NON-NEUTRALIZED ELECTRIC CURRENT PATTERNS IN SOLAR ACTIVE REGIONS: ORIGIN OF THE SHEAR-GENERATING LORENTZ FORCE

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ABSTRACT

Using solar vector magnetograms of the highest available spatial resolution and signal-to-noise ratio, we perform a detailed study of electric current patterns in two solar active regions (ARs): a flaring/eruptive and a flare-quiet one. We aim to determine whether ARs inject non-neutralized (net) electric currents in the solar atmosphere, responding to a debate initiated nearly two decades ago that remains inconclusive. We find that well-formed, intense magnetic polarity inversion lines (PILs) within ARs are the only photospheric magnetic structures that support significant net current. More intense PILs seem to imply stronger non-neutralized current patterns per polarity. This finding revises previous works that claim frequent injections of intense non-neutralized currents by most ARs appearing in the solar disk but also works that altogether rule out injection of non-neutralized currents. In agreement with previous studies, we also find that magnetically isolated ARs remain globally current-balanced. In addition, we confirm and quantify the preference of a given magnetic polarity to follow a given sense of electric currents, indicating a dominant sense of twist in ARs. This coherence effect is more pronounced in more compact ARs with stronger PILs and must be of sub-photospheric origin. Our results yield a natural explanation of the Lorentz force, invariably generating velocity and magnetic shear along strong PILs, thus setting a physical context for the observed pre-eruption evolution in solar ARs.

Key words: magnetohydrodynamics (MHD) – Sun: atmosphere – Sun: corona – Sun: flares – Sun: photosphere – Sun: surface magnetism

Online-only material: color figures

1. INTRODUCTION

In spite of its relative thinness, the solar photosphere plays an important role as the transitional layer between the fluid-dominated solar interior and the magnetically dominated solar atmosphere. Over the past few decades, the emergence process of magnetic flux through the photosphere has been thoroughly studied by observers and modelers. An early observational finding was the filamentary, fibril structure of photospheric magnetic-flux strands or tubes (e.g., Livingston & Harvey 1969; Howard & Stenflo 1972; Stenflo 1973) which defies the spatial resolution of our best magnetographs to this day. This fine, fibril structure of photospheric magnetic fields has yet to be fully understood and properly interpreted (Parker 1979, 2007).

Soon after the discovery of the filamentary photospheric magnetic fields, it was realized that emerging flux tubes must be twisted in order to maintain their structural integrity (Schuessler 1979). Recent simulations of magnetic-flux emergence (Murray et al. 2006; Archontis & Hood 2008, and references therein) further showed that magnetic-flux tubes cannot even emerge without some twist. Twist implies the presence of field-aligned electric currents, realized by the curl of the measured or simulated photospheric magnetic field vector per Ampère’s law. The existence of electric currents automatically implies departure of the magnetic structure from its minimum-energy, current-free (potential) configuration, as potential fields are defined by the gradient of a scalar potential calculated in a finite, bounded, or infinite, partially bounded, volume (Schmidt 1964; Sakurai 1982). Non-potentiality in solar magnetic fields is the undisputed underlying cause of solar eruptive activity typically originating in complex regions of interacting opposite-polarity magnetic fields, interfacing by strong polarity inversion lines (PILs). Observed photospheric PILs are typically deformed, shredded, and stretched by strong shear flows and associated magnetic shear, measured as the local angular difference between the observed field vector and the expected potential-field configuration (see, e.g., Wang 1999 for a review, but also Zirin & Wang 1993, Tiwari et al. 2010, and references therein).

In spite of strong mechanical forces and complexity in the photosphere, twist seems to remain almost unchanged in the corona (McClymont et al. 1997), where the substantially decreased plasma β-parameter allows for a nearly complete spatial filling of the coronal volume by magnetic field lines. The low-β coronal environment further implies almost purely field-aligned currents, except on thin current sheets that interface between flux tubes (Parker 1972, 2004). As a result, there is a volume current in flux tubes that is non-neutralized across any cross-section of the corona (e.g., Longcope & Welsch 2000). The notion of non-neutrality of electric currents implies the presence of a net (nonzero) current for a given magnetic polarity, as defined by previous works (e.g., Wilkinson et al. 1992; Wheatland 2000).

On the other hand, the presence of volume currents in twisted magnetic fibrils embedded in a relatively field-free space occupied by fluid plasma, which is the assumed case for the photosphere, necessarily implies the existence of return (skin or sheath) surface currents at the boundaries of these photospheric fibrils (Pizzo 1986; Ding et al. 1987; Longcope & Welsch 2000). In addition to a field-aligned twist component, therefore, photospheric electric current density shows a significant component perpendicular to the magnetic field B. This cross-field current density partially depends on ∇ × B − B × B-terms, caused by gradients.

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of the magnetic field strength $B$ (Zhang 2001; Georgoulis et al. 2004). As such, this component should peak on the surface of the flux tube where the interface between the magnetized and field-free media occurs. In the simplest case of isolated flux tubes, it can be shown (see Section 5) that the Lorentz force due to these cross-field currents is mainly due to magnetic pressure (see, e.g., Jackson’s 1962 decomposition of the Lorentz force into pressure and tension terms) and tends to expand the flux tube, hence competing with the twist that keeps it together in conjunction with the external non-magnetized plasma pressure.

Little doubt exists that photospheric magnetic fields are indeed forced, i.e., subjected to significant Lorentz forces (Metsala et al. 1995; Georgoulis & LaBonte 2004). Above the photosphere, however, the plasma pressure decreases abruptly, forcing flux tubes to expand rapidly to fill nearly the entire coronal volume, thus smoothing out large gradients $\nabla B$. Because of this, return currents cannot reach the corona—they fade when magnetic fields become force-free (i.e., showing only a volume current due to the twist along the field). Details of this process remain to be determined, but an interesting mechanism relying on torsional Alfvén waves has been suggested by Longcope & Welsch (2000).

