ON FLARE PREDICTABILITY BASED ON SUNSPOT GROUP EVOLUTION

M. B. KORSÓS, A. LUDMÁNY, R. ERDÉLYI, AND T. BARANYI

1 Debrecen Heliophysical Observatory (DHO), Research Centre for Astronomy and Earth Sciences, Hungarian Academy of Science, 4010 Debrecen, P.O. Box 30, Hungary; korsos.marianna@csfk.mta.hu, ladmany.andras@csfk.mta.hu, robertus@sheffield.ac.uk, baranyi.tunde@csfk.mta.hu
2 Solar Physics & Space Plasma Research Center (SP2RC), University of Sheffield, Hounsfield Road, Sheffield S3 7RH, UK

Received 2015 January 18; accepted 2015 March 12; published 2015 April 1

ABSTRACT

The forecast method introduced by Korsós et al. is generalized from the horizontal magnetic gradient ($G_M$), defined between two opposite polarity spots, to all spots within an appropriately defined region close to the magnetic neutral line of an active region. This novel approach is not limited to searching for the largest $G_M$ of two single spots as in previous methods. Instead, the pre-flare conditions of the evolution of spot groups is captured by the introduction of the weighted horizontal magnetic gradient, or $WG_M$. This new proxy enables the potential to forecast flares stronger than M5. The improved capability includes (i) the prediction of flare onset time and (ii) an assessment of whether a flare is followed by another event within about 18 hr. The prediction of onset time is found to be more accurate here. A linear relationship is established between the duration of converging motion and the time elapsed from the moment of closest position to that of the flare onset of opposite polarity spot groups. The other promising relationship is between the maximum of the $WG_M$ prior to flaring and the value of $WG_M$ at the moment of the initial flare onset in the case of multiple flaring. We found that when the $WG_M$ decreases by about 54%, then there is no second flare. If, however, when the $WG_M$ decreases less than 42%, then there likely will be a follow-up flare stronger than M5. This new capability may be useful for an automated flare prediction tool.

Key words: Sun: flares – sunspots

1. INTRODUCTION

The endeavor to establish reliable flare forecast methods has resulted in numerous attempts to identify promising physical quantities, proxies, features, and behavioral patterns to predict an imminent flare (see, e.g., Sawyer 1986; Hochedez et al. 2005; Benz 2008). The ultimate task is to construct a diagnostic tool that determines the unique conditions leading to flaring events triggered by magnetic reconnection (see, e.g., Yamada et al. 2010). The empirical study presented here focuses on features at the solar surface, namely investigating the pre-flare dynamics of sunspot groups.

Most of the attempts to develop flare forecast tools have employed suitably defined (and derived) quantities from magnetograms. The majority of previous efforts studied the behavior of the horizontal gradient of the line of sight component of the magnetic field, usually a well-observed property of an active region (AR). By investigating the Solar and Helioseismic Observatory’s Michelson Doppler Imager (SOHO/MDI) magnetograms, Schrijver (2007) found that energetic flares are connected to the separation line of opposite polarity regions with high magnetic gradient. Further works followed suit, including, e.g., Mason & Hoeksema (2010) who studied the gradient-weighted inversion line length which exhibits a significant increase prior to flares. The maximum horizontal gradient and the length of the neutral line were considered by Cui et al. (2006), Jing et al. (2006), Huang et al. (2010), and Yu et al. (2010). The fractal structure was addressed by Abramenko et al. (2003) and Criscuoli et al. (2009); however, Georgoulis (2012) was skeptical about this approach.

In the literature, there are a number of other indicators proposed to measure non-potentiality. Leka & Barnes (2007) suggested 8 categories of different distributions with an impressive list of 29 types of variables defined on them. All these methods above (and others) have advantages and caveats, however, none are yet accepted as a universal and reliable prediction tool.

Surprisingly, sunspots themselves are rarely considered as possible holders of information for flare forecast. Arguably, the simplest way to apply sunspot data is to approach non-potentiality by using their McIntosh classification (Bloomfield et al. 2012). However, the McIntosh classes are only based on morphology, and they do not contain what is perhaps the most important information relevant to the present context, i.e., the distribution of opposite magnetic polarities. Our preceding study (Korsós et al. 2014, hereafter Paper I) is the first attempt to track the details of the evolution of sunspots (umbrae) in order to identify signatures of flare imminence. Paper I implemented a proxy horizontal magnetic gradient, $G_M$, defined between two single spots of opposite polarities close to the magnetic neutral line. The pre-flare behavior of this proxy quantity exhibited characteristic and unique patterns: a steep rise, a high maximum, and a gradual decrease prior to flaring. These properties may yield a tool for the assessment of flare probability and intensity within a 2–10 hr window.

