Visualizing and predicting CMEs and geomagnetic storms from solar magnetic fields

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Because solar photospheric magnetic fields are the main source of the magnetic field in the corona and interplanetary space, changes in the photospheric field may be expected to drive transients in both regions. However, because the solar field is both complex and influenced by the solar wind, it is difficult to determine whether specific photospheric field features underlie the important transients called Coronal Mass Ejections (CMEs). Models enable us to link the photospheric field to coronal field changes and visualize the response. The potential field source surface (PFSS) model is known for its combination of relative simplicity and ability to approximate coronal hole geometry and eclipse images. We utilize PFSS models and specialized synoptic maps of the solar magnetic field to study the relationship between coronal field changes and CMEs, and to attempt to predict CMEs and geomagnetic storms. For prediction purposes, updated synoptic maps in real time are needed. Several solar observatories and SOHO/MDI are currently providing such maps on a roughly daily basis, although the potential exists for hourly updates. Our results to date suggest that the combination of photospheric field observations and coronal models can provide a useful addition to the collection of space weather forecast tools.

1. INTRODUCTION

The existence of the solar magnetic field makes the sun more fascinating. The well known solar activity cycle, sunspots and many other interesting features are all at least in part due to magnetic fields. Essentially all solar activity, including the spectacular solar flares and CMEs, is due to magnetic energy release. Solar magnetic fields are carried out by solar wind and transient activities such as CMEs into interplanetary space. When the solar wind with the magnetic fields reaches the Earth, interaction with the geomagnetosphere occurs. Transients in the solar wind often create disturbances in the geomagnetosphere including geomagnetic storms.

The solar magnetic fields are both complex and influenced by the solar wind. It is difficult to determine whether specific photospheric field features underlie the important transients, CMEs. Coronal models enable us to link the photospheric magnetic fields to coronal field changes and visualize the responses. Existing coronal models include potential field source surface (PFSS), force free, and MHD models (Altschuler et al, 1977; Sakurai, 1981; Wu et al, 1990; Linker et al, 1999) Some of them have been applied in CME studies (Luhmann et. al., 1998; Mikic and Linker, 1994; Linker and Mikic, 1995). Each model has its particular advantages and problems. The PFSS model is known for its combination of relative simplicity and ability to approximate coronal hole geometry and eclipse images (Altschuler et al, 1977; Levine, 1982; Gibson et al., 1999; Zhao et al., 1999). We utilize PFSS models and specialized synoptic maps of the solar magnetic field to study the relationship between coronal field changes and CMEs, and attempt to predict CMEs and geomagnetic storms. This approach was first suggested in Luhmann et al (1998) .

2. SOLAR MAGNETOGRAPH AND SYNOPTIC MAPS

Full disk magnetograms are regularly available from several providers. Among these, Wilcox Solar Observatory (WSO) takes one or two magnetogram(s) per day, National Solar Observatory (NSO) at Kitt Peak takes one magnetogram per day, and Mt. Wilson Observatory (MWO) makes 10 observations per day. Global Oscillation Network Group (GONG) takes one magnetogram per hour at each site, and every 20 min within the network of six sites. SOHO/MDI takes one magnetogram per 96 min at the L1 point. All the observatories listed above make standard Carrington Rotation synoptic maps. Although the formats are basically the same, the resolutions and details of constructing the maps can be different from observatory to observatory.

The Carrington Rotation synoptic maps cannot meet the need of having new information on the magnetic fields in real time. "Daily updated" synoptic maps have been recently suggested by Hoeksema and Zhao, and are now routinely constructed at WSO, MWO, NSO and from SOHO/MDI data. Unlike the Carrington Rotation synoptic map, a daily updated synoptic map is constructed by merging the latest observation into the left side of the previous synoptic map and remove a corresponding portion of the old map from the right side. This provides the latest synoptic magnetic field information. This does not have to be daily, as updated maps can be made whenever there is a new full disk magnetogram. Therefore any time cadence of magnetograms can be used in the attempt to keep up with near realtime. Higher cadence updates are now available for MDI and GONG magnetograms, for which 24-hour observation also exist.

Daily updated synoptic maps use magnetic field measurements from the last observation to about 27 days ago. These measurements are merged to approximate the instantaneous global solar magnetic field. To better approximate the global field, a special map referred to as a synoptic frame was proposed by Zhao et al (1999). To approximate the global magnetic field at a certain time, these authors make a global map centered at the time of interest using measurements 13.5 days before and 13.5 days after, then replace the center portion using the full disk magnetogram at the time of interest. This gives the best approximation until we have measurements from the back of the sun. But synoptic frames obviously cannot be used in real time, because they depend on 13.5 days of later data. In this paper we show results only from the previously described daily updated maps.

3. OUR APPROACH

3.1. The method

The solar coronal magnetic field must respond to photospheric field changes. We assume that some of the responses give rise to CMEs. Our approach is based on the idea that we may be able to visualize the responses using photospheric field measurements and coronal models. Our first attempt, described here, uses PFSS models. PFSS models use photospheric magnetic synoptic maps as the inner boundary, and a "source surface" (usually at 2.5 Rs) as an outer boundary, where the assumption of radial magnetic field is applied. La Place's equation for the magnetic potential is solved in the space between the photosphere and the source surface (Altschuler et al, 1977; Hoeksema, 1995; Wang, 1995). The solution of the PFSS model is represented by spherical harmonics.