While it is generally established that a net electric current exists in any coronal cross-section, debate remains over whether photospheric currents are neutralized. Parker (1996b) argued that for isolated magnetic fibrils embedded in a field-free volume, regardless of twist, the total current must be neutralized across the photospheric cross-section of any given flux tube. Simply, then, the vertical components of the volume and the surface current densities cancel out in each fibril. Parker (1996b) further suggested that the common practice of inferring the vertical electric current density $J_z$ via the differential form of Ampère’s law ($\nabla \times \mathbf{B}$), using photospheric magnetic field measurements $\mathbf{B}$ bears no physical meaning. Thus, the presence of non-vanishing vertical currents in several observational cases is, according to Parker, an artifact caused by the limited spatial resolution of the observing magnetograph that tends to attribute an artificially continuous magnetic field where the magnetic field is inherently discontinuous.

Melrose (1991, 1995) followed a different approach by pointing out that observations are more consistent with non-neutralized photospheric current patterns. Therefore, currents have to emerge from the solar interior with the emergence of magnetic flux. That $\nabla \cdot \mathbf{J} = 0$ implies that currents have to close at the base of the convection zone (i.e., the tachocline) where magnetic fields are generated. This has profound implications for flare initiation: while Parker’s neutralized currents require in situ storage and release of energy, Melrose’s large-scale current paths imply the existence of a strong inductive coupling between the coronal flaring volume and the convection zone. Melrose (1995) described magnetic loops as electric circuits (the [E, J]-paradigm) and cited observations that showed an increase of magnetic shear after solar flares (Wang et al. 1994) to argue that the energy released in flares is replenished by pumping non-potential energy through electric currents from deep in the solar interior.

Parker (1996a) responded to Melrose’s proposition by arguing that the [E, J]-paradigm results in a set of dynamical equations that are mathematically intractable. In contrast, the magnetohydrodynamical (MHD) description of solar processes, in terms of a magnetic field $\mathbf{B}$ and a velocity field $\mathbf{u}$ (the [B, u]-paradigm) is more natural and straightforward. The [E, J]-paradigm may hold in laboratory conditions where magnetic fields are generated by current-carrying coils wrapped around metals, but not in stellar conditions where the dynamo-generated magnetic fields are the ones giving rise to electric currents.

A number of studies followed or preceded the debate, all focusing on the observational aspect, namely, whether there is non-neutralized current in the active-region (AR) photosphere meaning that net electric currents are injected into the atmosphere. The study of Wilkinson et al. (1992) was the only one to conclude that photospheric currents may be neutralized. All other studies (Leka et al. 1996; Semel & Skumanich 1998; Wheatland 2000; Falconer 2001) concluded that the AR photosphere includes current-carrying magnetic-flux tubes, although currents are roughly balanced at AR scales, that is, non-neutralized currents of opposite senses close onto each other in a given AR. The inferred non-neutralized currents are interpreted as sub-photospheric in origin. Where these currents close, however, is unclear from observations and only Wheatland (2000) appeared to openly favor Melrose’s electric circuit analog. The above studies used both the differential form of Ampère’s law that Parker (1996b) had criticized for failing to provide a physical current and the integral form of Ampère’s law, i.e.,

$$ I = \frac{c}{4\pi} \oint_S (\nabla \times \mathbf{B}) \cdot \mathbf{n} \, dS = \frac{c}{4\pi} \oint_C \mathbf{B} \cdot d\mathbf{l} \quad (1) $$

where the total current $I$ is obtained either over a cross-section $S$ of a flux tube, where $\mathbf{n}$ is the unit vector normal to $S$, or along a closed curve $C$ bounding the cross-section $S$.

Although the expressions in Equation (1) are equivalent (Stokes’ theorem), in practice, numerical errors can give rise to notable, distinct uncertainties. First and foremost, the inference of magnetic field components via inversion of Stokes images and profiles includes uncertainties subject to the specific inversion model (see, e.g., Section 1.3 of Borroero & Ichimoto 2011, and references therein). Because of these uncertainties and since different numbers of pixels are being used for the differential and the integral forms of Equation (1), these uncertainties are different for the two theoretically equivalent expressions of Ampère’s law. The integral representation of Ampère’s law is often preferred because it involves fewer magnetogram pixels (i.e., the outline of a magnetic polarity, rather than the entire polarity used in the differential representation). Moreover, the azimuthal $180^\circ$ ambiguity, inherent in vector magnetic fields measured by the Zeeman effect (Harvey 1969), includes further uncertainties if incorrectly resolved. Further, magnetic field measurements are sometimes affected by Faraday rotation (Leka et al. 1996; Su et al. 2006) which is another source of uncertainties. When evaluating Equation (1), finite differencing introduces truncation errors depending on the various differentiation schemes used, whereas the curve integral requires precise knowledge of the sequence of contiguous points on the bounding contour, regardless of this contour’s shape complexity.

The differential form of Ampère’s law gives rise to an electric current density $J \sim \nabla \times \mathbf{B}$, of which only the vertical component $J_z$ can be readily calculated in the photosphere. While calculation gives rise to large $J_z$-values, a valid question is whether these current density patterns are real. Leka et al. (1996) provide several interesting arguments supporting the realism of these currents. The most important is that in the case of flux emergence, the increase in currents cannot be accounted for by the action of photospheric motions alone. In addition, patterns of the vertical current density $J_z$ are known to reflect the
expected morphology of the photospheric magnetic field (see, e.g., Socrates-Navarro 2005 and Balthasar 2006, among others). This evidence, however, cannot be conclusive as \( J_z \sim (\nabla \times B_z) \), should naturally reflect the shape of the field. McClymont et al. (1997), in their Appendix B, provided further physically based arguments, namely that (1) the strongest non-neutralized currents occur in sunspots, where Parker (1996b) admits that the fibril state of the magnetic fields probably breaks down, (2) inclined, spiral flux tubes cannot be maintained in their observed position without a true field-aligned current (i.e., twist) reflected in \( J_z \), and (3) \( J_z \) assumes a characteristic pattern along sheared magnetic PILs, with narrow ribbon-like structures extending along both sides of the PIL. This, they argued, implies that the individual sheared flux strands are indeed blurred due to the insufficient instrumental resolution but, nonetheless, the current patterns are real, albeit smoothed, and only partially resolved. An important conceptual step along the same lines was achieved by Semel & Skumanich (1998), who hinted that currents cannot be neutralized in the case of interacting flux tubes with opposite polarities, that is, when a tight PIL interfaces between them. In this case, one cannot argue for isolated flux fibrils, an apparent prerequisite for Parker’s neutralized currents.

