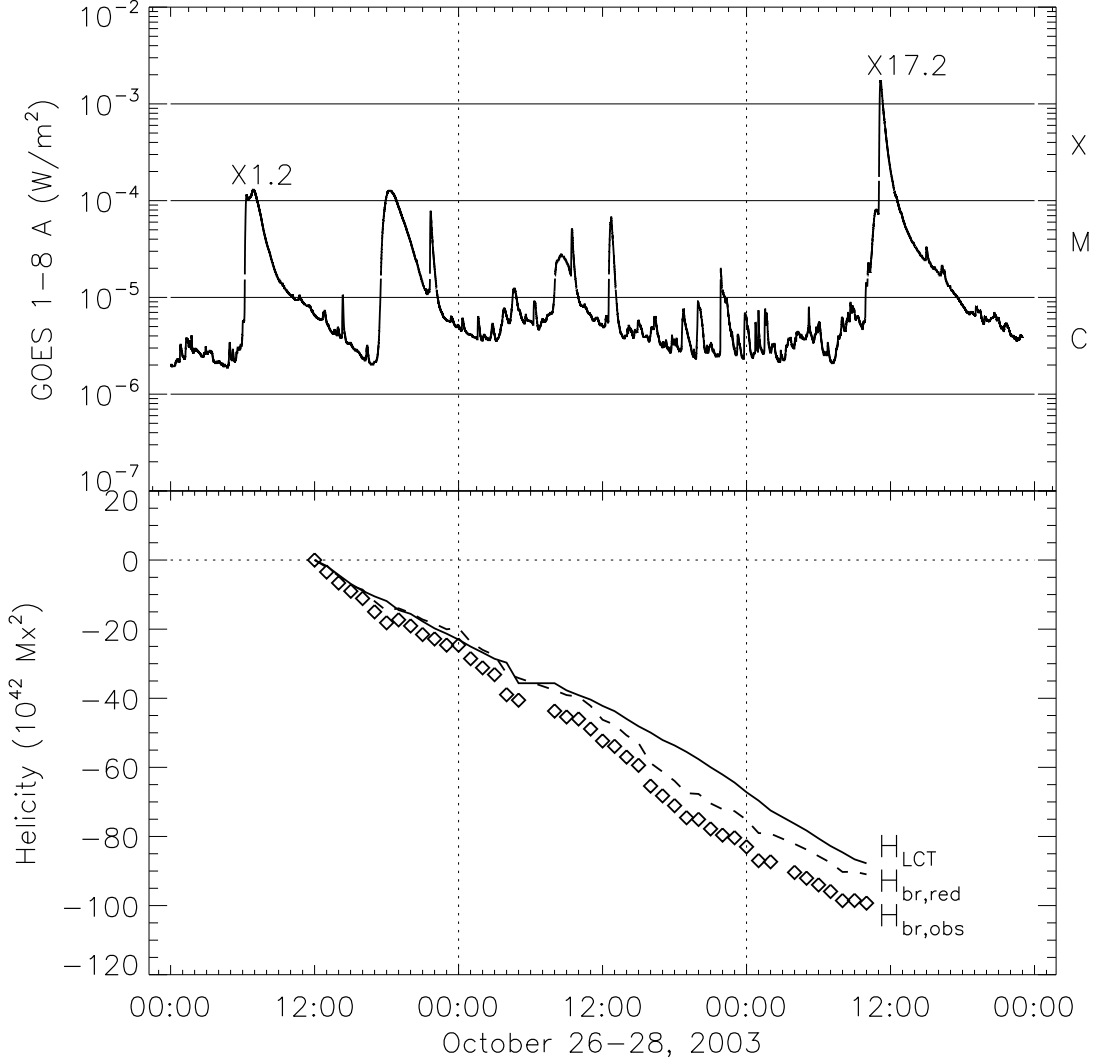


Fig. 1.— The GOES 1–8Å light curve (top) and the integrated helicity injected by the photospheric motions (bottom). In the bottom panel, the solid curve is the result of applying Equation (1) to the LCT velocity field, H_{LCT} . The \diamond s are the braiding helicity, Equation (2) from the motion of the region centroids ($H_{br,obs}$) and the dashed line is the same for the reduced model ($H_{br,red}$).

