SIGN SINGULARITY AND FLARES IN SOLAR ACTIVE REGION NOAA 11158

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ABSTRACT

Solar Active Region NOAA 11158 has hosted a number of strong flares, including one X2.2 event. The complexity of current density and current helicity are studied through cancellation analysis of their sign-singular measure, which features power-law scaling. Spectral analysis is also performed, revealing the presence of two separate scaling ranges with different spectral index. The time evolution of parameters is discussed. Sudden changes of the cancellation exponents at the time of large flares and the presence of correlation with Extreme-Ultra-Violet and X-ray flux suggest that eruption of large flares can be linked to the small-scale properties of the current structures.

Key words: Sun: flares – Sun: magnetic fields – turbulence

Supporting material: animation

1. INTRODUCTION

Solar magnetic activity is often accompanied by spectacular, abrupt phenomena, such as solar flares (Benz 2008) and coronal mass ejections (Chen 2011). These eruptive, highly energetic features can produce variations in the Sun–Earth connection, resulting, for example, in geomagnetic storms and other disturbances that can affect human activities and health (Schwenn 2006; Pulkkinen 2007). The increasing amount and the improved quality of solar observations from both space and Earth have provided enormous advances in the understanding of the physical processes occurring in the solar regions associated with flares, i.e., the solar active regions (ARs). These are regions where the emerging photospheric magnetic field concentrates in bipolar or multipolar structures, which may include the presence of pores and sunspots. Driven by convective motions of the layers in the outer convection zone of the Sun, magnetic fields may become entangled and twisted in ARs, therefore storing a nonpotential magnetic energy. The rapid release of such energy, probably due to magnetic reconnection processes, is thought to be the basic mechanism of solar flares (Carmichael 1964; Sturrock 1968; Hirayama 1974; Kopp & Pneuman 1976; Priest & Forbes 2002; Benz 2008; Krucker et al. 2008; Fletcher et al. 2011; Shibata & Magara 2011; Su et al. 2013).

One important topic in solar physics is the identification of magnetic signatures of the occurrence of flares within ARs. In recent years, confirming evidence of the turbulent nature of the ARs magnetic field dynamics has emerged (Abramenko & Yurchyshyn 2010b). In this context, the complexity of the photospheric magnetic field structure arises from the strongly nonlinear, coupled interactions between the plasma flow and magnetic fluctuations on different scales and results in the superposition of correlated structures (Frisch 1995; Biskamp 2003). Typical power-law spectra of photospheric magnetic energy have been reported (Abramenko 2005; Zhang et al. 2014), with spectral indexes compatible with a turbulence-type phenomenology (Kolmogorov 1941; Frisch 1995). Turbulent photospheric magnetic fields have also been described as intermittent and multifractal (Abramenko & Yurchyshyn 2008, 2010b), features which are typical of turbulent plasmas. This implies the presence of a hierarchy of correlated fluctuations, which concentrates energy on localized, small-scale structures, where enhanced dissipation occurs.

In order to capture the dynamical properties of the intermittent structures, cancellation analysis has recently been used with the aim of correlating the complexity of solar magnetic fields in ARs to the occurrence of flares (Abramenko et al. 1998; Yurchyshyn et al. 2000, 2012; Sorriso-Valvo et al. 2004). Such analysis has highlighted the importance of sign singularities in the energy storage process that could lead to flare eruption. In this paper we use for the first time cancellation analysis to describe the fine time and space resolution dynamics of AR NOAA 11158. Corroborated by the study of other observables, this analysis confirms the presence of nontrivial correlations between the topological changes of magnetic structures and flaring activity.

2. SIGNED MEASURE AND CANCELLATION ANALYSIS

Solar ARs are often characterized by scale-dependent formation of energetic and localized magnetic structures (Abramenko et al. 1998). Because of their coherence, structures can be viewed as smooth regions of the magnetic field, embedded in a highly fluctuating background. For zero-mean fields, they can be associated with scale-dependent, signed fluctuations of the fields. By introducing a signed measure (as opposed to the usual positive defined probability measure), it is possible to characterize the scaling properties of sign oscillations (or sign persistence) of the fields (Ott et al. 1992). Therefore, the presence and the topological characteristics of sign-defined structures can be studied. Signed measure has been successfully used to describe the cancellation properties of the magnetic dynamo (Ott et al. 1992), as well as the characteristics of current structures in turbulent magnetohydrodynamic (MHD; Sorriso-Valvo et al. 2002; Graham et al. 2005), Hall-MHD (Martin et al. 2013), and kinetic (Wan...
et al. 2012; De Vita et al. 2014] numerical simulations. Applications to measurements of magnetic vectors in solar ARs have confirmed cancellation analysis as an interesting tool to detect changes in the scaling properties of the field fluctuations and of the fractal dimension of the associated gradients (Abramenko et al. 1998; Yurchyshyn et al. 2000; Sorriso-Valvo et al. 2004).