Most of the above studies, including Parker’s, underlined the importance of studying vector magnetograms with exceptionally high spatial resolution, sufficient to provide a better view of the fibril, discontinuous magnetic fields. The recent study of Venkatakrishnan & Tiwari (2009) uses an ultra-high-resolution vector magnetogram to conclude the absence of net currents in (isolated) sunspots, as Parker suggested. We also undertake this task here, but with a focus on (1) not restricting the analysis to isolated magnetic structures, and (2) applying detailed error propagation to enable safe results and subsequent conclusions. We utilize two vector magnetograms obtained by the Spectro-Polarimeter (SP) of the Solar Optical Telescope (SOT) on board the Hinode spacecraft (Kosugi et al. 2007). As we shall see below, the spatial resolution and noise level of the Hinode magnetograms are unparalleled compared to magnetograms used in the previously cited studies of the 1990s. Therefore, these data are most appropriate and timely for the targeted sensitive calculations.

The data and preliminary analysis are described in Section 2. The methodology for calculating the total electric currents of “individual” (given the spatial resolution) flux tubes and entire ARs is outlined in Section 3. In Section 4 we present our results and in Section 5 we attempt a heuristic physical interpretation of them, connecting them with the observed evolution in the photosphere. We summarize our study and conclude in Section 6.

2. VECTOR MAGNETOGRAM DATA PROCESSING

The SP (Lites et al. 2001) is part of the SOT suite on board the Hinode spacecraft. The instrument records the four Stokes polarization signals at the FeI 6301.5 and 6302.5 Å photospheric magnetically sensitive spectral lines by scanning a portion of the solar disk with a spectral sampling of 21.6 mA. The normal scanning mode consists of 2048 steps at a nominal pixel spacing of 0.1585 and with a full slit length equal to 1024 pixel lengths (Lites et al. 2008).

The inversion of the Stokes profiles is achieved via the Advanced Stokes Polarimeter Milne–Eddington inversion code (Lites et al. 1993 and references therein). The inversion returns the magnetic field components with a \( 1\sigma \) sensitivity \( \sigma B_\ell = 2.4 \text{ Mx cm}^{-2} \) (G), for the line-of-sight field component, and \( \sigma B_\ell = 41 \text{ Mx cm}^{-2} \) for the transverse field component. The full-resolution pixel size being \( 0.1585 \), tests on quiet-Sun measurements revealed a spatial resolution of \( \sim 0.3 \) (Lites et al. 2008). These can hardly be compared with pixel sizes of the order 1” or larger (spatial resolution of the order 2” or lower) and noise levels \( \sigma B_\ell \), of the order several tens to 100–200 G, respectively, achieved by magnetographs used in the earlier studies of electric current patterns and their neutrality properties.

The resolution of the azimuthal 180° ambiguity in the selected Hinode vector magnetograms was achieved via the non-potential magnetic field calculation (NPFC) method of Georgoulis (2005), refined as discussed in Metcalf et al. (2006). The NPFC method is quite insensitive to noise (Leka et al. 2009) and also performs well in the case of discontinuous and partially unresolved magnetic-flux bundles (Georgoulis 2012), despite claims by Leka et al. (2009). The NPFC method is the method of choice for the automatic disambiguation of vector magnetograms obtained by the Vector Spectromagnetograph of the Synoptic Optical Long-Term Investigation of the Sun facility (Georgoulis et al. 2008; Henney et al. 2009).

2.1. Hinode/SOT Data on NOAA Active Region 10930

The first Hinode SOT/SP data set refers to NOAA AR 10930, a well-studied region observed on 2006 December 11. Figure 1(a) depicts a continuum image of the AR photosphere, showing a clearly interacting \( \delta \)-sunspot complex (i.e., interacting, opposite-polarity pattern including at least one strong PIL). The respective NPFC-disambiguated vector magnetogram is shown in Figure 1(b). The scanning of the AR started at 13:10 UT and ended at 16:05 UT. Even from this single snapshot one notices the extreme magnetic shear (\( \sim 90° \)) along the main PIL of the AR, whose area is selected and expanded in the inset of Figure 1(b). Notice also the significant magnetic-flux fragmentation everywhere in the field of view. Flux strands with a cross-section of \( \sim 1″−2″ \) are abundant, both close to the sunspots and to the extended plage areas surrounding them. The typical vertical field of these strands ranges between several hundred \( G \) and \( \sim 1.5 \text{ kG} \). Such fragmented field concentrations were first observed by the balloon-borne vector magnetograph on board the Flare Genesis Experiment (pixel size 0.18; spatial resolution \( \sim 0.5 \); Bernasconi et al. 2002), but could only be guessed at in previous studies (see, for example, Zirin 1988 for a collection of sunspot groups with notable fibril structure observed in Hz wavelengths). Adjacent to the PIL (inset), one notices flux bundles, aligned with the PIL with a width as small as \( \lesssim 2″ \). These “channels” or “lanes” were first reported by Zirin & Wang (1993) and were exemplified by Wang et al. (2008) for this particular AR. The total field strength of these flux bundles is \( \sim 2 \text{ kG} \), with a vertical component \( |B_v| \sim 1.5 \text{ kG} \). The vertical field component on the PIL dropping precipitously to zero, the horizontal field shows an amplitude \( B_\ell \sim 1.5−1.9 \text{ kG} \).

