(Top) 24 of the 28 participants to the young scientist poster competition outside of Reed Hall, main venue for the poster program, with A. Hillier coordinating (center). (Bottom) 5 worthy winners were celebrated during the conference dinner at the Imperial Hotel, Torquay: from left to right, R. Chiba, N. Hussain, V. Pant, S. Mahajan and M. Korsos; with A. Hillier and C. Foullon standing behind and to the right authors of book prizes A. Choudhuri, J. Luhmann and C. Russell.

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Part 7. Forecasting Models

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Numerical Short-Term Solar Activity Forecasting

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Abstract. It is well known that the energy for solar eruptions comes from magnetic fields in solar active regions. Magnetic energy storage and dissipation are regarded as important physical processes in the solar corona. With incomplete theoretical modeling for eruptions in the solar atmosphere, activity forecasting is mainly supported with statistical models. Solar observations with high temporal and spatial resolution continuously from space well describe the evolution of activities in the solar atmosphere, and combined with three dimensional reconstruction of solar magnetic fields, makes numerical short-term (within hours to days) solar activity forecasting possible. In the current report, we propose the erupting frequency and main attack direction of solar eruptions as new forecasts and present the prospects for numerical short-term solar activity forecasting based on the magnetic topological framework in solar active regions.

Keywords. solar activity, magnetic field, forecast

1. Introduction

Solar eruptions have been revealed to be disturbances propagating through interplanetary space, resulting in space weather events in nearby the Earth, which are dangerous to high-tech systems including aerospace, communication, power grids etc. Short-term solar activity forecasting models provide users products described with probability of solar eruptions within hours to days. Conventional forecasting models are mostly based on the statistical relation between solar eruptions and measures from observations. The most popular measures are obtained through the classification of sunspot groups (e.g. McIntosh 1990). In the era with only simple optical imaging solar telescope, the classification of sunspot groups was the best way to forecast solar activity. With the development of solar instrumentation, multi-band solar observations with high spatial and temporal resolution have been realized in the ground and the space since 1950s. The vector magnetic field measurement of the solar surface provides us with a numerical boundary to understand MHD processes in the solar atmosphere. It is reasonable that some of parameters derived from observational data have been taken as measures of solar activity forecasting models supported with statistical method or artificial intelligence technology (Falconer *et al.* 2003; Cui, *et al.* 2006; Wang *et al.* 2008; Yu *et al.* 2009; Bobra & Couvidat 2015; Liu *et al.* 2017) The current products of short-term solar activity forecasting models, however, can hardly meet the demand of our users from different fields. Wang (1998) first proposed a concept of solar magnetic synoptic meteorology, in which magnetic interfaces among independent flux loop systems are regarded as frontier surfaces where violent solar events frequently happen. With incomplete theoretical modeling for eruptions in the solar atmosphere, dynamic processes at the magnetic interface cannot be easily described with MHD equations, although many theoretical works have been done (Chen 2011; Amari *et al.* 2014; Jiang *et al.* 2016). On the other hand, the "big data" from ground and space solar observations stimulate us to begin our work on numerical short-term solar activity forecasting. For this reason, the current paper is structured as follows: a new concept of solar activity forecasting is proposed in the second section; solar magnetic topological framework is introduced in the third; the analysis of two cases is presented in the fourth section, before a final summary.

2. New Concept of Solar Activity Forecasting

Disturbances caused by solar eruptions propagate through interplanetary space, and create shock waves in the solar wind interacting with the magnetosphere. This means that there exists two problems in forecasting solar eruption: (1) When and how will it happen? (burstiness); (2) Will it have an effect on the Earth? (harmfulness). The burstiness means that the solar eruption is regarded as a phenomenon of large scale free energy release from solar magnetic field, which is always triggered by some unexpected internal or external disturbances. This is the reason why solar eruptions are hard to predict. The harmfulness means that the solar magnetic field and it's rotation make the environment of interplanetary space complicated. The current propagation model of solar disturbances suffers from uncertainties in the upper boundary at $2.5R_{\odot}$ and the observational characteristic of energetic particles is related to solar rotation, shock, IMF, and orbit motion of the Earth (Reames *et al.* 1996).