The signed measure of a zero-mean scalar field \( f(\mathbf{r}) \) can be defined on a \( d \)-dimensional set \( Q(L) \) of size \( L \) as follows (Ott et al. 1992). Let \( \{ Q_i(l) \subset Q(L) \} \) be a partition of \( Q(L) \) in disjoint subsets of size \( l \). Then, for each scale \( l \) and for each disjoint box \( Q_l(l) \), the signed measure is

\[
\mu_i(l) = \frac{\int_{Q_i(l)} d\mathbf{r} f(\mathbf{r})}{\int_{Q(L)} d\mathbf{r} |f(\mathbf{r})|}. \tag{1}
\]

When the size of the subset \( Q_i(l) \) is large, cancellations between small structures of opposite sign occur within each box, resulting in small contribution to the signed measure. However, as the boxes become smaller and reach the typical size of the structures, each one is more likely to contain one single, sign-defined structure, reducing the level of cancellations. The way this happens can be statistically characterized through the cancellation function

\[
\chi(l) = \sum_{Q_i(l)} |\mu_i(l)| \tag{2}
\]

where the sum is extended to all disjoint subsets \( Q_i(l) \). Contrary to positive defined probability measures, the signed measure holds information on the sign of the field fluctuations. In particular, if the measure changes sign on an arbitrarily fine scale (i.e., if for any subset \( Q_A(l) \) for which \( \mu_A(l) = 0 \) there exists a subset \( Q_B(l') \subset Q_A(l) \) such that \( \mu_B(l') \) has opposite sign from \( \mu_A(l) \)), then the measure is called sign-singular (Ott et al. 1992). Upon performing a scale-dependent partition of the whole domain, the sign-singularity of the measure can be quantitatively estimated through the cancellation exponent \( \kappa \), that is the scaling exponent of the cancellation function, defined as

\[
\chi(l) = \sum_{Q_i(l)} |\mu_i(l)| \sim l^{-\kappa}, \tag{3}
\]

where the sum is extended to all disjoint subsets \( Q_i(l) \) that cover the domain \( Q(L) \). The cancellation exponent represents an effective measure of the efficiency of the field cancellations. Specific examples are represented by a smooth field (with no sign-singularity), for which the cancellation function has a constant value (so that \( \kappa = 0 \)), and by a homogeneous field with random discontinuities (i.e., Brownian noise), for which \( \kappa = d/2 \). Cancellation exponents between those two limiting values indicate the presence of smooth structures embedded in random fluctuations. Moreover, their values can be related to the geometrical properties of structures. It is possible, indeed, to establish a phenomenological relationship between the cancellation exponent and the fractal dimension \( D \) of the typical dissipative structures of the flow (Sorriso-Valvo et al. 2002),

\[
\kappa = (d - D)/2. \tag{4}
\]

On the other hand, cancellation exponents larger than the typical value for random fields \( \kappa > d/2 \) indicate the presence of enhanced cancellations with respect to random fluctuations. This is normally attributed to the presence of sign antipersistent structures, i.e., pairs of adjacent structures of opposite sign. It should be pointed out that the use of one single fractal dimension cannot fully capture all the fine details of the typical plasma turbulence processes, which are more likely characterized by multifractal scaling (Muller & Biskamp 2000). Nonetheless, \( D \) still represents a useful indicator of the topological characteristics of the “mean” intermittent structures of the flow.

3. SOLAR AR NOAA 11158

3.1. Observations and Data Reduction: AR 11158

In order to perform the cancellation analysis of a solar AR, we derived the temporal evolution of magnetic fields in NOAA 11158, using a series of high-resolution vector magnetograms. A 6 days uninterrupted, 12 minute cadence data set allowed us to study in detail the long-term, gradual evolution, as well as the rapid changes during an X-class flare. In this section we describe the data set and the reprojection we used.

NOAA 11158 was the source of an X2.2 flare on 2011 February 15 starting at 01:44 UT, peaking at 01:56 UT, and ending at 02:06 UT. A front-side halo CME accompanied the flare (Schrijver et al. 2011). Prior to the X2.2 flare, the largest flare in this region was an M6.6 on 2011 February 13 at 17:28 UT, a little more than 30 hr before the largest flare under study.

The Helioseismic and Magnetic Imager (HMI) of NASA’s Solar Dynamics Observatory (SDO) satellite (Pesnell et al. 2012) observed the NOAA 11158 in high detail, routinely generating filtergrams in six polarization states at six wavelengths on the Fe I 617.3 nm spectral line. From these filtergrams, images for the Stokes parameters, I, Q, U, and V, were derived, which, using the Very Fast Inversion of the Stokes Algorithm code (Borrero et al. 2011), were inverted into the magnetic field vector components. To resolve the 180° azimuthal field ambiguity we used the “minimum energy” method (Metcalf et al. 1994; Leka et al. 2009). In addition, we corrected a few episodes of single-frame fluctuations in the direction of the transverse magnetic field vector by nearly 180° (Welsch et al. 2013). To study preflare photospheric magnetic evolution and to baseline this evolution against postflare evolution, we retained 153 hr of 12 minute-cadence 0.5°, pixel-resolution HMI vector-magnetogram data from the beginning of the AR emergence, around 4 days before the X2.2 flare, to 2 days after the flare: \( t_{\text{start}} = 2011 \text{ February 10 14:11 UT (S19, E50)}, t_{\text{end}} = 2011 \text{ February 16 23:35 UT (S21, W37)} \).