The method developed here allows us to elaborate on some of the most important properties of an imminent flare: its intensity and its onset time. The prediction of intensity is found to be more reliable, as a linear relationship has been found between the pre-flare maximum of $G_M$ and the peak intensity emitted in the 1–8 Å range, according to Geostationary Operational Environmental Satellite (GOES) X-ray measurements. This result may be considered to be an indicator of the existing relationship between the proxies of free and released energies. Next, the onset time prediction is found to be somewhat less precise, as the most probable time of flare onset is between 2 and 10 hr after the $G_M$ maximum. The aim of the present work is to find more reliable forecasting methods for the onset time as well as the likelihood of consecutive flaring.

http://www.ngdc.noaa.gov/stp/satellite/goes/dataaccess.html
2. METHOD OF EXAMINATION

The empirical basis of this study, similar to Paper I, is the SDD (SOHO/MDI-Debrecen Data) sunspot catalog, the most detailed of its kind covering the years of MDI operations (1996–2010). In addition, the intensity peaks of the examined flares in the GOES solar flare database are employed. The SDD is efficient for tracking the internal dynamics of spot groups. It contains data on position, area, and magnetic field for all spots with a cadence of 1.5 hr (Györi et al. 2011).

Let us now consider the involvement of all magnetic spots in an appropriately selected area at the region of a Polarity Inversion Line (PIL). When a new spot (min. 3 MSH) emerges close (within 40 ± 5 Mm, which is always enough to capture the emergence) to the existing spots of opposite polarity, we determine the maximum $G_M$ between the emerging and existing spots. Once a pair of spots of opposite polarities with a maximum $G_M$ is found, we compute the area-weighted center between them. Next, there is a defined circular area around this weighted location where $G_M$ is highest, whose diameter is $3^\circ$ ± 0.5 in Carrington heliographic coordinates. The center of the circle is fixed and spot groups within this area are now monitored.

We assume that the underlying process driving a flare is a collective one between nearby spots. Therefore, a new proxy parameter, a generalization of the GM collective one between nearby spots. Therefore, a new proxy is found, we compute the area-weighted center

$$W_G = \frac{\sum B_{p,i} \cdot A_{p,i}}{d_{pm}}$$

Here, $B$ (determined by $f(A)$ in Paper I) and $A$ denote the positive and negative polarities, $i$ and $j$ are their running indices in the selected spot cluster, and $d_{pm}$ is the distance between the area-weighted centers of two subgroups of opposite polarities in this cluster.

We have analyzed 45 single and 16 multiple flare cases that are stronger than M5 between 1996 and 2010. This limitation is based on the findings of Paper I, i.e., the present method seems to be suitable for energetic flares above M5. Besides some similarities between the behavior of $G_M$ and $W_G$, the current approach results in significant, previously unseen pre-flare behavioral patterns. Let us demonstrate the key features with two randomly selected, but typical, examples.

Figure 1 shows a typical AR, AR 8771, with a single flare. The right-hand panels of Figure 1 are: the white light image (top), magnetogram (bottom), and a cartoon reconstructing the AR from the SDD catalog (middle). The $W_G$ (top left) shows a steep rise and a high maximum (called $W_G^{\max}$) followed by its decrease until the $G_M$ is highest, whose diameter is $3^\circ$ ± 0.5 in Carrington heliographic coordinates. The center of the circle is fixed and spot groups within this area are now monitored.

3. DIAGNOSTIC POTENTIALS WITH SPOT DYNAMICS

We test the proposed diagnostics on a statistical sample by applying the following requirements. First, the examined pre-flare variation is within $\pm 70^\circ$ from the central meridian to avoid geometrical foreshortening close to the limb. Next, the flare onset is no further eastward from the central meridian than $-40^\circ$ to have sufficient time to follow the development of $W_G$.

In Paper I, a linear relationship was found between the maximum value of $G_M$ preceding a flare and the peak intensity of flares. This behavior is confirmed for $W_G$ by Figure 3, 45 single flares (crosses, left panel) and 45 single with additional 16 largest of multiple flares (circles, right panel) show a linear relationship between $W_G^{\max}$ and the corresponding GOES flare...
Figure 1. NOAA AR 8771, for 1999 November 23–26. Right column: continuum white-light image (top), reconstruction from SDD (middle), and magnetogram (bottom). Left column: variation of $W_{Gm}$ (top), distance between the area-weighted centers of the spots of opposite polarities (middle), and unsigned flux of all spots in the encircled area (bottom).

Figure 2. Same as Figure 1, but of NOAA AR 9393 with a single (i.e., X1.7) and multiple (i.e., X1.4 and X20) flares, for 2001 March 26 April 3.
intensity. Here, we restrict the empirical analysis for flares between M5 and X4 classes only.