Clearly, NOAA AR 10930 does not comply with the Hale–Nicholson polarity law (e.g., Zirin 1988): the leading/trailing polarity pattern is unclear and the AR axis shows a north–south, rather than an east–west, orientation. Given the extremely sheared PIL, on the other hand, it is not surprising that the AR, during its passage from the visible disk (i.e., between 12/06/06 and 12/18/06) gave an impressive series of flares (3 X-class, 2 M-class, about a dozen C-class, and \( \sim 100 \) B-class events). The most intense of these flares, a GOES X3.4, took place at 02:14 UT on 2006 December 13, \( \sim 1.5 \) days after the Hinode observations of Figure 1.
Figure 1. Views of NOAA AR 10930, observed by SOT/SP on 2006 December 11, at around 13:10 UT. (a) Continuum image of the active-region photosphere. (b) The corresponding photospheric magnetic field vector on the heliographic plane. A vector length equal to the tic mark separation corresponds to a horizontal field strength of 2000 G. (c) The corresponding photospheric vertical electric current density. In all images, a part of the AR, enclosed by the blue boxes, has been expanded and shown in the insets. Tic mark separation for the full images is 10″. Tic mark separation for the insets is 2″. A vector length equal to the tic mark separation in the inset of b corresponds to a horizontal field strength of 1000 G. North is up; west is to the right.

A map of the vertical electric current density $J_z$ is shown in Figure 1(c), with the $J_z$-solution for the PIL expanded and shown in the inset. A brief look at the $J_z$-map roughly confirms the expected fine structure: in the penumbrae of both sunspots and away from the PIL there are roughly radial structures in agreement with previous studies (for example, Semel & Skumanich 1998, Balthasar 2006, and others). Further, in a secondary PIL north of the negative-polarity sunspot there are paired upward/downward $J_z$-patterns along the PIL. Along the AR’s main PIL (inset) the strong shear indeed creates “tongue”-like upward and downward current patterns. Finally, the $J_z$-signature of the extended plage fields is much weaker, noisier, and lacks a coherent structure, which is evidence of magnetic fields nearly normal to the photosphere in these areas (Martinez Pillet et al. 1997).

Overall, the vertical electric current density solution for NOAA AR 10930 shows striking fine structure. Magnetic-flux fragmentation easily reaches the spatial-resolution capability of the observing instrument. Therefore, we cannot claim that the observed magnetic configuration is fully resolved. The observed $J_z$-structure might, in fact, be what McClymont et al. (1997) argued for, namely, the result of multiple unresolved magnetic fibrils that are imperfectly observed as a single flux tube.
Figure 2. Same as Figure 1, but for NOAA AR 10940, observed by SOT/SP on 2007 February 2, around 01:50 UT. A vector length equal to the tic mark separation in the inset of b corresponds to a horizontal field strength of 1900 G. North is up; west is to the right.
(A color version of this figure is available in the online journal.)

2.2. Hinode/SOT Data on NOAA Active Region 10940

The second data set pertains to Hinode’s SOT/SP observations of NOAA AR 10940, observed on 2007 February 2. The scanning of the AR started at 01:50 UT and ended at 02:53 UT. Figure 2(a) shows a continuum photospheric image of the AR. From this image, the AR consists of a fairly undisturbed sunspot surrounded by extended plage and a number of smaller spots and pores. Evidence for a small emerging-flux sub-region exists just west of the main sunspot, where the continuum image shows dark fibril structures such as those expected in arch filament systems (Bruzek 1967). This area is expanded and shown in the inset. The PIL of the AR is in the same area but is much weaker than the main PIL of NOAA AR 10930. The NPFC-disambiguated solution for the heliographic magnetic field vector is shown in Figure 2(b). The horizontal field vector shows the typical radial arrangement expected for an undisturbed sunspot while some weak shear can be seen along the PIL.

The solution for the vertical current density, shown in Figure 2(c), is also enlightening: the sunspot’s penumbra generally exhibits radial $J_z$-patterns except close to the PIL, where these patterns are deformed (inset). There, the $J_z$-patterns roughly follow the orientation of the dark fibrils of the arch filament system as seen in the continuum (Figure 2(a)). Weak, plage, $J_z$-patterns can also be seen, while the small radial pattern in the westernmost part of the AR indicates that the darkening in
the continuum image and the coherent negative-polarity feature in the vector-field image correspond to a small sunspot with almost no umbra. In this example, too, the \(J_\perp\)-patterns provide physical information on the studied AR. As such, they may not be completely artificial.

The NOAA AR 10940 is much more quiescent compared to NOAA AR 10930 of Figure 1. During its passage from the visible disk (~01/28 to 02/09 2007) the AR gave only 3 weak C-class flares and ~25 B-class events. At the time of the Hinode observations on February 2, the AR was almost totally flare-quiet.

We seek qualitative and quantitative differences between the electric current patterns in the two ARs. The findings will be used to determine, using the highest possible spatial resolution, whether current-injecting magnetic-flux tubes are widespread, rarely occurring, or simply non-existent.

3. THE ANALYSIS METHOD

To calculate the total electric current in an entire AR or in polarities of it, we take the following steps: first, we translate the pixelized photospheric magnetic-flux distribution into a collection of partitions, each with a relatively large (\(\gg 1\)) number of pixels. Second, we apply the integral form of Ampèrè’s law (Equation (1)) to these partitions to calculate their total electric current. Third, we algebraically sum the total currents of all partitions to calculate the total current of each polarity and of the entire region.

Alternatively, the total current can be obtained by, first, deriving the normal component \(J_n\) of the electric current density from a vector magnetogram and then integrating the \(J_n\)-distribution over the area of a given partition with \(N\) pixels or the AR as a whole. Calculating the total current from the integral Ampèrè’s law does not rely on the current densities of all \(N\) pixels of a studied partition but it uses the magnetic field components of only \(\sim \sqrt{N}\) pixels—those that belong to the perimeter of the partition. Choosing a sufficiently high magnetic field threshold in the outline of the partitions we achieve a relatively high signal-to-noise ratio, and hence a reasonable uncertainty in our calculations.

3.1. Magnetic-flux Partitioning

Photospheric flux partitioning is achieved following the partition method of Barnes et al. (2005). Partitioning the vertical component \(B_z\) of a magnetogram \(B\) aims to “discretize” the otherwise continuous magnetic-flux distribution, by translating it into a series of well-defined, non-overlapping partitions of different polarities with uniquely defined outlines, areas, and flux contents. Numerically, our method of choice is a “gradient-based” flux tessellation scheme that uses a downhill-gradient algorithm (e.g., Press et al. 1992) to define photospheric partitions based on the two-dimensional morphological and polarity characteristics of \(B_z\). In addition, a simplification rule is applied, merging partitions that interface by saddle points in \(B_z\).

