JOURNAL OF THE KOREAN ASTRONOMICAL SOCIETY
41: 181 ∼ 186, 2008 December

MULTIPLE FLUX SYSTEMS AND THEIR WINDING ANGLES IN HALO CME SOURCE REGIONS

HYERIM KIM[1], Y.-J. MOON[1], MINHWAN JANG[1], R.-S. KIM[2], SUJIN KIM[1], AND G. S. CHOE[1]
[1] Department of Astronomy and Space Science, Kyung Hee University, Yongin 446-701, Korea
E-mail: judith@khu.ac.kr, moonyj@khu.ac.kr, & mjang@khu.ac.kr
[2]Korea Astronomy and Space Science Institute, Daejeon 305-348, Korea
(Received November 14, 2008; Accepted December 8, 2008)

ABSTRACT

Recently, Choe & Cheng (2002) have demonstrated that multiple magnetic flux systems with closed configurations can have more magnetic energy than the corresponding open magnetic fields. In relation to this issue, we have addressed two questions: (1) how much fraction of eruptive solar active regions shows multiple flux system features, and (2) what winding angle could be an eruption threshold. For this investigation, we have taken a sample of 105 front-side halo CMEs, which occurred from 1996 to 2001, and whose source regions were located near the disk center, for which magnetic polarities in *SOHO*/MDI magnetograms are clearly discernible. Examining their soft X-ray images taken by *Yohkoh* SXT in pre-eruption stages, we have classified these events into two groups: multiple flux system events and single flux system events. It is found that 74% (78/105) of the sample events show multiple flux system features. Comparing the field configuration of an active region with a numerical model, we have also found that the winding angle of the eruptive flux system is slightly above 1.5π.

Key words : Sun: coronal mass ejections (CMEs) — Sun: magnetic fields

I. INTRODUCTION

The solar eruption is the origin of most variations in the near-earth space environment. The energy released by a solar eruption is believed to be stored in the pre-eruption magnetic field. Since the time scale of the magnetic energy accumulation (∼days) is much longer than the time scale of the energy release (∼hours), solar eruption is considered as a spontaneous transition process from a high energy state to a lower energy state. Among diverse solar eruptive phenomena, coronal mass ejections (CMEs) are of the grandest scale and exert the most serious influence on the earth's space environment. Observations show that a CME always starts in a closed magnetic field region, and eventually stretches out magnetic field lines in radial directions (Hundhausen 1998). This phenomenon is called field opening. If a field opening is a part of a CME, which is considered as a spontaneous process, the pre-eruption closed magnetic field should have more energy than the open field appearing in the later stage. This possibility is, however, denied by the so-called "Aly-Sturrock theorem," which states that no closed force-free fields with the same boundary normal field distribution can have more energy than the corresponding open field. This argument was first conjectured by Aly (1984) and physical proofs for it were independently provided by Aly (1991) and Sturrock (1991).

The proofs by Aly and Sturrock are seemingly flawless, but are based on some implicit assumptions that cannot be taken for granted. Although Aly himself recognized the pitfall of his proof procedure (Aly 1991), the solar physics community has accepted the theorem without much doubt. It was Choe & Cheng (2002) who first raised serious skepticism about the A-S theorem and tried to find a counter-example among multiple flux systems. By constructing force-free fields numerically, they have found that some force-free multiple flux systems indeed have outstandingly more energy than the corresponding open fields. It is also interesting that the configurations of those high energy fields quite resemble the pre-eruption field configurations observed by *Yohkoh* SXT (Moore et al. 2001). Comparing numerical models with observations, Choe (2008) has found that the winding angle between flux tubes in active regions bearing CMEs lies between 2π and 2.5π.

In this study, we identify multiple flux systems that turned out to produce CMEs between 1996 and 2001 and weigh their importance in eruption compared to single flux systems. We also attempt to find multiple flux configurations similar to two-flux systems constructed by Choe (2008) and estimate the winding angle between the sub-flux systems so that it may be presented as a threshold of solar eruption. In section II, the procedure of our data analysis is expounded, and our results are presented in section III. A brief summary and discussion is delivered in section IV.