It is obvious that solar eruptions impacting on the Earth cannot be fully provided with a normal solar activity forecast presented in probability. We suggest that the erupting frequency and the main attack direction of solar eruptions should be included in forecasts. According to historical records, a group of solar eruptions is more dangerous than occasional one. In fact all major solar storms originated in super active regions, which had multiple eruptions, such as 1859's Carrington event, 1989's great solar storm, 2000's Bastille day event, 2003's Halloween event. The erupting frequency is defined as a number of solar eruptions during a specific forecasting time window, which can be considered as a parameter of solar active regions. The topology of local and global magnetic fields in the solar corona plays an important role in determination of solar eruption's behaviors and characteristics. In order to provide our users with new forecasts concerning the erupting frequency and the main attack direction of solar eruption, we need numerical reconstruction of 3D magnetic field in the corona. The domain for the numerical reconstruction is currently confined in solar active regions, because a global magnetic field reconstruction requires real time global solar magnetic field observations at different sites in deep space.

3. Solar Magnetic Topological Framework

Taking vector magnetic fields on the solar surface as boundaries, we can reconstruct solar coronal magnetic fields with different models. Here we employ a non-linear force-free field (NLFFF) model proposed by Yan and Sakurai (2000). The coronal field is reconstructed with boundary integration based on a Green's function:

$$Y(\lambda, r) = \frac{cos(\lambda r)}{4\pi r}, \tag{3.1}$$

where the parameter λ is determined with a best fitting algorithm for a specific active region, and then the 180 degree ambiguity is also removed with a reference field in linear

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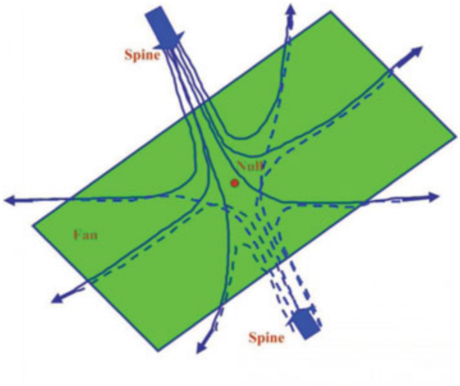

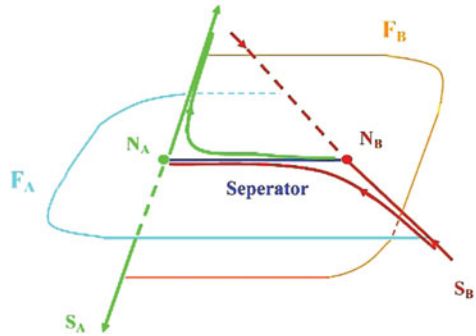

Figure 1. Topological features of Type B null (left) and topological connections between nulls in Types A and B(right)

force-free field (LFFF) model suitable for this parameter (Wang *et al.* 2001). We take a solar active region with NOAA number 11719 (AR 11719) as an example. The vector magnetic field observed with the HMI/SDO instrument at 07:16:00UT on April 11, 2013 is taken as the boundary. When the value of λ is well determined, a reasonable alignment between the reconstructed 3D field and the EUV features will be reached. The best fitting value of λ is about $-9.0 \times 10^{-7} m^{-1}$, which means that the dominant magnetic flux in this active region has negative force-free factor.

It has been widely accepted that the magnetic reconnection is regarded as an important process of magnetic energy release for solar flares since Sweet (1958) proposed a model concerning the neutral point theory of solar flares, in which the topology of solar magnetic field is inevitably changed. Up to now several magnetic configurations beneficial to the reconnection have been investigated in detail (Longcope 2005). Null points in solar magnetic fields are regarded as a kind of important configurations associated with the reconnection (Lau & Finn 1990; Priest *et al.* 1997). Near a null point located at $\mathbf{x} = 0$, the magnetic field $\mathbf{B}$ can be given with Taylor expansion,

$$\mathbf{B}(\mathbf{x}) = \delta\mathbf{B} \cdot \mathbf{x}, \tag{3.2}$$

where $\delta\mathbf{B}$ is a real matrix with 3×3 elements. The topological property of a magnetic null is determined by eigenvalues of $\delta\mathbf{B}$. Here we only consider the situation that all eigenvalues are real because our reconstructed solar corona magnetic field is derived from a NFFF model (Lau & Finn 1990). Since the trace of this matrix is zero, the sign distribution of three eigenvalues has two types: one is $(+--)$, which we will call “Type A”, and the other $(-++)$, $i.e$ Type B. The left panel of Figure 1 shows the topological framework of Type B, while that of Type A has inverse field line directions. The right of Figure 1 demonstrates topological connections between two types of nulls, in which topological components of nulls, such as spine and fan, are indicated. It should be note that the intersection between fans F_A and F_B, namely separator, is the most important interface where solar events might be initiated due to magnetic reconnections. Here the magnetic topological framework is defined as a set including topological features of nulls and their connections. Magnetic fields extrapolated from solar data have quite different topological frameworks, which would be useful to determine the erupting frequency and the main attack direction of solar eruptions.