If no thresholds were imposed in the course of partitioning, the entire magnetogram area, including AR and quiet-Sun patches, would be included in an excessive number of different partitions. It is of little meaning, however, to include weak and/or tiny partitions from the highly fragmented Hinode magnetograms, as these partitions are unlikely to contribute strong currents due to their weak fields. For this reason, we focus on strong-flux AR patches by defining relatively high thresholds for the basic parameters of partitioning: (1) \(B_{\text{lim}} = 100\) G as the minimum \(B_z\)-value for each pixel of a given partition, (2) \(\Phi_{\text{thres}} = 10^{19}\) Mx as the minimum magnetic flux \(\Phi\) of a partition, and (3) \(S_{\text{thres}} = 40\) pixels as the minimum partition area \(S\). A partition qualifies for further study only if all three thresholds are exceeded; otherwise, it is discarded.

A slight mean-neighborhood smoothing is also applied to the original \(B_z\)-maps in order to reduce an excessive jaggedness of the partition contours. Once these contours are determined, however, the original, non-smoothed maps of the horizontal field components are used to calculate the total currents.

3.2. Calculation of the Total Electric Current and Uncertainties

3.2.1. For Individual Magnetic-flux Partitions within Active Regions

Discretizing the integral Ampère’s law (Equation (1)), we obtain for each qualifying partition \(i\) the total current

\[
I_i = \frac{c \lambda}{4\pi} \sum_{k=1}^{K_i} (B_{xk} \Delta x_k + B_{yk} \Delta y_k),
\]

where \(\lambda\) is the pixel size in physical units and \(K_i\) is the number of pixels along the contour \(C_i\) of the partition. Each \(x\)th pixel of the contour is characterized by a horizontal magnetic field \(B_{\Delta x} = B_{xk} \hat{x} + B_{yk} \hat{y}\) and a vector \(\Delta k = \Delta x_k \hat{x} + \Delta y_k \hat{y}\), whose components assume one of three possible values (0, +1, and −1) and represent the unit displacement along the contour.

A practical issue is the specification of the sequence of contiguous points that comprise the bounding contour \(\Delta k\) of a partition. For this we use an “edge tracker” algorithm introduced by Georgoulis et al. (2012). The algorithm minimizes the length of the curve by iteratively selecting pairs of adjacent contour points. Contour-length minimization is achieved by a simulated annealing method (Press et al. 1992).

From Equation (2), we can estimate the corresponding uncertainty \(\delta I_i\) of \(I_i\). We assume that \(\delta I_i\) stems only from the uncertainties \(\delta B_{xk}\) and \(\delta B_{yk}\) of the field components \(B_{xk}\) and \(B_{yk}\), respectively, while \(\Delta x_k\) and \(\Delta y_k\) are known without uncertainties. Considering also \(\delta B_{\Delta x}\) and \(\delta B_{\Delta y}\) to be independent from each other, we obtain from Equation (2)

\[
\delta I_i = \frac{c \lambda}{4\pi} \sum_{k=1}^{K_i} (\Delta x_k^2 \delta B_{xk}^2 + \Delta y_k^2 \delta B_{yk}^2).
\]

If \(B_{xk}\) and \(B_{yk}\) are the horizontal heliographic field components on the image (observer’s) plane, then their uncertainties, \(\delta B_{xk}\) and \(\delta B_{yk}\), respectively, can be calculated by implementing the analytical method described in Appendix I of Georgoulis & Labonte (2004). We use this approach in the following.

Thus, for each partition \(i\) we calculate the total electric current \(I_i\) from Equation (2) and its uncertainty \(\delta I_i\) from Equation (3). As a sanity check, Equation (2) is also used to calculate the total electric current \(I_i\) using a potential magnetic field vector calculated from the disambiguated solution of the photospheric \(B_z\)-distribution. An exact potential field implies that \(I_i = 0\) for every \(i\). However, due to various numerical effects, all \(I_i\) show a nonzero value. Comparison between \(I_i\) and \(I_i\) can help assess the significance of the nonzero total current \(I_i\) of a given partition \(i\) and hence the non-neutrality of this partition.

To calculate the photospheric potential field \(B_p\) from a given photospheric \(B_z\) distribution, we apply the analytical Green’s function method proposed by Schmidt (1964).
This method is much slower, but quite more accurate—for a given choice of boundary conditions—than the numerical fast-Fourier-transform method of Alissandrakis (1981). In the analytical method we assume $B_p = -\nabla \psi$, where $\psi$ is a smooth scalar potential, i.e.,

$$\psi(r) = \frac{1}{2\pi} \int \int \frac{B_z'(r')}{|r - r'|} dx' dy', \quad (4)$$
defined at a given point $r = x\hat{x} + y\hat{y}$ of the photospheric plane. $B_z'$, on the other hand, is a known function of position $r' = x'\hat{x} + y'\hat{y}$ ($r \neq r'$).

Taking into account the above uncertainties, we characterize a given partition $i$ as non-neutralized if

$$|I_i| > 5|I_i'| \quad \text{and} \quad |I_i| > 3 \delta I_i. \quad (5)$$

In other words, we impose a $5\sigma$ significance level toward the spurious total currents $I_i'$ of the potential field and a $3\sigma$ significance level toward the calculated uncertainties $\delta I_i$.