In order to account for the nonzero viewing angle of the observed vector magnetic fields and Doppler velocities, we reprojected the HMI-data cube to the disk center and transformed it to Cartesian coordinates (Welsch et al. 2013). To do that, in the first step we reprojected the observed magnetic vectors’ components onto radial/horizontal coordinate axes. We then determined the shift of the grid’s center between frames. After we determined a shift, we converted—and then translated by the decided-upon shift—the Cartesian grid’s points to line-of-sight/plane-of-sky (LOS/POS) coordinates. We then interpolated the radial and horizontal components of the magnetic field, \( B_r, B_\theta \) onto the grid. Finally, we interpolated data in LOS/POS coordinates onto a fixed, Cartesian grid that accounts for shifts. This interpolation implied a reprojection of the magnetogram surface from
spherical to a regular, Cartesian grid based on the Mercator reprojection, with regular longitudes/latitudes (Welsch et al. 2009). After reprojection, to preserve physical quantities of magnetic fields and velocities, we corrected the fluxes for the distortion of pixel areas introduced by reprojection; the details of the applied correction factors are given in appendix A of Kazachenko et al. (2014). For the minimum magnetic field to consider, we chose a threshold of $|B| = 250$ Gauss, consistent with the upper limit of the uncertainty in the horizontal magnetic field (Liu et al. 2012). To avoid spurious signals in magnetic fields, we applied a mask, where we set any pixel’s magnetic field components to zero, if in any of the three consecutive frames it has $|B| < 250$ Gauss. We also added a boundary area, 55 pixels in width and height, padded with zeros (Kazachenko et al. 2014). The final data cube after reprojection and addition of the boundary area consists of 768 time steps ($\Delta t = 720$ s) and has a field of view of $665 \times 645$ pixels with a pixel size of 360.16 km, which is equivalent to the original 0.5” pixels HMI-data resolution. More details on the data cube preparation and calibration for a shorter time range can be found in Welsch et al. (2013).

Figure 1 shows the final magnetic field components in a subregion of the full-disk data array after reprojection at two different times of the magnetogram sequence on 2011 February 12 at 22:24 UT (left panels) and on 2011 February 14 at 03:24 UT (right panels), namely, before and after the complete AR magnetic flux emergence. The black solid line box indicates the reduced area used for the cancellation analysis. From the figure, the evolution of the magnetic structure of the AR is evident. The full time evolution of the magnetic field component $B_z$ will be illustrated in the movie linked as supplemental material to Figure 8 in Section 5, where it is possible to visualize the clear flux emergence, and the successive increase of the magnetic complexity. The positive and negative magnetic fluxes, shown in Figure 2, balance each other; the magnetic flux increases from essentially zero to roughly $1.4 \times 10^{22}$ Mx at the time of the X2.2 flare (vertical dashed line).

3.2. Preliminary Analysis and Complementary Measurements

In this section we introduce the fields and parameters obtained from the magnetograms, which have been used for our analysis.

The measurements of the magnetic field vector allowed us to calculate the current density component perpendicular to the solar surface, $J_z$, shown in panels (a) and (b) of Figure 3 at the same two times presented in Figure 1. The vertical component of the current density $J_z(x, y)$ has been estimated through the photospheric vector magnetic field $B(x, y)$, where $(x, y)$ are the
Cartesian coordinates of the Mercator deprojected observations, as the line integral of the transversal component of the magnetic field over a closed contour $G$:

$$4\pi J_i/c = (\nabla \times B)_i = s^{-1} \oint_G B \cdot dr. \quad (5)$$

The integral along the contour $G$ of each pixel of area $s = (0.361 \times 0.361)\text{Mm}^2$ was computed using Simpson’s rule and the field values on the four pixels adjacent to $G$. Note that alternative techniques for the calculation of the current gave identical results. Previous studies of cancellations in solar AR have shown that it is convenient to use the current helicity $H_c = J \cdot B$ (Abramenko et al. 1998; Jing et al. 2012). In fact, this field carries important information about the nonpotential magnetic energy available in the AR. Furthermore, it is normally less noisy than the current density, so that cancellation effects are easier to identify. As a matter of fact, previous analyses were unable to identify sign-singularities in the current density. These were only observed in current helicity (Abramenko et al. 1998; Yurchyshyn et al. 2000, 2012; Sorriso-Valvo et al. 2004). It should be pointed out that because it is not possible to measure the full current density vector with the available two-dimensional magnetic field measurements, in this work we limit our discussion to the current vertical component and the reduced current helicity $h_c(x, y) = Bz(x, y)J_z(x, y)$ and assume that they are good approximations of the corresponding full quantities (Abramenko et al. 1998; Jing et al. 2012). Panels (c) and (d) of Figure 3 show, for the same two snapshots as in the previous figures, the estimated current helicity, which has a smoother appearance than the current $J_z$, as expected. The movie linked to Figure 8 also reproduces the full temporal evolution of the current density and helicity fields, highlighting the important establishment of the AR current structure at one given time (see below).

In order to describe the overall properties of the AR, some useful global quantities can be estimated for each snapshot of the time series.

The amount of power connected to small-scale magnetic fields can be quantitatively visualized through the typical fluctuation level of the magnetic field vector, $B_{\text{rms}} = (\delta B_x^2 + \delta B_y^2 + \delta B_z^2)^{1/2}$, where $\delta B_i = B_i - \langle B_i \rangle$ are the fluctuations of the $i$th magnetic field component, and the brackets indicate spatial average over the whole AR at one given time.

Another useful quantity is the mean squared current $\langle J_i^2 \rangle$, the spatial average being again estimated over the whole AR. Being proportional to the level of small-scale gradients, this quantity is related to the level of dissipation of magnetic energy and is customarily used in numerical simulations to describe the evolution of turbulence (Mininni et al. 2006; Perrone et al. 2013).