Using these solutions, we trace the coronal field lines from a fixed grid of starting points on the photosphere. We find that the first 9 harmonics are adequate for the WSO magnetograph resolution. But note that WSO resolution may become inadeqate around solar maximum due to the many active regions present on the disk. Field lines are traced for two consecutive updated synoptic maps starting from the same fixed grid, and are compared. Those field lines that change from closed at the earlier time to open at the next time are isolated and plotted. We refer to these field lines as newly opening field lines. For further description of the method, see Luhmann et al [1998]. If there are some newly opening field lines between the times of two maps, we assume there was a possibility for CME occurrence(s) between these times. In particular, if there are newly opening field lines near the solar disk center, an Earth-directed CME may have been generated.

3.2. Examples

Coronal field lines were traced for the two maps updated on August 24 00:34 UT and August 24 21:33 UT, 1998, resulting in the newly opening field lines shown in Figure 1. A group of field lines at the southeast limb, another at the northwest limb, and a group of field lines at the disk center were closed at 00:34 UT and open at 21:33 UT, at least as seen in the PFSS models. According to our assumption, the group of field lines near the disk center may indicate the occurrence of an Earth-directed CME sometime between the observation times of these two magnetograms.

Newly opening field lines between September 2, 20:02 UT and September 3, 22:44 UT, 1998 are shown in Figure 2. There are many newly opening field lines around the limb and the poles, but no field lines near the disk center. According to our assumption, this picture indicates that there should be no Earth-directed CME between these two observations.

Using the above results of the modeling, on August 24 we predict that there will be a geomagnetic storm during the following few days; and on September 3 we predict that there will be no geomagnetic storm in the following few days. Dst measurements from August 23 to September 10, 1998 by WDC at Kyoto are shown in Figure 3. We see a magnetic storm of the minimum Dst=-155 on August 27 and quiet geomagnetic condition several days following September 3.

3.3. Routine prediction web site and summary of the results

Our procedure for visualizing newly opening field lines has been automated to update every day using WSO daily synoptic maps, and posted at the www (http://sprg.ssl.berkeley.edu/mf_evol/) since mid 1998. Newly opening field line calculations and our estimated Dst index using real time ACE solar wind data (Fenrich and Luhmann, 1998) are running in parallel on the WWW. We monitor the newly opening field lines and cross check with the Dst predicitons routinely, although we chose to use Kyoto observed Dst index in this paper.

We present results for two months with the best coverage of the magnetograph observations at WSO. The results of the visualized newly opening field lines are color coded and displayed against Dst indices in Figure 4, where red color bars indicate that there are substantial numbers of newly opening field lines near the disk center on that day, green color bars indicate no newly opening field lines near the disk center, and yellow color bars indicate a few newly opening field lines near the disk center, but we are uncertain about their significance. July 1999 in the top panel was a geomagnetically quiet month. Our newly opening field line calculation showed mostly no field lines near the disk center (green), from which we predict no geomagnetic storms in the following few days. During this quiet month there were three cases with uncertain situations (yellow). Only on one day there were newly opening field lines near the disk center (red) followed by a small storm about two days later. September 1999, the bottom panel in Figure 4, has more geomagnetic activity or disturbances. We have many uncertain days in this month. The red case on the 4th was followed by only minor disturbances, which should be counted as a false alarm. As to the two red cases on the 11th and 12th, a storm of minimum Dst=-71 began on September 12, which was followed by a long disturbed period (about 10 days). The two red cases on September 20 and September 21 followed by a large storm of minimum Dst=-164 on September 23. In general, from the relative frequency of the yellow and red conditions, we would have predicted September to have been a more disturbed month overall.

Newly opening field line results from July 1998 to December 1999 have all been color coded and plotted against the Kyoto Dst index as in Figure 4. Since there have been many solar magnetogram data gaps mainly due to weather conditions, it is difficult to give statistics of successful and unsuccessful predictions with reasonable confidence. One interesting and important point is that almost all large storms were preceded, by a few days, by substantial newly opening field structure near the central meridian, subject to the availability of the solar magnetograms. But there are some "false alarms". As to "missed" cases, we cannot judge because of data gaps. Magnetograms and updated synoptic maps from other observatories can be used to confirm (or not) a particular prediction from WSO. This is expected to increase confidence in any given case, an approach we are currently testing.

4. REMARKS

Solar magnetic fields and their variations are complex. We have the following questions and concerns regarding our approach. (1). Can we distinguish CME related field changes from other changes? (2). What if the solar magnetic field changes more rapidly than our updates (especially near solar maximum). (3). How well can the PFSS model represent large scale coronal fields? (4). How serious is the problem that changes in the invisible hemisphere are not known? (5) Can our method tell us much about the potential geoeffectiveness of a particular CME (e.g., its strength of southward interplanetary magnetic field and/or speed)?

To address the above questions and concerns we have the following plans for future studies. (1). To search for additional information and criteria for selecting changing field lines that are related with CMEs or geoeffective CMEs. (2). To use SOHO/MDI data and GONG network data to look at higher cadence changes. (3). To look for more realistic model(s) (e.g., an affordable MHD model). (4). To use vector full disk magnetograms for boundary conditions (e.g., from SOLIS). (5). To use data from future missions that obtain global solar magnetic fields.

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Figure 1. Newly opening field lines between August 24 00:34 UT and August 24 21:33 UT, 1998. These field lines, starting from the same grid points on the photosphere, were all closed at 00:34 UT, and all open at 21:33 UT. The group of field lines at the disk center are thought to indicate the occurrence of an Earth-directed CME between the observation times. See text for details of the method to isolate newly opening field lines.

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