3.2.2. For Active Regions as a Whole

In an given AR, let $N$ be the number of qualifying partitions per the criteria of Section 3.1, and let $\Phi, I_i$ be the magnetic flux and total current, respectively, of a given partition $i$. The total currents $I_+$ and $I_-$ of the positive and negative polarities, respectively, of the region are then given by (e.g., Wheatland 2000)

$$I_+ = \sum_{i=1}^{N} s_i^+ I_i, \quad \text{where} \quad s_i^+ = \frac{1}{2} \left[ 1 + \frac{\Phi_i}{|\Phi_i|} \right],$$

$$I_- = \sum_{i=1}^{N} s_i^- I_i, \quad \text{where} \quad s_i^- = \frac{1}{2} \left[ 1 - \frac{\Phi_i}{|\Phi_i|} \right]. \quad (6)$$

with uncertainties

$$\delta I_+ = \left( \sum_{i=1}^{N} s_i^+ \delta I_i^2 \right)^{1/2}, \quad \delta I_- = \left( \sum_{i=1}^{N} s_i^- \delta I_i^2 \right)^{1/2}. \quad (7)$$

Evidently, significant (i.e., sufficiently larger than applicable uncertainties) $I_+, I_-$ imply non-neutralized currents for the respective polarities. Moreover, the net current in the AR is given by

$$I_{\text{net}} = \sum_{i=1}^{N} I_i = I_+ + I_- \quad \text{(9)}$$

and has an uncertainty

$$\delta I_{\text{net}} = \left( \sum_{i=1}^{N} \delta I_i^2 \right)^{1/2} = \sqrt{\delta I_+^2 + \delta I_-^2}. \quad (10)$$

The solar plasma is considered electrically neutralized since all the physical processes in the Sun are relatively slow. Then, the conservation of the electric charge in the solar atmosphere implies that the electric current density $\mathbf{J}$ must be solenoidal, i.e., $\nabla \cdot \mathbf{J} = 0$. In integral form, this means that the net current through any closed surface, such as the photosphere, must be zero. Taking into account that the strongest coronal magnetic fields and, thus, the currents are localized within solar ARs, we expect that magnetically isolated ARs should be current-balanced ($I_{\text{net}} \sim 0$). In practice, however, there may be large-scale magnetic connections between the AR and its surroundings, so the net current may be different from zero. This may also happen if the observed area does not include the entire AR.

To jointly characterize imbalances of the total current and the magnetic flux in a given AR, we introduce the following dimensionless parameters: the electric current imbalance and the magnetic-flux imbalance, $I_{\text{imb}}$ and $F_{\text{imb}}$, respectively, where

$$I_{\text{imb}} = \frac{|I_{\text{net}}|}{\sum_{i=1}^{N} |I_i|}, \quad (11)$$

$$F_{\text{imb}} = \frac{|\Phi_+ + \Phi_-|}{|\Phi_+ - \Phi_-|}. \quad (12)$$

Here $\Phi_+ = \sum_{i=1}^{N} s_i^+ \Phi_i$ and $\Phi_- = \sum_{i=1}^{N} s_i^- \Phi_i$ are the total magnetic fluxes in the positive and negative polarities of the AR, respectively. We will consider the currents in a given AR to be balanced if the inequality

$$I_{\text{imb}} \ll F_{\text{imb}} \quad (13)$$

is satisfied. This means that the smaller the ratio $I_{\text{imb}}/F_{\text{imb}}$ (ideally $I_{\text{imb}} \ll F_{\text{imb}} \ll 1$), the more confident we are that the AR is current-balanced.

If the criterion of Equation (13) is satisfied, it is also meaningful to obtain a uniform, normalized degree of neutrality (or non-neutrality, thereof) within each polarity of the AR. For this purpose we introduce the global (current) non-neutrality factor

$$T_{\text{nn}}^+ = \frac{1}{2} \left( \frac{|I_+|}{\sum_{i=1}^{N} |s_i^+ I_i|} + \frac{|I_-|}{\sum_{i=1}^{N} |s_i^- I_i|} \right). \quad (14)$$

This dimensionless parameter determines the degree to which different partitions of the same polarity show the same sense of total electric current. For strongly non-neutralized, but also coherent polarities, whose partitions predominantly show a given sense of non-neutralized total current, one obtains $I_{\text{imb}} \ll T_{\text{nn}}^+ \sim 1$. For very incoherent, or current-neutralized, polarities, $I_{\text{imb}} \sim T_{\text{nn}}^+ \ll 1$. The intermediate cases $I_{\text{imb}} \ll T_{\text{nn}}^+ < 1$ and $I_{\text{imb}} < T_{\text{nn}}^+ < 1$ imply a degree of incoherence and/or non-neutrality for each polarity.

4. CURRENT PATTERNS IN THE SELECTED ARS

4.1. NOAA AR 10930

Figure 3(a) shows the flux-partitioned vertical magnetic field of NOAA AR 10930. We identified a total of $N = 531$ flux partitions, of which $p = 246$ show positive polarity and $n = 285$ show negative polarity. To cross-check our calculation, we infer the mean vertical electric current density of each partition in two different ways: first, by dividing the total current $I_i$ of each partition $i$ by the area $S_i$ of the partition ($J_z = I_i/S_i$) and, second, by averaging all the local vertical current densities $J_{zi}$ within each partition $i$ ($J_z = \langle J_{zi} \rangle$), where $J_{zi}$ have been obtained from the differential expression...
of Ampère’s law. Close correlation between these two \( J_z \)-maps implies precise calculation of the bounding contours of the partitions. The results from the two mean-\( J_z \) calculations are depicted in Figures 3(c) and (d), respectively, and are compared in Figure 3(b). Evidently, there is close agreement between the two alternative current density calculations. The generally small discrepancies are mostly caused by uncertainties in the calculation of the differential \( J_z \) via finite differencing. This action is expected to slightly overestimate the magnitudes \( |J_z| \) of the differential \( J_z \). Indeed, Figure 3(b) shows \( (J_z)_{\text{integral}} \approx 0.94(J_z)_{\text{differential}} \), implying a flatter least-squares best fit (black line) than the analytical equality (red line).