Finally, because we aim to connect the magnetic properties of the AR with the occurrence of flares, we have collected the measurements of the X-ray (X) and Extreme-Ultra-Violet (EUV) fluxes, as measured by GOES and AIA/SDO (131 Å channel), respectively. GOES provides the X-ray flux measurements integrated over the whole solar disk. This could include in the measurement flaring activity from other ARs. However, we have checked that during the time interval under study the X-ray flux was mainly originated in NOAA 11158. On the contrary, the EUV flux measurement retains the spatial information. Images taken at the 131 Å band pass have been selected for their sensitivity to hot ($\sim$10 MK) plasma to complement the GOES data. Level 1.5 data (cutout service) have been used at a 12 minute cadence. The maps have been integrated over the AR NOAA 11158, using the same field of view as the magnetograms studied in this work, resulting in a time series of EUV emission from the area under study. Some data gaps are present in the EUV time series. For the statistical analysis, such gaps have been filled through cubic spline interpolation of the data. Note that during flaring times, the brightest parts of the flaring region are generally saturated. Therefore, the absolute value of the EUV emission does not correctly represent the intensity of the flare. Nevertheless, higher intensity might still represent larger flares, as generally large flares tend to have larger areas of saturated pixels. In any case, what is important for the study presented in this paper is that the time series indicates flaring times properly. Therefore the saturated pixels are not of importance for the conclusions drawn in this paper. Moreover, the correspondence with flare eruptions estimated through the X-ray flux avoids any ambiguity.

The temporal evolution of the parameters introduced in this section, namely, $B_{\text{rms}}(J_i^2)$, and the X-ray and EUV fluxes, will be described in detail in Section 5.

4. SCALING LAWS IN NOAA 11158: SPECTRAL AND CANCELLATION ANALYSIS

4.1. Spectral Analysis

In order to characterize the possible presence of turbulent-like behaviors in the AR magnetic field, for each snapshot of the time series we have calculated the (omnidirectional) magnetic power spectral density $E_B(k) = \int_{|k| \leq k} |B(k)|^2 dk$, where $k$ indicates the wave-vector (Zhang et al. 2014). The integral is calculated in a given wave-vector shell, i.e., for $|k| \approx k$. Examples of magnetic spectra are shown in Figure 4, at the same two times as in Figure 1, suggesting the presence of a power-law decay in the intermediate range of wave-vectors (the inertial range), approximately between $k = 1\$\text{Mm}^{-1}$ (or 6 Mm) and $k = 3.5\$\text{Mm}^{-1}$ (corresponding to 1.8 Mm). In this range, a power-law fit $E_B(k) \propto k^{-\alpha}$ (yellow line in Figure 4) provided the spectral index $\alpha_{\text{large}}$, where the subscript “large” was used to indicate that the value was obtained from the fit in
the larger-scale range. At the early stage of the AR emergence, the spectral power is smaller (Figure 4), the power law is less defined, and the spectral index is very variable. At later times, when the AR is emerging, the scaling exponent is more stable, $\alpha > 2$. This behavior is clearly visible in the supplemental material linked in Figure 8, where the movie reproduces the time evolution of the spectra. The observation of a power-law spectrum, with spectral index not very dissimilar to a turbulence-like phenomenology (typically, $\alpha \approx 5/3$ for a Kolomogorov phenomenology; see, e.g., Biskamp 2003), confirms once again that the AR magnetic fields can be studied in the framework of turbulent flows, as has already been suggested in the past (Abramenko & Yurchyshyn 2010b).

At larger wave-vectors, the spectrum is compatible with the presence of a secondary, different power law (blue line in Figure 4), with $\alpha_{\text{small}} \approx 3.3$ (the subscript “small” indicating a fit in the small-scale range), although the range of scales is rather limited. This behavior indicates the presence of a characteristic scale, around 1.8 Mm, where the physical processes could change. Note that recent estimates of the Batchelor integral scales in the quiet solar photosphere provided similar values (Abramenko et al. 2013). The presence of a spectral break is commonly observed in plasmas—for example, at the transition between the MHD range and the kinetic scales, where particle effects are not negligible and produce variations in the energy cascading mechanisms, resulting in steeper spectra. Examples of spectral break followed by steeper spectra are observed in solar wind plasmas (Leamon et al. 1998; Alexandrova et al. 2007; Sahraoui et al. 2009), as well as in a variety of numerical simulations (Mininni et al. 2007; Wan et al. 2012). At very large wave-vectors $k \gtrsim 5.8 \text{ Mm}^{-1}$ the spectrum flattens, suggesting that scales $\lesssim 1$ Mm (approximately corresponding to 3 pixels) may be affected by instrumental noise. These spectral properties are roughly in agreement with previous analysis of the same AR.

Figure 3. Vertical component of the current density $J_z$ (panels (a), (b)) and the reduced current helicity $h_c$ (panels (c), (d)), computed for NOAA 11158 on February 12 at 22:24 UT (left panels) and on February 14 at 03:24 UT (right panels).

Figure 4. Magnetic power spectral density estimated on February 12 at 22:24 UT (circles) and on February 14 at 03:24 UT (diamonds). Power-law fits (full lines) and the corresponding spectral indexes are indicated.

(Georgoulis 2013; Guerra et al. 2014; Zhang et al. 2014) and of other ARs (Abramenko & Yurchyshyn 2010a) where, however, only inertial range spectral indexes were evaluated.