Corresponding Author: Y.-J. Moon

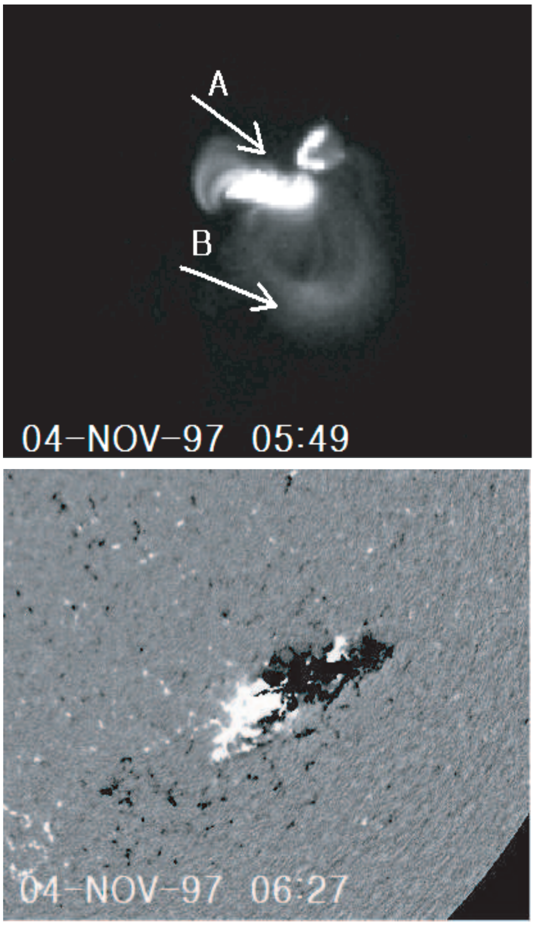

Fig. 1.— *Yohkoh*/SXT image (top) and *SOHO*/MDI magnetogram (bottom) of one example of multiple flux systems, observed on 1997 November 4. In the MDI magnetogram, the black (white) area indicates the negative (positive) polarity.

II. DATA ANALYSIS

To investigate source regions of halo CMEs, we have made use of a list of front-side halo CMEs compiled by Kim et al. (2005), and the relevant information in the *SOHO* CME online catalog (Yashiro et al. 2004, http://cdaw.gsfc.nasa.gov/CME_list). The total number of the front-side halo CMEs compiled is two hundred in 1996 through 2001. Then, we have examined Soft X-ray images of the sun in their pre-eruption stages taken by *Yohkoh* SXT. Among them, we have selected those events whose source regions are near the disk center, because for limb events, it is difficult to recognize field structures in SXT images. As a result, a total number of 105 events are selected. For the identification of their magnetic polarities, we have used the corresponding *SOHO*/MDI magnetograms (Scherrer et al. 1995). The synoptic data for given NOAA active regions are taken from Solar Monitor online site (http://www.solarmonitor.org). In the case that more than one NOAA active region are closely located or no information about the source active region is available, we select the active region that is the closest to the event position given in *Yohkoh* SXT Observing Log.