Theoretically, a magnetic null is not a necessary condition for magnetic reconnection (Priest & Démoulin 1995), but it can be detected in most of solar active regions with complicated magnetic configurations, which are important for major solar eruptions. For this reason, the detection of magnetic nulls in the reconstructed 3D magnetic field is the main task of numerical short-term solar activity forecasting model. Wang & Wang (1996) suggested a method to detect two-dimensional magnetic singular points in solar active regions. Zhao *et al.* (2005) developed a new method to detect null points in 3D magnetic fields, and then this method was used to analyze topological frameworks in 3D magnetic fields extrapolated from observed magnetic fields in some active regions (Zhao *et al.* 2008). We employ this method to analyze topological frameworks of 3D magnetic fields reconstructed with HMI/SDO data obtained from AR 11719, in which two nulls in Types A and B are detected, respectively. It is very interesting that the flaring and ejecting processes are exactly confined by the topological framework in this active region. An enhanced study for this active region will be done and relevant results will be reported in a separated paper.

4. Case Analyses

It is widely believed that the free energy building in solar active regions is driven by the evolution of photospheric magnetic field, and then released by magnetic reconnection in separators of topological frameworks. Although how solar eruptions are triggered by has not been well described with modern solar physics, how topological frameworks effect solar eruptions can be understood. Separators in topological frameworks can be located with numerical computation, and some hot points related to these separators can also be found by multi-band solar observations. The information concerning the complexity of separators and the location of hot points can tell us the erupting frequency and which parts of topological frameworks will get involved in the eruptions. We show two active regions as our case analyses.

The first case is AR 11158 from February 14, 2011, when this region appeared near the center of solar disk. The data set includes SDO/HMI vector magnetograms; SDO/AIA 171Å images; SoHO/Lasco images and GOES 15 soft X-ray flux. Table 1 is obtained from observational data of GOES 15 and SoHO/Lasco during 00h-20h(UT), in which nine C or M flares and five CMEs are listed. The second CME might be originated from other locations because it's central position angle (CPA) is quite different from that of others. Sun *et al.* (2012) selected one of several homologous non-radial eruptions to study how these eruptions were modulated by the local 3D magnetic field in which a null was detected at about 9Mm above the solar surface. In the current work, we employ the model suggested by Yan and Sakurai (2000) for the coronal field reconstruction, the tool proposed by Zhao *et al.* (2005) for the topological framework analysis. There exist two nulls in the topological framework shown in Figure 2. One of them is the same as that obtained by Sun *et al.* (2012), while another one might be ignored as it has a height over 80Mm. A separator is detected within a height range of (9Mm, 90Mm). We select a small sector area ($\theta = 6$ deg, $r = 200$Mm) along the direction of outflow to construct a space-time diagram, in which 400 AIA 171Å images with 3min interval are used (see left panel of Figure 3). It is interesting that a stable point is detected, which is probably the intersection between the sector and the separator in the transition region, and variations of EUV intensity well correspond to all of the eruptions originated in AR11158 (see right panel of Figure 3). Sun *et al.* (2012) believe that homologous non-radial eruptions was only caused by the null at the lower height, but we strongly suggest that the topological framework provides a robust platform for these eruptions. Actually the flux systems involved in eruptions are