4.2. Cancellation Analysis

Upon confirmation that the AR magnetic field can be reasonably described in the framework of turbulence, cancellation analysis has been performed on the vertical current $J_z$ and on the reduced current helicity $h_c$ for each snapshot of the time series. Note that the magnetic field is relatively smooth, so that its cancellation analysis does not provide information about the dynamics of the AR (Abramenko et al. 1998). Figure 5 shows one example of the signed measure maps, calculated from the data through Equation (1) at four different partition scales. While at large partition scales the positive and negative fluctuations cancel each other, resulting in small values of the signed measure, at smaller partition scales the sign-defined
structures emerge as brighter regions of the maps. Note also the sign-defined large structures in the umbral part of the sunspots, where the magnetic field direction is well-defined. The way structures influence the overall signed measure at different scales is summarized by the cancellation function, depicted (for the same two snapshots as in previous Figures 1, 3, and 4) in Figure 6, for both the current (top panels) and the current helicity (bottom panels). A clear power-law range is visible in the intermediate range of scales, conservatively between 1.4 and 6 Mm, roughly corresponding to the “inertial range” of the spectrum shown in Figure 4. A power-law fit has been performed in this range, as indicated in Figure 6, and the corresponding cancellation exponents have been evaluated. For the examples given here, exponents are steeper before the magnetic flux emergence, \( \kappa_c = 0.72 \pm 0.02 \) and \( \kappa_h = 0.55 \pm 0.03 \), whereas after the transition they become shallower, \( \kappa_c = 0.41 \pm 0.01 \) and \( \kappa_h = 0.13 \pm 0.01 \). Based on the phenomenological argument given in Section 2, the first two values correspond to the presence, in the emerging stage, of broken current filaments with fractal dimension \( D_c = 0.56 \pm 0.04 \) and current helicity filaments, \( D_h = 0.9 \pm 0.06 \), calculated using Equation (4). At a later stage, current filaments dominate, with fractal dimension \( D_c = 1.18 \pm 0.02 \), while well-resolved, almost smooth current helicity structures are observed, \( D_h = 1.74 \pm 0.02 \). The faint saturation to \( \chi = 1 \) at small scales shows that small-scale features are rather smooth, probably because of the instrumental noise, and in agreement with the spectral observations. The high quality of the HMI/SDO data thus allows a very accurate estimation of the cancellation effect. The complete temporal evolution of the

Figure 5. The signed measure \( \mu_c(l) \) calculated for the vertical current density \( J_z \) on February 14 at 03:24 UT. The color scale is arbitrary.
cancellation function is represented in the movie linked to Figure 8 in Section 5, where it is possible to confirm the good quality of the fit during the whole AR observation and the clear changes occurring during the AR evolution. As a striking difference with previous results, sign singularities are measured not only in the smoother current helicity, but also directly on the current density. This is the first observation of this kind, demonstrating the excellent quality of the data and providing further information on the field dynamics. Note also that, while earlier results on AR cancellation analysis were affected by limited spatial resolution (Abramenko et al. 1998; Yurchyshyn et al. 2000; Sorriso-Valvo et al. 2004), a more recent study of Hinode magnetic fields has shown a similarly high spatial resolution (Yurchyshyn et al. 2012) but was still lacking full time coverage at high temporal resolution.

5. RESULTS: TIME EVOLUTION OF THE MAGNETIC FIELD COMPLEXITY AND RELATIONSHIP WITH LARGE FLARES

Previous results on cancellation analysis have suggested that the topological properties of ARs magnetic fields experience changes corresponding to the eruption of major flares (Abramenko et al. 1998; Yurchyshyn et al. 2000, 2012; Sorriso-Valvo et al. 2004). The first observations indicated that such abrupt changes may anticipate the flares by a fraction of an hour. However, the limited time resolution of the data used so far has been a serious obstacle to the detailed description of the time evolution of the magnetic field complexity. The HMI/SDO data used here provide for the first time high time resolution and full time coverage of the AR from the beginning of the emergence phase. This data set represents a unique opportunity to study the dynamical properties of the magnetic complexity, as well as their relationship with the occurrence of flares. Previous studies of temporal evolution of AR NOAA 11158 focused on the properties of magnetic flux; potential, nonpotential, and free energies; number of loops; magnetic helicity; and misalignment angle (Liu & Schuck 2012; Sun et al. 2012; Vemareddy et al. 2012; Tziotziou et al. 2013; Aschwanden et al. 2014).

5.1. Temporal Properties: Turbulent Dissipation and Flares

Looking at the gross temporal behavior of the various parameters introduced so far can give information about the general magnetic and energetic properties of the AR. To this aim, in Figure 7 we have collected the time-dependent parameters of the AR, as measured by the instruments or calculated for this work (see Section 3 for description of the parameters).

Figure 7(a) shows the time evolution of X-ray (black solid line) and EUV (red dotted–dashed line) fluxes. After a quiet interval in the early stage of the AR prior to the flux emergence, the background level of both X-ray and EUV fluxes significantly increases by a factor of about two, starting around February 13. After that time, several flares were released by NOAA 11158, as evident from the peaks in the temporal profile of both X-ray and EUV fluxes. These include 18 C-class, 3 M-class, and 1 X2.2-class flares. Vertical dashed lines identify the exact time of eruption of the M and X flares in all panels of Figure 7.

Figure 7(b) shows the positive ($\chi_{\text{pos}}$) and negative ($\chi_{\text{neg}}$) magnetic fluxes of the whole AR, indicating the slow and steady emergence of the magnetic flux throughout the observation time. In the same panel, the temporal evolution of $B_{\text{rms}}$ is also plotted, showing the increase of fluctuations starting at the beginning of the emerging phase of the AR and then an evident decrease in the final part of the observation.