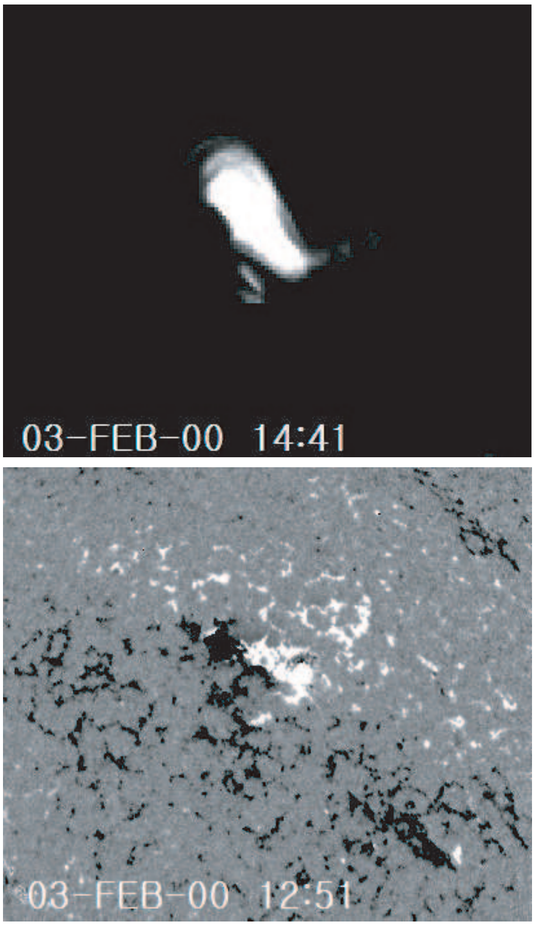

Fig. 2.— *Yohkoh*/SXT image (top) and *SOHO*/MDI magnetogram (bottom) of one example of single flux systems, observed on 2000 February 3.

The first major task of our study is to find out whether each active region associated with an eruptive event in our sample is a multiple flux system or a single flux system. Our criteria for multiple flux systems are (1) that footpoints in one polarity region should be apparently detached and (2) that the magnetic fields emanating from them should be directed differently. We have classified the sample events by the criteria into two groups: multiple flux system events and single flux system events. As an example of multiple flux systems, Figure 1 shows the *Yohkoh* SXT image and the corresponding *SOHO*/MDI magnetogram of the Active Region AR 8100 that was observed on 1997 November 4. The SXT image clearly shows two distinguishable sub-flux systems. The sub-flux system A showing many twists is positioned near the solar surface and constitutes a bright core of the active region. The faint sub-flux system B is of a distended loop shape hanging over A, while its legs seemingly creeping under A. Thus, we infer that the two sub-flux systems are interwound. One may ask why multiple sets of loops necessarily correspond to multiple flux systems. For example, a curved flux rope that is tightly twisted near its axis and very loose at regions far from the axis could display both sets of loops. To address the question we have compared our images with the pictures of other numerical simulations of flux ropes (e.g., Figures 4-7, 4-8 of Jeong 2008, Figure 8 of Magara & Longcope 2003, and Figure 2 of Manchester et al. 2008). One of the main differences between our Figure 1 and their images is that while the footpoints of their field lines are rather continuously distributed, our left two footpoints are clearly separated. On the other hand, Figure 2 shows an example of single flux systems events in the Active Region AR 8851 that was observed on 2000 February 3. In *Yohkoh* SXT image, the flux system showing only one bright core of the active region.

Recently, Choe (2008) has constructed two types of numerical models of interwinding two-flux systems. In the first type (Case 1), one sub-flux system takes a finite volume and the other takes an infinite volume. Thus, the former looks like a bright core and the latter looks like a faint distended loop (Figure 2). In the second type (Case 2), both sub-flux systems take a semi-infinite volume. In this case, the two sub-flux systems show a certain degree of symmetry (Figure 3). Choe & Cheng (2002) and Choe (2008) have found that the model two-flux systems have more energy than the corresponding open fields when the winding angle between the sub-flux systems exceeds 1.5π. If an observed multiple flux system resembles either of the model two-flux systems, we may be able to roughly estimate the winding angle between the two sub-flux systems by comparing it with the model systems. It is the second major task of our study to find an active region whose magnetic structure looks like one of Choe's model and estimate the winding angle.

III. RESULTS

In Table 1, we summarize the observational information of the selected 105 events. It lists the erupting time, the location of the source region, its Active Region (AR) number, and the flux system class, i.e., either a multiple flux system or a single flux system. It is found that 74% (78/105) of the sample events belong to the multiple flux systems. This fact indicates that multiple flux systems are far more heavily involved in major solar eruptions than single flux systems.