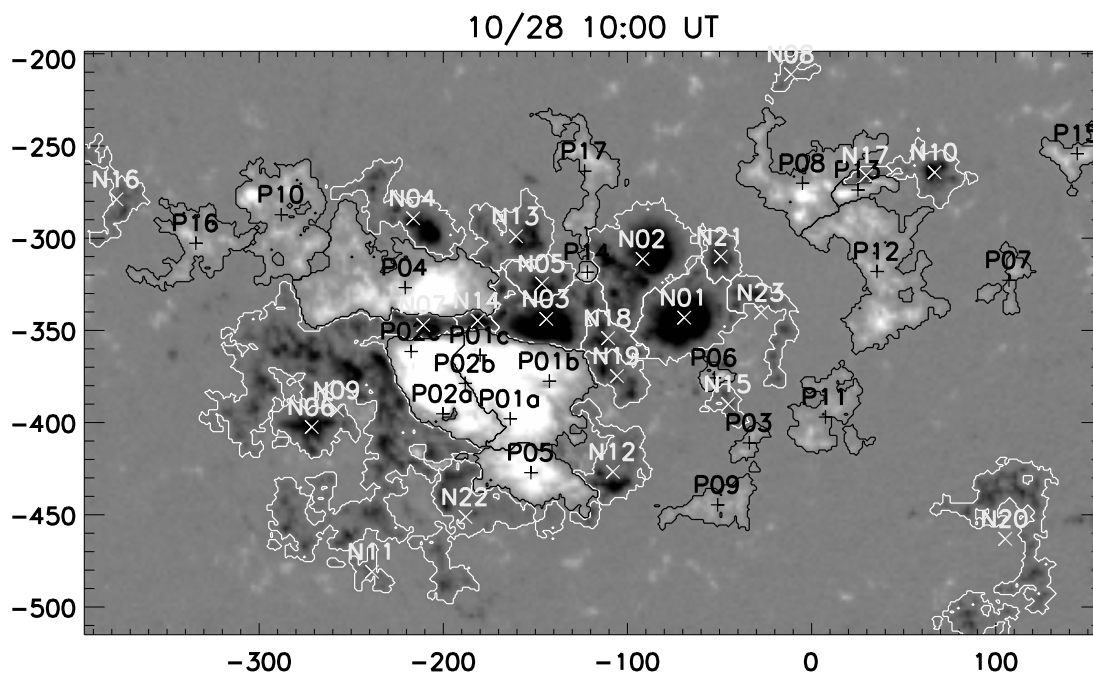


Fig. 2.— Positive (P) and negative (N) polarity partitions for NOAA 10486 on October 28 10:00 UT, one hour before the start time of the X17 flare (see Section 2). The gray-scale magnetogram shows the magnetic field $B_s(x, y)$ scaled from -1000G to 1000G. The partitions are outlined and the centroids are denoted by +’s and x’s (positive and negative respectively). Axes are labeled in arc-seconds from disk center.