Panel (c) of Figure 7 shows the time profile of the space-averaged squared vertical current ($J_z^2$) (black solid line), related with the level of turbulence of the AR. A sharp increase of $J_z^2$ is seen at $t^* = 1:24$ UT on February 13 (indicated by a vertical red dashed line), during the initial stage of the flux emergence. This interestingly suggests that, unlike the smooth, slower, and progressive emergence of magnetic flux and magnetic fluctuations, the transition toward a high mean vertical current state, associated with enhanced magnetic field gradients, occurs in a very short time, estimated as $\Delta t^* = 192$ minutes. After the abrupt onset of turbulence, a relatively steady state sets up (indicated as a gray area in the plot) preceding a final smooth decrease. The latter is in agreement with the decrease of $B_{\text{rms}}$ (Figure 7(b)). Note that the transition time $t^*$ roughly represents the time at which the X-ray and EUV fluxes start to enhance.

The spectral indexes $\alpha_{\text{small}}$ (thin blue line) and $\alpha_{\text{large}}$ (thick yellow line), obtained from the power-law fit of the spectra in both ranges of scale, as described in Section 4, are presented in Figure 7(d). Their overall time evolution is only weakly affected by the AR dynamics. Indeed, the spectral exponents reach a steady state at early times (about February 12 for the small range spectral index, and mid-February 11 for the large-scale exponent), 1–2 days in advance with respect to the flux emergence and the sharp jump observed in $J_z^2$. While there is no evidence of later evolution for $\alpha_{\text{large}}$ (for example, not at the full emergence of the AR, nor in correspondence with the enhancement of the flaring activity; Georgoulis 2013; Guerra
et al. 2014), the small-scale spectral index shows a decrease of its fluctuation amplitude and reaches a broad steady state, from the beginning of day 14 up to about 14 hr in day 15 (the gray area in Figure 7). The larger values, $\alpha_{\text{small}} \simeq 3.5$, indicate a steeper scaling exponent, which could be attributed to a time interval of more efficient transport toward small scales and dissipation of turbulent energy. This spectral modification, to our knowledge observed here for the first time, occurs in agreement with the increase of X-ray and EUV background fluxes, as well as with the enhanced flaring activity. In either case, while the large-scale properties of the AR magnetic fluctuations do not seem to be affected by the flaring activity, the small scales are sensitive (although just weakly) to the erupting phase of the AR.

Finally, the time evolution of the cancellation exponents, estimated from the power-law fit of the cancellation functions for both the vertical current ($\kappa_{Jz}$, green thin line) and the reduced current helicity ($\kappa_{hc}$, thick red line), is shown in panel (e) of Figure 7. In the early stage of the AR emergence, the current and current helicity structures are not yet well-defined, the AR being dominated by noise. In these conditions, the cancellation functions show variable sign-singularity, so that the cancellation exponents are highly fluctuating. A similar behavior was recently observed in direct numerical simulations for the study of the transition to turbulence in kinetic dynamics of plasmas (Wan et al. 2012; De Vita et al. 2014) and is due to the presence of not yet fully developed structures. At $t^*$, an abrupt decrease of the exponents synchronizes well with the sharp jump of the averaged squared current density. This indicates, once again, that the complexity of the magnetic field changes in a very short time, according to the fast increase of currents in the AR and contrary to the slower increase of the X-ray and EUV flux, magnetic flux, and magnetic fluctuations. Such change is followed by a slower, steady decrease, lasting about 1 day. Then, the two cancellation exponents reach a steady state, with values $\kappa_{Jz} \simeq 0.42$ and $\kappa_{hc} \simeq 0.13$, typical of smoother structures expected in a highly dissipating plasma (gray area in the plot). After about 36 hr, the cancellation exponents start growing again, indicating an increase of complexity of the AR magnetic fields. This final increase occurs in correspondence with the decrease of the small-scale spectral index, $B_{\text{rms}}$ and $\alpha_{\text{small}}$.

Based on the above considerations, the whole gross temporal evolution of the AR can therefore be summarized as follows: (1) the early stage of the AR, with no flaring activity, showing randomly emerging disrupted current filaments associated with
weak turbulent energy; (2) the setup of the flaring activity and magnetic flux emergence, marked by the sharp onset of turbulence occurring at $t^*$, with stabilization of the structures, and the following day of steadier change in the parameters; (3) a period of strong flaring activity, associated with an enhanced level of magnetic fluctuations and turbulent dissipation and characterized by a steady state of the structures’ geometry (gray area in Figure 7); and, finally, (4) the weakening of the flaring activity, associated with the steady decrease of the turbulence level, weakening of the dissipation (shallower small-scale spectrum), and increase of the magnetic complexity. This final step of the AR temporal evolution seems to indicate the transition to a different state, where finer magnetic structures can build up without necessarily resulting in large flares, suggesting an improved capacity of energy storage at smaller scales. This scenario is fully consistent with the association between the eruption of flares and the general properties of the AR dissipation and small-scale magnetic complexity.

As already mentioned above, an interesting feature is the remarkable difference in the timescale of the changes observed around $t^*$ for the X-ray flux, magnetic flux, and magnetic fluctuations with respect to electric current density and cancellation exponents. While the former quantities are likely to be related to the slow magnetic field emergence, the latter represent a signature of the magnetic field structuring and are associated with the presence of enhanced magnetic gradients. However, the comprehension of the mechanism underlying this difference requires a more detailed study besides the scaling analysis presented in this work.

For a better visualization of the features discussed above, the complete temporal evolution of the parameters depicted in Figure 7 can be observed in more detail in the movie linked to Figure 8.