For the estimation of winding angles in multiple flux systems, we have searched for events whose field configurations are similar to one of the model two-flux systems in Choe & Cheng (2002) and Choe (2008). Here the winding angle is defined as a sum of the rotation angles on each side of the polarity inversion line. It is a little disappointing that we have found only one active region (Figure 1) that is similar to Case 1 of Choe & Cheng (2002). This is because most real field configurations are more complex than the model configurations and the resolution of the *Yohkoh* SXT is not so good as to clearly identify field connectivity. From a direct comparison of the selected observation with the numerical model, we have estimated the winding angle between two observed flux tubes. For a more accurate explanation we present a cartoon in Figure 5 which simply describes the field connectivities between two fluxes (A, B) and shows two possible flux tube footpoints (B1 and B2) on the magnetogram. As seen in the cartoon, the existing loops are interwound by at least 1.5π with respect to the case with zero winding angle (dashed circle). This value is a little larger than the open field threshold 1.5π obtained by Choe & Cheng (2002). In this regard, it is interesting that two of the pre-eruption sigmoidal structures in Moore et al. (2001) are found to have winding angles greater than 2π (Choe 2008).

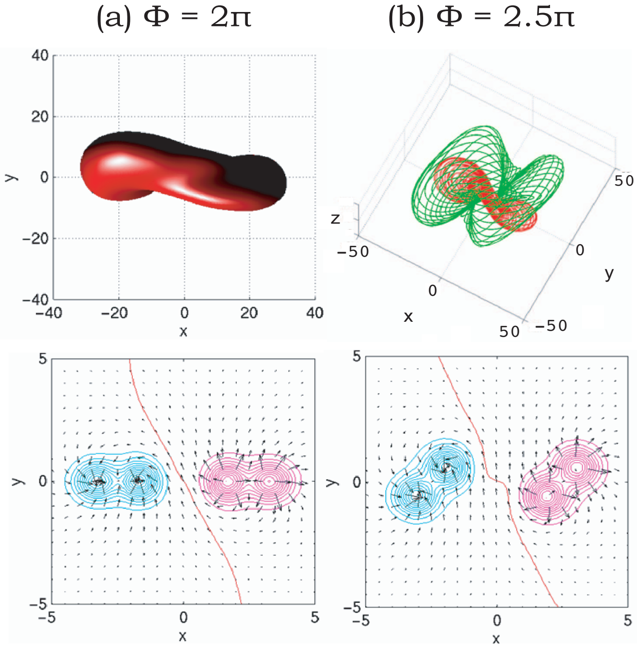

Fig. 3.— Projected images of the model two-flux systems for Case 1 (top panel) and the corresponding vector magnetograms (bottom panel) for two different winding angles ($\Phi = 2\pi,\ 2.5\pi$) (Choe 2008).

IV. SUMMARY AND DISCUSSION

In this paper, we have studied the importance of multiple flux systems in CMEs. Having selected 105 halo CME events which occurred in 1996 through 2001 and whose source regions are near the solar disk center, we have examined their field connectivities in *Yohkoh* SXT images and magnetic polarities in *SOHO*/MDI magnetograms. The sample active regions are classified as either multiple flux systems or single flux systems.