Next, the new method revealed further important connections, which are conspicuous in Figures 1 and 2. This connection is between the durations of the converging–diverging motion of the centers of opposite polarities. This intriguing pattern was found in all 61 cases investigated here. The question rises as to whether there is a relationship between the duration of the converging motion (the duration from the moment of the first point when the distance began decreasing to the moment of the minimum point of the parabolic curve) and the time elapsed from the moment of minimum distance until the flare onset (duration of the diverging motion and the follow-up time until the flare onset). To determine these two time intervals for each flare, parabolic curves were fitted to their distance data. For a sample see the top left panel of Figure 4 which is a parabolic fit to the distance data from the left middle panel of Figure 1, showing the converging–diverging behavior of this relative motion.

Figure 4 gives further insight into the relation between these intervals by plotting the time from the moment of minimum distance to the flare onset as a function of the duration of converging motion. First, the upper right diagram depicts the duration of diverging motion as a function of the duration of converging motion for the 45 single (crosses) and 16 multiple (circles) flare cases. Note that the duration of diverging motion is shorter than the time period from the moment of minimum distance to that of the flare onset (see bottom panels of Figure 4). However, the converging-motion phase and the diverging-motion phase have the same duration. Yamada et al. (2010) found similar properties in laboratory reconnection experiments and called them the “push and pull-mode.” The present observations are a confirmation of those laboratory experiments.

The lower diagrams plot the time from the moment of closest position to the flare onset as a function of the duration of the converging motion phase. In the cases of multiple flares, we investigated the time from the moment of closest position to the first flare onset as a function of the duration of the converging motion phase. The left/right panel contains those cases when the spot groups are younger/older than 3 days at the time of flare onset. The regression lines of the two cases are, surprisingly, different. By estimating the time the magnetic fields younger than 3 days should be distinguished from the older ones, the relevant formulae are given in the lower panels of Figure 4. One may be able to estimate a rough onset time of the flare. Note the considerable dispersion. If the study area is younger than 3 days then about a mere hour is needed to be added to the duration of the corresponding scaled duration of converging motion where the scale factor is 1.3 for younger ones to obtain the flare onset time. However, if the area is older than 3 days then the scale factor is 0.85, and one needs to add $12 \pm 3$ hr to the scaled duration of converging motion.

Next, a relationship is found between the values of $W_{GM}$ at its maximum prior to flaring ($W_{GM}^{\text{max}}$) and at the time of flare onset ($W_{GM}^{\text{Flare}}$), as visualized in Figure 5. We investigate separately the 45 cases when only a single flare took place after the maximum of $W_{GM}$, and the 16 cases when more flares erupted after the maximum within an 18 hr window after the occurring flare on the decreasing phase of the $W_{GM}$. The left panel depicts the cases of single energetic flares (crosses). The right panel depicts the first flares (circles) of those ARs where multiple flares are produced. The plots are interpreted as follows: a single flare erupted when the $W_{GM}^{\text{max}}$ was less than $5 \times 10^{6}$ Wb m$^{-1}$ and the $W_{GM}$ decreased by more than half of the $W_{GM}^{\text{max}}$ in the pre-flare phase (for example, the X1.4 flare in the NOAA 8771 in Figure 1 and the X1.7 flare in the AR NOAA 9393 in Figure 2). This is likely due to the fact that the magnetic energy in the region decreases so significantly during this first flare that there is simply not enough energy left to release another flare. In that case, if the decrease is smaller than half (about 42%) by the onset of the first flare, some further flaring may be expected, meaning that the disturbance of this first flare could be forcing opposite polarity fields together in the solar atmosphere leading, for example, to the “homologous” flaring that is often observed. On the other hand, a $W_{GM}^{\text{max}}$ larger than $5 \times 10^{6}$ Wb m$^{-1}$ seems to be enough in itself to predict a multiple flaring event. We cannot comment yet on further flares (i.e., third, etc.) in the case of multiple flares as the temporal resolution of the SDD catalog is too coarse. For an example, see the case of AR NOAA 9393 where an X 1.4 flare was followed by an X 20 one within 12 hr (Figure 2).
In this paper, we present advancements in the classification of pre-flare conditions with an application to flare prediction. Sixty-one cases were investigated in the vicinity of PILs of ARs. We assumed the flare onset to be a collective response to their dynamics. This assumption needs further investigations both observationally (with higher resolution) and theoretically (e.g., numerical simulations).

First, we found that the pre-flare behavior of the weighted horizontal magnetic gradient ($W_G^m$) exhibits similar patterns to those found with the single spot-pair method: a steep rise, a high maximum, and a gradual decrease until flare onset as a function of duration of the compressing phase of motion of opposite polarities. The study area is younger (left)/older (right) than 3 days.