### 5.2. Short Time-scale Features at Flaring Times

Besides the gross dynamical behavior of the AR, the high temporal resolution of HMI/SDO allows for the first time the detailed analysis of short time-scale features and, specifically, their changes during solar flares. In order to study the possible relationship between flares and magnetic turbulence properties (Sorriso-Valvo et al. 2004), the study can be focused on the most intense flares that occurred in NOAA 11158. Previous studies have indeed shown that most major flares can be associated with variations of the magnetic complexity (Abramenko et al. 1998; Abramenko & Yurchyshyn 2010b; Georgoulis 2013). In Figure 7, four vertical lines indicate the times of eruption of the largest flares of NOAA 11158. As already mentioned, these are three M-class (one of which is considerably larger than the others) and one X-class flare.

It is evident from panels (b) and (d) of Figure 7 that at the time of the flares no specific temporal features are observed in the magnetic flux and in the magnetic spectral exponents. However, finer observation of such and other similar parameters evaluated in the flare-triggering regions have revealed significant changes (Petrie 2013; Song et al. 2013). On the contrary, the magnetic fluctuations $B_{\text{rms}}$ show a clear sudden increase at the times of the first M and X2.2 flares. This is highlighted in Figure 9, where a magnification around the M
and X flaring periods is shown (panel (a)). In the same figure, the time derivative of the two fields are also shown, with the evident peaks at the first M flare and at the X flares. No features are visible for the second and fourth M flares (Petrie 2013; Song et al. 2013). At the same times, the mean squared current \( \langle J_z^2 \rangle \) also exhibits interesting features. The M-class flare is associated to a jump in the mean dissipation, while at the X-class flare an evident broad peak is present. In the latter case, the turbulent dissipation level increases by 27% (two orders of magnitude larger than the 0.2% relative standard deviation evaluated in the steady period preceding the flare) in about 216 minutes, peaks about \( \sim 48 \) minutes before the flare, and then decreases back to its steady value in about the same amount of time (Song et al. 2013). Similar features are also observed at the X flare for both cancellation exponents, where a 6% and 28% growth is present for the current density and current helicity indicators, respectively. These increases are larger by one order of magnitude than the 0.5% and 0.8% standard deviation levels in the steady period preceding the flare. The duration of the increase and decrease phases is approximately the same as for \( \langle J_z^2 \rangle \), i.e., of the order of 200 minutes. The same kind of behavior seems to hold for the weaker features observed at the time of the first M-class flare for the current cancellation exponent, although these changes are not as evident as for the X2.2 flare and are absent in the current helicity exponent.

The increase of the mean squared current and of the magnetic complexity (as estimated through the cancellation exponents), which represents the main result of this work, can be interpreted as follows. During that phase, the AR is in a highly turbulent state (as shown by the spectra), with a steady, high level of dissipation (shown by the slightly steeper small-scale spectra with respect to the nonflaring stage and by the higher background of X-ray and EUV flux) and associated with the presence of relatively smooth current and current helicity structures. Shortly before the flare, magnetic gradients and complexity increase, suggesting the injection of an excess of magnetic energy, which is not fully dissipated but rather stored through the build-up of field complexity, with resulting enhancement of the current filamentation in the AR. This finally results in the conditions for flaring. After the flare eruption, the conditions come back to the steady state, while the typical level of magnetic fluctuations starts to decrease.

### 6. Evaluating Correlations

The observation of the temporal behavior of the AR magnetic structure has revealed the correspondence between changes in magnetic field properties and the eruption of large flares. This is visible both in the gross evolution of the parameters and in the short time-scale features, as shown in Figure 7. In order to give a quantitative measure of the

#### Table 1
The Time Lags \( \tau_p \) and \( \tau_s \) (in Hours) and the Corresponding Maximum Correlation Coefficients \( \rho_p \) and \( \rho_s \), Estimated Between the X-ray and EUV Fluxes and the Indicated Parameters

|        | EUV | X   |
|--------|-----|-----|
|        | \( \tau_p[h] \) | \( \rho_p \) | \( \Delta \rho_p \) | \( \tau_s[h] \) | \( \rho_s \) | \( \Delta \rho_s \) |
|        | \( \kappa_z \) | -1.60 | 0.49 | [0.38, 0.58] | -0.80 | 0.33 | [0.20, 0.45] |
|        | \( \kappa_x \) | -1.40 | 0.32 | [0.19, 0.44] | -1.40 | 0.19 | [0.05, 0.32] |
|        | \( \langle J_z^2 \rangle \) | -1.60 | 0.36 | [0.23, 0.48] | -1.40 | 0.34 | [0.21, 0.46] |
|        | \( \alpha_{\text{large}} \) | 1.00 | -0.18 | [-0.31, -0.04] | 1.20 | 0.13 | [0.01, 0.27] |
|        | \( \alpha_{\text{small}} \) | 1.80 | 0.52 | [0.41, 0.62] | 2.40 | 0.25 | [0.11, 0.38] |

|        | EUV | X   |
|--------|-----|-----|
|        | \( \tau_s[h] \) | \( \rho_s \) | \( \Delta \rho_s \) | \( \tau_p[h] \) | \( \rho_p \) | \( \Delta \rho_p \) |
|        | \( \kappa_z \) | -1.40 | 0.59 | [0.49, 0.67] | -1.40 | 0.50 | [0.38, 0.60] |
|        | \( \kappa_x \) | -1.40 | 0.31 | [0.18, 0.43] | -1.20 | 0.19 | [0.05, 0.32] |
|        | \( \langle J_z^2 \rangle \) | -1.20 | 0.27 | [0.13, 0.40] | -1.20 | 0.30 | [0.17, 0.42] |
|        | \( \alpha_{\text{large}} \) | 0.60 | -0.27 | [-0.40, -0.13] | -0.80 | -0.19 | [-0.32, -0.05] |
|        | \( \alpha_{\text{small}} \) | 1.80 | 0.55 | [0.44, 0.63] | 1.80 | 0.49 | [0.38, 0.59] |