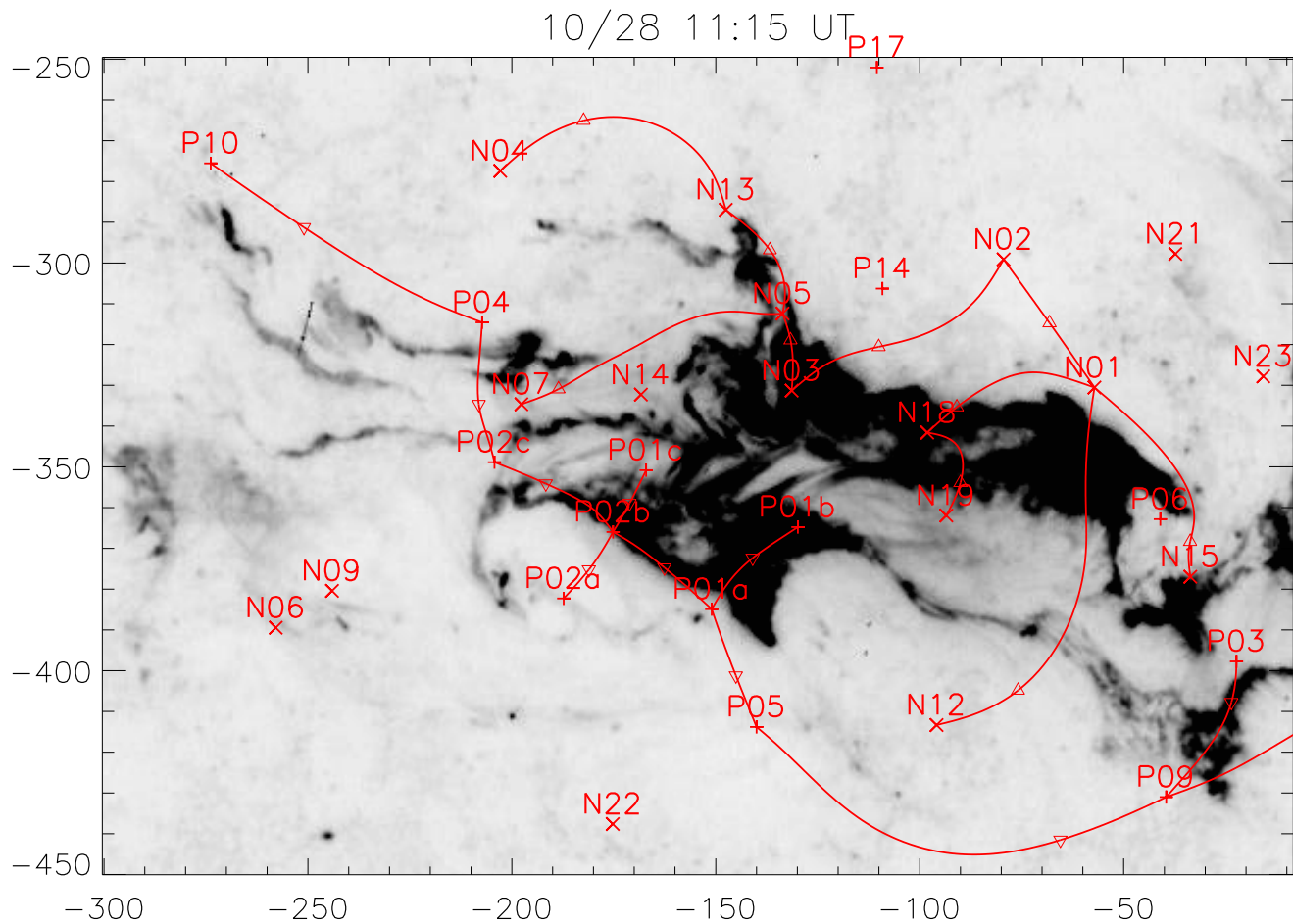


Fig. 4.— TRACE 1600Å image, plotted as reverse gray scale, with elements of the topological skeleton superimposed. The skeleton calculated for October 28 10:00 is projected onto the sky after its tangent plane has been rotated to the time of the TRACE observations (11:15 UT). Positive and negative sources are indicated by +’s and x’s respectively. The triangles represent the labeled null points. The curved line segments show spine lines associated with the reconnecting domains, as discussed in Section 4. Axes are in arc-seconds from disk center.