TABLE 1.
OBSERVATIONAL INFORMATION OF THE 105 HALO CME EVENTS

CME time[a]	Location	AR number	Class[b]	CME time[a]	Location	AR number	Class[b]
961219 1630	S14W09	8004	M	000429 0154	S13W36	8970	M
970106 1510	S18E06	-	M	000510 2006	N17W02	8989	M
970407 1427	S30E19	8027	S	000520 0626	S21E35	8996	M
970512 0630	N21W08	8038	S	000520 1450	N18304	9002	M
970521 2100	N06W15	8040	S	000809 1630	N11W11	9114	M
970830 0130	N28E11	8076	M	000829 1830	S19E07	9143	M
970917 2028	N28301	8086	M	000901 1854	N12E18	9149	M
971006 1528	N23E08	8091	S	000905 0554	N14W36	9149	M
971021 1803	N16E07	8097	S	000912 1154	S17W09	9163	S
971023 1126	N16W28	8097	S	000915 2150	N12E04	9165	M
971104 0610	S20W27	8100	M	001002 0350	S09E04	9176	S
971117 0827	N21E16	8108	M	001009 2350	N01W14	9182	M
971119 1227	N19E03	8108	M	001025 0826	N18W37	9201	M
980125 1526	N21E25	-	M	001101 1626	N10E20	9212	M
980228 1248	N17W51	8164	S	001124 1530	N21W07	9236	M
980427 0856	S16E50	8210	M	001125 0131	N07E50	9240	S
980429 8210	S18E20	8210	M	001125 0930	N18W24	9236	M
980502 0531	S15W15	8210	M	001126 1706	N18W38	9236	M
980621 0535	N18W39	8243	M	001214 1706	N08E02	9267	S
981104 0754	N18E07	8375	M	001218 1150	N15E01	9269	S
981105 0202	N18W07	8375	M	010110 0054	N13E36	9306	M
981107 1154	N18W49	8375	M	010210 0054	S20W15	9338	M
981109 1818	N23W13	8377	M	010215 1354	N28W05	9349	S
981218 1809	N25E21	8414	S	010228 1450	N13W32	9359	M
990413 0330	N16E00	8508	M	010316 0350	S07W20	9373	M
990503 0606	N15E32	8525	S	010318 0226	S07W48	9373	S
990510 0550	N16E19	8535	M	010328 1250	N18E02	9393	M
990612 2126	N27W43	8569	M	010405 1706	S24E05	9415	S
990622 1854	N22E37	8598	M	010406 1930	S21E31	9415	M
990623 0731	N23E42	8598	M	010409 1554	S21W04	9415	M
990624 1331	N23E30	8598	M	010411 1331	S22W27	9415	M
990628 1206	N27E55	8598	S	010412 1031	S19W43	9415	M
990629 1854	S14E01	8603	M	010426 1230	N16W29	9433	M
990630 1154	S15E00	8603	S	010620 1954	N08W17	9504	M
990723 2130	N21W01	8636	M	010825 1650	S17E34	9591	M
990728 0906	S15E03	8649	M	010911 1454	N13E35	9610	M
990804 0626	N26W31	8651	M	010924 1030	S16E23	9632	M
990817 1331	N23E27	8668	S	010927 0454	S18W39	9628	M
990828 1826	S24W49	8624	M	010928 0854	N10E18	9636	M
990921 0330	S22E15	8704	S	010929 1154	S18W01	9535	M
991018 0026	N13W33	8731	M	011009 1130	S28E08	9653	M
991206 0930	N10E43	8788	S	011019 1650	N15W29	9661	M
991220 1806	N18E44	8806	M	011022 1506	S19E13	9672	S
991222 0230	N10E30	8807	M	011023 1826	S21E18	9672	S
991222 1931	N24E19	8806	M	011025 1526	S16W21	9672	S
000118 1754	S19E11	8831	M	011101 2230	N12W23	9682	M
000128 2012	S31W17	8841	M	011104 1635	N05W29	9684	M
000203 1230	N26W10	8851	S	011117 0530	S13E42	9704	M
000208 0930	N25E26	8858	M	011121 1406	S14W19	9704	M
000209 1954	S17W40	8853	M	011122 2330	S17W38	9704	M
000210 0230	N31E04	8858	M	011128 1730	N04E16	9715	M
000217 2130	S25W12	8869	S	011213 1454	N16E09	9733	M
000410 0030	S13E01	8948	M				

---

[a] Dates are given as yymmdd. Time is expressed in universal time.

[b] Indicates the flux system classification. M refers to multiple flux systems and S refers to single flux systems.