Note. \( \Delta \rho_p \) and \( \Delta \rho_s \) represent the 95% confidence intervals for the correlation coefficients obtained though a Fisher test.
relationship between the observed features and the occurrence of flares, a statistical study of the correlations between the different parameters presented in Figure 7 can be performed. This is possible thanks to the high time cadence of the data, which allows for the first time a significant statistical study. In order to limit the effect of transients, noise, and smaller flares, we performed the correlation analysis only in the stationary stage of the activity, indicated by the gray area in Figure 7. The cross-correlation coefficients between several pairs of parameters has been computed, and results are collected in Table 1. We have used both the Pearson and the Spearman (ranks) cross-correlation coefficients, evaluated at the time lag where they are larger (in Table 1, a time lag of 0 hr indicates the absence of significative correlation). The Spearman coefficient is less sensitive to nonstationarity of the samples and to nonlinearity of correlations. Since there is no particular reason to expect linear correlations, we believe that the Spearman coefficient could be a more efficient parameter accounting for correlations in this system. Examples of correlation functions (for both ordinary and Spearman ranks correlations) are shown in the left panels ((a), (c), and (e)) of Figure 10. Peaks are evident for the current helicity cancellation exponents and for the small-scale spectral index, whereas correlations are poor for the mean squared vertical current. The dashed vertical line indicates the time lag at which the Spearman correlation is maximum. As can be seen in Table 1, while some of the pairs are not correlated, for others it is possible to highlight a relevant correlation. For example, EUV flux exhibit a strong degree of correlation $\rho_S = 0.59$ with the current helicity complexity $k_{hc}$ (at $\tau = -1.4$ hr lag), or $\rho_S = 0.55$ with the small-scale spectral index $\alpha_{small}$ (at $\tau = 1.8$ hr lag). Note that maximum correlation time lags are negative, indicating that the changes in the parameters anticipate the X-ray and EUV emission, except for the spectral indexes, which on the contrary

Figure 10. Left panels: the correlation coefficients $\rho_P(\tau)$ and $\rho_S(\tau)$ as a function of the time lag $\tau$ for the indicated pairs of variables. The dotted–dashed vertical line indicates the time of the maximum Spearman correlation. Right panels: the corresponding scatter plots at the time lag of the Spearman correlation peaks.
react after the flares. The sign of the correlation suggests the causality direction of our observations. Increase of magnetic complexity and gradients anticipates the flares, whereas the dissipation (relaxation of the magnetic complexity) becomes more efficient after the flares. The most relevant correlation is found between the EUV flux and the current elicty cancellation exponent. This confirms that sign-singularity analysis is a suitable, sensitive tool, able to capture the fine variations in the AR magnetic complexity preceding the eruption of large flares. Furthermore, there is no need to focus on the specific location of the flare (Petrie 2013; Song et al. 2013) because the parameters studied here are global quantities of the entire AR.

Finally, more details about the nature of the observed correlations can be evidenced by showing the corresponding scatter plots for each pair of parameters, delayed by the time lag of the Spearman correlation peaks. These are shown in the right panels ((b), (d), and (f)) of Figure 10. It appears evident that most of the correlation comes from the large flares (the top part of the scatter plots), whereas smaller X-ray or EUV records (the background emission) are more randomly distributed with the other parameters. Interestingly, all major X-ray and EUV fluxes occur above given values of the correlated variables, i.e., for the cancellation exponents and for the small-scale spectral index. This suggests the presence of a threshold of the magnetic dissipation and topological complexity, below which no large flares are observed. This quantitative observation further confirms that flares are strictly related to small-scale turbulent and dissipative processes in the photospheric magnetic fields and that higher complexity of the currents enhances the probability of observing large flares.

7. CONCLUSIONS

Motivated by the high-quality HMI/SDO photospheric magnetic field vector measurements, we have studied some magnetic properties of the solar AR NOAA 11158 and their relationship with large flares (M and X class). We have found that the dynamics of the magnetic field fluctuations and mean vertical current describes quite well the transition of the AR into the flare activity stage. The spectral properties of the magnetic field fluctuations were also studied, suggesting the presence of a double range of scales. In the larger-scale range, approximately corresponding to the inertial range of turbulence, the spectral properties are steady during most of the AR lifetime, and no particular features are observed at the time of major flares. On the contrary, the small-scale range is characterized by a variable spectral index, which shows nontrivial correlations with the X-ray and EUV emission. In particular, the spectral slope increases (indicating more efficient dissipation of turbulent energy) during the central part of the observation, when flaring activity is enhanced. The magnetic field complexity was studied by means of the cancellation analysis of its sign-singularities, as evidenced through the study of the vertical current and of the reduced current helicity. Cancellation analysis applied to the AR provided the qualitative estimation of the fractal dimension of the current structures, which is reasonably steady during the flaring time interval. However, interesting peaks are observed in correspondence of the largest flare of the AR (X2.2) and, to some extent, also for the M class flares. A quantitative evaluation of correlations between flaring activity and magnetic complexity was finally performed. The results shown here suggest that it is possible to quantitatively measure the magnetic complexity evolution of the AR during flares, which supports the scenario of increasing entanglement of current and magnetic field 1–2 hr ahead of big flares.

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