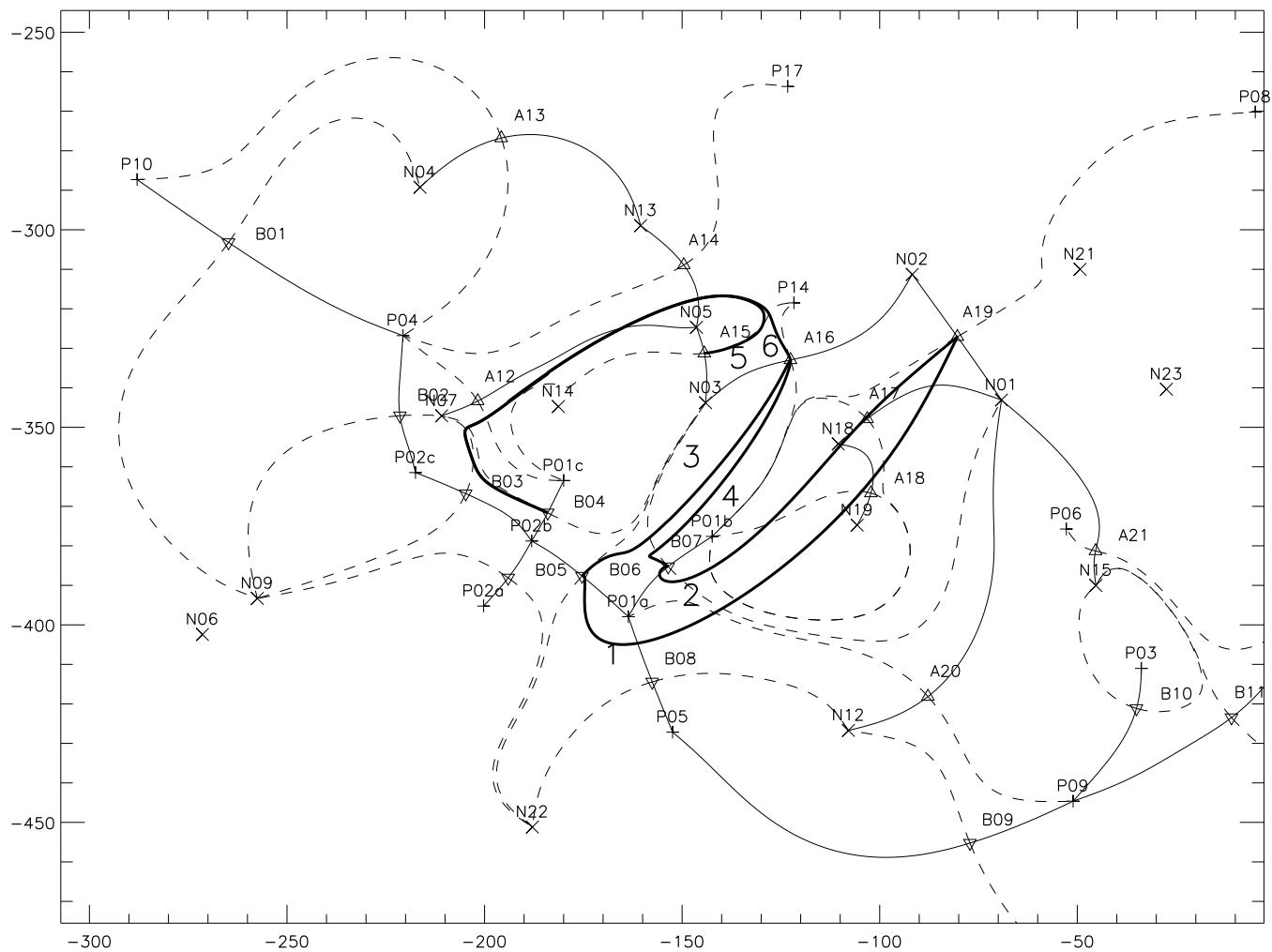


Fig. 5.— Elements of the topological skeleton footprint on October 28 10:00 UT, plotted on the tangent plane, see Section 4. Thin solid lines are the spine curves and dashed lines are the photospheric footprints of separatrices. Thick solid lines are flaring separators. The large numbers near each separator are the separator indices i , as in Table 1 and Table 2. Axes are in arc-seconds from disk center.

Table 1: Properties of the flaring separators derived from the MCC model, *rotating case*. Separators are listed by their index (i) shown in Figure 5. Listed are the names of the nulls linked by the separator, the length L_i , and maximum altitude $z_{i,\max}$, of the separator in the potential field at October 28 10:00 UT. The flux discrepancy, $\Delta\psi_i$, between that field and the initial one (October 26 12:00 UT), leads to the current I_i , which in turn leads to self-free-energy \mathcal{E}_i and helicity H_i on each separator.

i	nulls		encloses	L Mm	z_{\max} Mm	$\Delta\psi_i$ 10^{21} Mx	I_i GAmps	ΔW_i 10^{30} ergs	H_i 10^{42} Mx ²
	–	+							
1	A19	B06	P01a-N03*	185.8	72.7	-1.98	-262.6	22.82	-19.81
2	A19	B07	P01b-N03*	101.8	31.4	-1.97	-548.7	46.37	-23.58
3	A16	B06	P01a-N03*	85.1	26.3	-1.67	-523.2	37.86	-17.13
4	A16	B07	P01b-N03	74.9	24.2	-1.66	-575.3	41.49	-16.60
5	A15	B04	P01c-N03	134.0	31.4	-0.46	-76.5	1.58	-2.55
6	A16	B04	P02b-N03*	129.3	31.6	-1.80	-469.5	35.16	-15.86
total								185.28	-95.53

Table 2: Properties of the flaring separators derived from the MCC model, *non-rotating case*.

For header information see Table 1.

i	nulls		encloses	L	z_{\max}	$\Delta\psi_i$	I_i	ΔW_i	H_i
	–	+							
				Mm	Mm	10^{21} Mx	GAmps	10^{30} ergs	10^{42} Mx ²
1	A19	B06	P01a-N03*	185.8	72.7	-1.88	-245.4	20.31	-18.52
2	A19	B07	P01b-N03*	101.8	31.4	-1.81	-487.9	38.09	-20.97
3	A16	B06	P01a-N03*	85.1	26.3	-1.58	-487.2	33.55	-15.95
4	A16	B07	P01b-N03	74.9	24.2	-1.51	-508.1	33.57	-14.66
5	A15	B04	P01c-N03	134.0	31.4	-0.40	-63.9	1.15	-2.13
6	A16	B04	P02b-N03*	129.3	31.6	-1.72	-436.5	31.30	-14.75
total								157.97	-86.96

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