We now focus on the total electric currents of individual partitions. In random order, these currents appear in Figure 4(a). We also check which of these currents survive our significance test of Equations (5). Notably, 120 of the 531 identified partitions satisfy the significance criteria. Of them, however, only \( \sim 25 \) have strong enough total currents to be discernible in Figure 4(a) (non-neutralized currents shown with red columns and green error bars). Regardless, it is evident that there are flux partitions in the AR with non-neutralized currents. What is more instructive is the spatial distribution of these currents, shown in the detail of Figure 4(b). We find that partitions with the strongest non-neutralized currents are adjacent to the PILs of the AR. The two main interacting sunspots (labeled 1 and 2 in Figures 4(a) and (b)) have large total currents with values \( \sim 45 \times 10^{11} \) Å and \( \sim -35 \times 10^{11} \) Å, respectively. Partitions adjacent to the secondary PILs of the AR, some of them labeled (3–5), have total currents of the order \( (5-10) \times 10^{11} \) Å. There is virtually no partition with clearly non-neutralized total current that is far from the AR’s PILs. We conclude, therefore, that the intensely flaring NOAA AR 10930 includes strong non-neutralized currents only where opposite-polarity flux-tube footprints are close enough to interact, that is, in proximity to PILs.

NOAA AR 10930 as a whole has a net current \( I_{\text{net}} = (8 \pm 1.6) \times 10^{11} \) Å. With much stronger \( I_+ \) and \( I_- = (80-90) \times 10^{11} \) Å, the AR has a total current imbalance \( I_{\text{imb}} \approx 0.036 \). This is more than an order of magnitude smaller than the magnetic-flux imbalance of the AR, \( F_{\text{imb}} \approx 0.4 \). Consequently, NOAA AR 10930 as a whole can be considered current-balanced. This being said, the non-neutrality factor \( I_{\text{imb}} / F_{\text{imb}} \approx 80 \), so \( I_{\text{imb}} \gg F_{\text{imb}} \). As a result, besides strong non-neutrality in the AR, there is a large degree of coherence in the sense of electric current for each polarity: in particular, \( \sim 80\% \) of partitions of a given polarity show a given sense of electric current (positive/ negative for positive/negative magnetic polarities). This opposite current-sense preference per polarity achieves an overall current-balanced AR so that non-neutralized currents of opposite polarities approximately close onto each other.

4.2. NOAA AR 10940

The flux-partitioned vertical magnetic field of NOAA AR 10940 is depicted in Figure 5(a). Here we identified a total of \( N = 297 \) partitions, of which \( p = 156 \) show positive polarity and \( n = 141 \) show negative polarity. The average vertical current densities for each partition via the integral and the differential calculation are shown in Figures 5(c) and (d), respectively, and are compared in Figure 5(b). For this flare-quiet AR the average current densities are generally smaller than those of the flaring NOAA AR 10930. As expected, the differential \( J_z \) slightly overestimates the electric current density. From Figure 5(b), \( (J_z)_{\text{integral}} \approx 0.93(J_z)_{\text{differential}} \) (black line).

Important quantitative differences between NOAA ARs 10930 and 10940 are revealed, however, when the total currents of partitions are plotted for NOAA AR 10940:
currents are encircled and labeled (1–5). The total currents with red columns and green error bars. Five of the largest non-neutralized total although the total currents $I_i$ are substantially smaller than those of the flaring NOAA AR 10930 and (4) NOAA AR 10940 is much less coherent (a factor-of-two difference) in terms of preference of electric current sense per polarity, compared to NOAA AR 10930.

**4.3. Dependence of Results on Partitioning Threshold and Varying Spatial Resolution**

To obtain the results of Sections 4.1 and 4.2 we used a fixed, arbitrarily chosen threshold $B_{\text{thres}} = 100$ G for the magnetic-flux partitioning and we took advantage of the high spatial resolution of Hinode’s SOT/SP magnetograms. To complete the analysis, we investigate the role of both the arbitrary $B_{\text{thres}}$ and the spatial resolution in our findings.

#### 4.3.1. Varying Partitioning Threshold

First, we vary the value of $B_{\text{thres}}$ from 100 G to 1000 G and perform the same analysis as in Sections 4.1 and 4.2. We find that non-neutralized currents in both ARs continue to accumulate in the partitions identified in Figures 4 and 6, that is, close to the PILs of the ARs. In Figure 7 we show this behavior for NOAA AR 10930. In Figure 7(a), the black curve indicates the fraction of the total (unsigned) magnetic flux of the AR that is represented by the partitioning for each $B_{\text{thres}}$-value. Understandably, as more flux is left out of the partitioning for increasing $B_{\text{thres}}$, this fraction decreases. The magnetic-flux imbalance $F_{\text{imb}}$ and the total-current imbalance $I_{\text{imb}}$ for various $B_{\text{thres}}$ are shown with blue and red curves, respectively. For all $B_{\text{thres}}$, $I_{\text{imb}}$ is always 5–40 times smaller than $F_{\text{imb}}$, regardless of the value of $B_{\text{thres}}$. Therefore, irrespective of $B_{\text{thres}}$, NOAA AR 10930 includes non-neutralized current patterns close to its PILs but stays current-balanced globally. The non-neutrality factor $F_{\text{imb}}$ is substantial at all times ($\gtrsim 0.8$) and increases nearly monotonically for increasing $B_{\text{thres}}$. Therefore, we can safely conclude that $I_{\text{imb}} \ll F_{\text{imb}} \sim 1$ so the two different polarities in NOAA AR 10930 have both strong non-neutralized currents and a clear preference of sense of electric currents, independently of $B_{\text{thres}}$.

In Figure 7(b) the blue curves show $I_+$, for the positive-polarity partitions, and $I_-$ for the negative-polarity ones, while the red curve shows the net current $I_{\text{net}}$. That $I_+ < 0$ and $I_- > 0$ indicates a predominantly left-handed, counterclockwise twist in the AR. Note also that $|I_+|$ and $|I_-|$ tend to decrease for increasing $B_{\text{thres}}$. This indicates that non-neutralized currents become weaker if stronger, less interacting, fields are chosen for partitioning. Indeed, moving to thresholds $B_{\text{thres}}$ from several hundred G to 1 kG, we exclude some parts of the PILs of the AR. Regardless, the total current balance of the AR does not depend sensitively on $B_{\text{thres}}$: $|I_{\text{net}}|$ is always $\sim 3$–4 times smaller than $|I_+|$ and $|I_-|$.