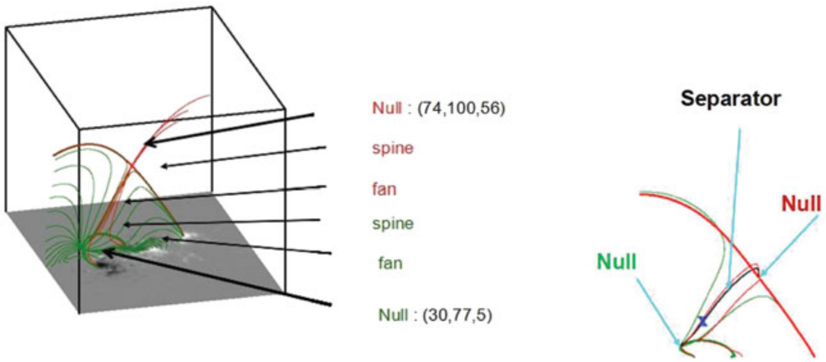

Figure 2. Topological frameworks in AR11158. (Left) All components of the topological framework, 1 unit=1.5 Mm; (Right) Separator connecting nulls in Types A and B

date	begin	end	peak	class
20110214	0235	0246	0242	C1
20110214	0429	0509	0449	C8
20110214	0651	0703	0658	C6
20110214	0839	0904	0849	C1
20110214	1151	1226	1200	C1
20110214	1241	1258	1253	C9
20110214	1347	1442	1427	C7
20110214	1720	1732	1726	M2
20110214	1923	1936	1930	C6

CME Number	Begin Time	Central PA(deg)	Angular width(deg)	Linear fit (km/s)	Accel (m/s^2)
1	08:12:06	288	057	303	06.3
2	11:00:05	051	007	217	07.4
3	14:00:07	306	022	380	-23.3
4	17:24:05	263	038	229	-08.5
5	18:24:05	Halo	360	326	04.6

Table 1. Solar flares (left) and CMEs (right) during 00h-20h(UT)of February 14,2011

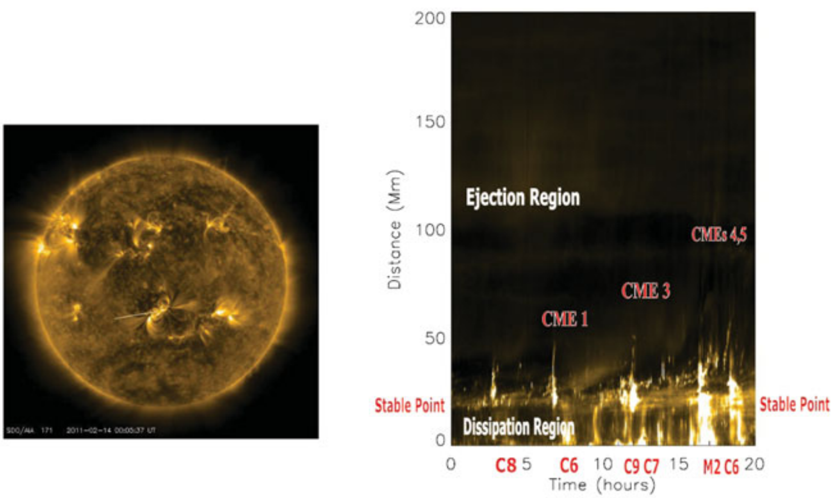

Figure 3. AIA 171Å image(left) and space-time diagram from a small sector area of the AIA images (right)

non-radial. This case analysis demonstrates that the topological framework determines the erupting frequency and main attack direction of solar eruptions, and plays a role like the frontier surface where violent solar events frequently happen.

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Another case is AR 12192 on October 24, 2014, the largest active region in the solar cycle 24. The data set includes SDO/HMI vector magnetograms; SDO/AIA 171Å images. It is well known that when this active region rotated onto the disk, it only had flares, but no CMEs. The analysis on the topological framework demonstrates that the magnetic flux involved in ejections is not open, and ejected particles return to the lower atmosphere. An enhanced study should be done since the size of this active region is very large.

5. Summary

With a special method to deal with the boundary condition, in which observed vector fields are incorporated as part of the bottom boundary conditions consistently, we are able to reconstruct 3D magnetic fields in the corona as force-free fields and then determine the topological framework. The analyses on two cases demonstrate that the magnetic topological framework in solar active regions plays a role like the frontier surface where violent solar events frequently happen. This situation could be termed as solar magnetic synoptic meteorology. The erupting frequency and the main attack direction of solar eruptions can be forecasted according to properties of topological features obtained from numerical computation. The numerical short-term solar activity forecasting provides our users new products.

In order to improve the numerical short-term solar activity forecasting, the following points should be emphasized: improved models for coronal magnetic field reconstruction; reliable tools for magnetic topological analysis; improved solutions to the MHD equations.

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