4. DISCUSSION

Figure 4. Upper left: the converging–diverging pattern with a parabolic fit to the data for AR 8771. Upper right: relationship between the durations of the converging and the diverging motion for all 61 flares. Crosses (45)/circles (16) indicate a single/the first of multiple flares. Please note that the apparent number of points may not be 45/16 in the plots because there are overlapping data points. Lower panels: duration of diverging motion until flare onset as a function of duration of the compressing phase of motion of opposite polarities. The study area is younger (left)/older (right) than 3 days.

Figure 5. Weighted horizontal magnetic gradient at flare onset $W_G^m_{\text{flare}}$ as a function of the maximum of the weighted horizontal magnetic gradient prior to flare $W_G^m_{\text{max}}$. Left panel: cases of a single flare. Right panel: first events of multiple flares after $W_G^m_{\text{max}}$.
confirm or refute this relation. There may be a yet unknown physical parameter not accounted for that would reduce the dispersion. This is the reason for the restriction on the currently considered GOES classes. However, the relationship found can still be regarded as a link between the proxy measures of the free energy and the released energy. A shortfall of the single spot-pair method was that one could not deduce the free energy and the released energy. A shortfall of the single still be regarded as a link between the proxy measures of the GOES considered dispersion. This is the reason for the restriction on the currently con

The Astrophysical Journal Letters, 802:L21 (6pp), 2015 April 1

Let us assume that $W_{GM}$ is a proxy of the available non-potential (i.e., free) energy to be released in a spot group. In this case, we may conclude from Figure 5: (i) if the maximum of the released energy is over half of the maximum of the accumulated (free) energy, no further energetic flare(s) can be expected and (ii) if the maximum of the released flare energy is less than about ~42%, further flares are more probable. In short, Figure 5 allows us to track the variation of the energy balance of ARs and to assess the probabilities of consecutive flares and their intensities.

Last but not least we provide some notes on the estimate of the onset time of an imminent flare. Here, its determination is refined. Paper I only presented the statistic that 60% of observed energetic flares are between 2–10 hr after the maximum of $G_{GM}$. Figure 4, however, allows a much stronger statement on the expected time of onset due to $W_{GM}$. The figure uncovers the relationship between the duration of the converging motion of opposite polarities (their compression) and the time elapsed between the closest position and flare onset following the diverging motion (see earlier motions; Yamada et al. 2010). By determining the duration of the converging motion, the flare onset can now be assessed for all cases. We also found that the data points of the motions of younger spot groups have smaller dispersion (left of Figure 4).

The research leading to these results has received funding from the European Community’s Seventh Framework Programme (FP7/2012-2015) under grant agreement No. 284461 (eHEROES project). M.B.K. and R.E. are grateful to the Science and Technology Facilities Council (STFC), UK for the financial support received. R.E. is grateful for the invitation, support, and hospitality received from the Hungarian Academy of Sciences under their Distinguished Guest Scientists Fellowship Programme (Ref. No. 1751/44/2014/KIF) which has allowed him to stay for three months at the Debrecen Heliophysical Observatory (DHO) of the Research Centre for Astronomy and Earth Sciences, Hungarian Academy of Sciences. R.E. is also grateful to NSF, Hungary (OTKA, Ref. No. K83133).

REFERENCES

Abramenko, V. I., Yurchyshyn, V. B., Wang, H., et al. 2003, ApJ, 597, 1135
Benz, A. O. 2008, LRSF, 5, 1
Bloomfield, D. S., Higgins, P. A., McAtreer, R. T. J., et al. 2012, ApJL, 747, L41
Criscuoli, S., Romano, P., Giorgi, F., et al. 2009, A&A, 506, 1429
Cui, Y., Li, R., Zhang, L., et al. 2006, SoPh, 237, 45
Georgoulis, M. K. 2012, SoPh, 276, 161
Györi, L., Barányi, T., & Ludmány, A. 2011, in Proc. IAU Symp. 273, The Physics of Sun and Star Spots, ed. D. P. Choudhary, & K. G. Strassmeier (Cambridge: Cambridge Univ Press), 403
Hochedez, J.-F., Zhukov, A., Robbrecht, E., et al. 2005, AnGp, 23, 3149
Huang, X., Yu, D., Hu, Q., et al. 2010, SoPh, 263, 175
Jing, J., Song, H., Abramenko, V., et al. 2006, ApJ, 644, 1273
Korsós, M. B., Barányi, T., & Ludmány, A. 2014, ApJ, 789, 107 (Paper I)
Leika, K. D., & Barnes, G. 2007, ApJ, 656, 1173
Mason, J. P., & Hockeema, J. T. 2010, ApJ, 723, 634
Sawyer, C. 1986, Solar Flare Prediction (Boulder, CO: Univ. Press Colorado)
Schrijver, C. 2007, ApJL, 655, L117
Yamada, M., Kulsrud, R., & Ji, H. 2010, RvMP, 82, 603
Yu, D., Huang, X., Hu, Q., et al. 2010, ApJ, 709, 321