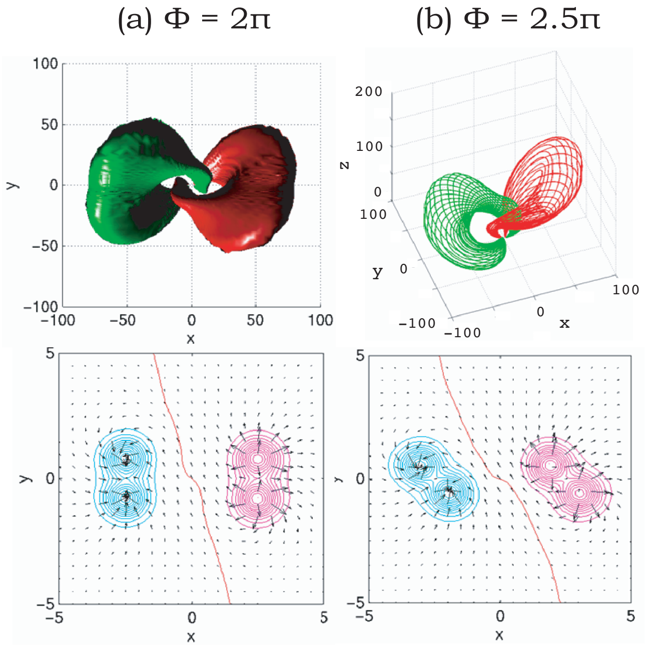

Fig. 4.— Projected images of the model two-flux systems for Case 2 (top panel) and the corresponding vector magnetograms (bottom panel) for two different winding angles ($\Phi = 2\pi,\ 2.5\pi$) (Choe 2008).

Our result shows that 74% (78/105) of the sample active regions belong to multiple flux systems. We guess that the possibility of mistakenly judging a multiple flux system as a single flux system is larger than the possibility of the opposite cases. For example, Figures 3 and 5 of Moore et al. (2001) also bear some ambiguity when one looks at the images at one time only. However, their overall evolutions are biased toward the multiple flux systems scenario.

We have also looked for active region configurations which look similar to numerical models of two-flux systems by Choe (2008), and have found one active region with a similar configuration. Comparison of this observed configuration with the model configuration tells that the winding angle of the observed system lies at least 1.5π. This result is consistent with that of Choe (2008), who has shown that the pre-eruption sigmoidal systems observed by Moore et al. (2001) also have winding angles above 1.5π. Our observation along with that of Moore et al. (2001) suggests that the winding angle threshold for eruption may be slightly above 1.5π.

Our result that multiple flux systems are much more heavily involved in major solar eruptions than single flux systems can be interpreted in the following two ways. First, multiple flux systems are vulnerable to diverse topological transition of states by magnetic reconnection. Second, multiple flux systems may have more magnetic energy than the open fields and may be able to create a CME manifesting field opening. The two interpretations are not exclusive against each other, but complementary to each other. The observations by us and by Moore et al. (2001) indicate a possibility that the magnetic fields of pre-eruption active regions have winding angles of 1.5π at least. This implies that the pre-eruption magnetic field has a more energy than the open field energy, and supports the second interpretation. However, since the sample size is small (only three events), further examinations are needed.

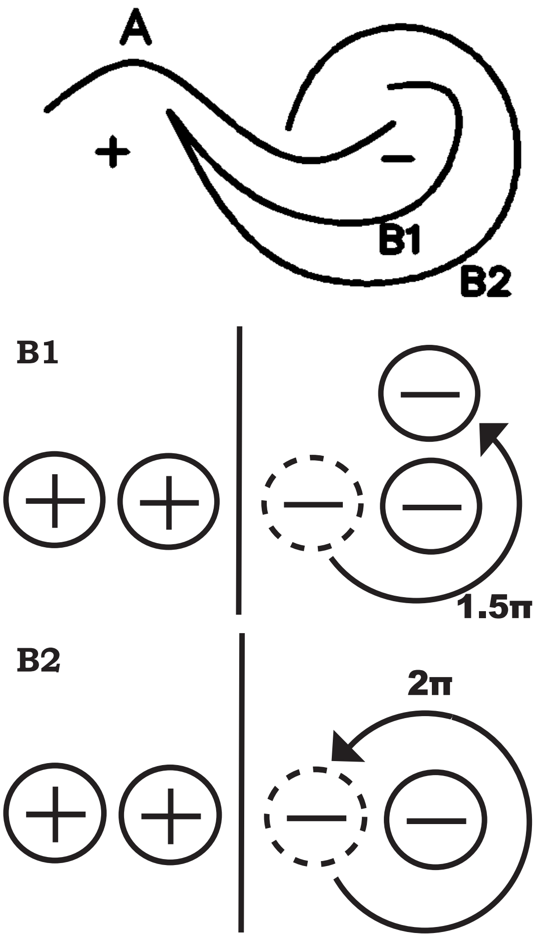

Fig. 5.— The corresponding sketch of field connectivities (top) for the event in Figure 1 and the vector magnetogram (middle,bottom) for two possible flux tube footpoints.

The winding number of an active region may be estimated by dividing the estimated magnetic helicity by the total magnetic flux squared (e.g., Jeong & Chae 2007). The resulting value is generally very small ($\sim O(0.1)$). Our finding and many observations of erupting prominences give a much larger value. This is still an unresolved puzzle in solar eruption physics. With reservation, we speculate that only part of the magnetic flux in an active region be ejected, which has a winding number larger than unity. However, this problem calls for extensive studies in the future.

ACKNOWLEDGEMENTS

We really appreciate the referee's constructive comments. This work was supported by the Korea Research Foundation Grant funded by the Korean Government (KRF-2005-070-C00059). R. S. K. was supported by the "Development of Korean Space Weather Center," a project of the Korea Astronomy and Space Science Institute (KASI). G. S. C. was also supported by the NASA Grant NNH04AA16I and by Korea Research Council of Fundamental Science and Technology through Grant KRCF-C-Res-07-14-KASI. The CME catalog used in this study is generated and maintained at the CDAW Data Center by NASA and the Catholic University of America in cooperation with the Naval Research Laboratory. *SOHO* is a project of international cooperation between ESA and NASA.

REFERENCES

Aly, J. J., 1984, On some properties of force-free magnetic fields in infinite regions of space, ApJ, 283, 349

Aly, J. J., 1991, How much energy can be stored in a three-dimensional force-free magnetic field?, ApJ, 375, L61

Choe, G. S. & Cheng, C. Z., 2002, Energy of force-free magnetic fields in relation to coronal mass ejections, ApJ, 574, L179

Choe, G. S., 2008, to be submitted to ApJ

Hundhausen, A., 1998, Coronal mass ejections, in The Many Faces of the Sun: a Summary of the Results from NASA's Solar Maximum Mission, edited by K. T. Strong, J. L. R. Saba, B. M. Haisch, and J. T. Schmelz, (New York, Springer), p. 143

Jeong, H., 2008, Magnetic helicity transfer through the solar surface, Ph.D. Dissertation, Seoul National University

Jeong, H. & Chae, J., 2007, Magnetic helicity injection in active regions, ApJ, 671, 1022

Kim, R.-S., Cho, K.-S., Moon, Y.-J., Kim, Y.-H., Yi, Y., Dryer, M., Bong, S.-C., & Park, Y.-D., 2005, Forecast evaluation of the coronal mass ejection (CME) geoeffectiveness using halo CMEs from 1997 to 2003, J. Geophys. Res., 110, 11104

Magara T. & Longcope D. W., 2003, Injection of Magnetic Energy and Magnetic Helicity into the Solar Atmosphere by an Emerging Magnetic Flux Tube, ApJ, 586, 630

Manchester IV, W., 2008, Shear Flows Driven by the Lorentz Force: An Energy Source for Coronal Mass Ejections and Flares, ASPC, 383, 91

Moore, R. L., Sterling, A. C., Hudson, H. S., & Lemen, J. R., 2001, Onset of the magnetic explosion in solar flares and coronal mass ejections, ApJ, 552, 833

Scherrer, P. H., et al., 1995, The solar oscillations investigation – Michelson Doppler Imager, Sol. Phys., 162, 169

Sturrock, P. A., 1991, Maximum energy of semi-infinite magnetic field configurations, ApJ, 380, 655

Yashiro, S., Gopalswamy, N., Michalek, G., St. Cyr, O. C., Plunkett, S. P., Rich, N. B., & Howard, R. A., 2004, A catalog of white light coronal mass ejections observed by the *SOHO* spacecraft, J. Geophys. Res., 109, 7105