The same analysis on NOAA AR 10940 is depicted in Figure 8. Because of the much weaker currents involved, increasing $B_{\text{thres}}$ in this case leads to more striking quantitative changes: for $B_{\text{thres}}$ ranging between 400 G and 800 G the current imbalance $I_{\text{imb}}$ increases to $\sim 0.5$ but still remains...
smaller than the respective flux imbalance \( F_{\text{imb}} \) which ranges between 0.5 and 0.6 for the same \( B_{\text{thres}} \)-range (Figure 8(a)). For \( B_{\text{thres}} > 800 \) G, \( I_{\text{imb}} \) decreases significantly to reach \( \sim 0.2 \) at \( B_{\text{thres}} = 1000 \) G. Apparently the combination of weak total currents (Figure 8(b)) and a strongly imbalanced, inhomogeneous magnetic-flux distribution where one or the other polarity is favored for different \( B_{\text{thres}} \)-values is the reason for these effects. The non-neutrality factor \( I_{\pm} \) initially increases and remains high at \( \sim 0.7 \) until \( B_{\text{thres}} \simeq 600 \) G, thereafter decreasing significantly to reach a value \( \sim 0.4 \). At all times, though, \( I_{\pm} > I_{\text{imb}} \). The polarity currents \( I_+ \) and \( I_- \) (Figure 8(b))
peak at $\sim 20 \times 10^{11} \text{ Å}$, $\sim 5$ times smaller than those in NOAA AR 10930. Their magnitudes also decrease for increasing $B_{\text{z, max}}$ and this causes $I_{\text{net}}$, and hence $I_{\text{imb}}$, to change significantly. Nonetheless, it would be biased to claim that whether NOAA AR 10940 is globally current-balanced depends on the value of $B_{\text{z, max}}$. For reasonable values of this threshold, sufficient to keep a reasonably balanced representation of both polarities in the partitioning, the flare-quiet NOAA AR 10940 has an overall current-balanced structure, includes non-neutralized currents along its PIL, and shows some preference in a given sense of current for each polarity, similarly to its flaring counterpart NOAA AR 10930. However, this preference is much weaker than in the flaring AR, as are the non-neutralized current patterns NOAA AR 10940 involves.

4.3.2. Varying Spatial Resolution

We now study the impact of changing spatial resolution to the current patterns of the two ARs. We first bin each magnetogram using different sampling factors and then we re-calculate the subsequent current patterns using the analysis of Section 3 and keeping a fixed $B_{\text{z, max}} = 100 \text{ G}$ in all cases. For NOAA ARs 10930 and 10940 the results are summarized in Tables 1 and 2, respectively.

For both ARs, we reach the following conclusions.

1. Decreasing the spatial resolution causes a decrease in the number of the identified partitions and a subsequent decrease in the number of partitions that include non-neutralized currents, that is, those satisfying the significance criteria of Equations (5). For the coarsest spatial resolution (pixel size $\sim 2.5''$) both NOAA ARs 10930 and 10940 include only three partitions. The identification of fewer partitions for coarser spatial resolution occurs because the morphological properties of the photospheric magnetograms—where partitioning relies—are suppressed or smoothed out when the resolution is reduced.

2. Decreasing the spatial resolution leads to a decrease in the total current magnitudes $|I_+|$ and $|I_-|$. Even in this case, however, strong non-neutralized current patterns in the flaring NOAA AR 10930 are easily discernible. This is not the case for NOAA AR 10940, whose current magnitudes fall almost within the uncertainty margins ($\sim 10^{11} \text{ Å}$) for pixel sizes equal to $\sim 1.3''$ and $\sim 2.5''$. That NOAA AR 10930 seems to largely maintain its strong non-neutralized currents around its PILs even for very coarse resolution justifies previous studies that advocate for non-neutralized currents with much lower-resolution magnetograms (Leka et al. 1996; Semel & Skumanich 1998; Wheatland 2000; Falconer 2001). Our results differ from those of Wilkinson et al. (1992) who did not find

Table 1

| Pixel Size (arcsec) | $N$ | $N_{\text{nn}}$ | $I_+$ ($\times 10^{11} \text{ Å}$) | $I_-$ ($\times 10^{11} \text{ Å}$) | $I_{\text{net}}$ ($\times 10^{11} \text{ Å}$) | $I_{\text{imb}}$ ($\times 10^{11} \text{ Å}$) | $I_{\text{imb}}^+ / I_{\text{imb}}$ | $F_{\text{imb}}$ |
|-------------------|-----|----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----|
| 0.1585            | 531 | 120            | $-84.9 \pm 1.1$ | $92.9 \pm 1.2$  | $8.1 \pm 1.6$  | 0.036           | 0.799           | 0.398 |
| 0.317             | 449 | 76             | $-86.1 \pm 0.8$ | $89.7 \pm 0.9$  | $3.7 \pm 1.1$  | 0.018           | 0.867           | 0.447 |
| 0.634             | 65  | 19             | $-58.7 \pm 0.6$ | $70.3 \pm 0.6$  | $11.6 \pm 0.8$ | 0.086           | 0.967           | 0.583 |
| 1.268             | 12  | 6              | $-47.9 \pm 0.4$ | $57.2 \pm 0.6$  | $9.3 \pm 0.7$  | 0.089           | 1.000           | 0.678 |
| 2.536             | 3   | 2              | $-38.8 \pm 0.6$ | $59.9 \pm 0.6$  | $12.1 \pm 0.8$ | 0.132           | 0.978           | 0.665 |

Notes. $N$ is the total number of partitions and $N_{\text{nn}}$ is the number of non-neutralized partitions. The pixel size has been modified by binning the original Hinode SOT/SP magnetogram of the AR. Shown are the total currents per polarity ($I_+$, $I_-$), the net current ($I_{\text{net}}$), the total-current imbalance ($I_{\text{imb}}$), the current non-neutrality factor ($I_{\text{imb}}^+ / I_{\text{imb}}$), and the magnetic-flux imbalance ($F_{\text{imb}}$).

Table 2

| Pixel Size (arcsec) | $N$ | $N_{\text{nn}}$ | $I_+$ ($\times 10^{11} \text{ Å}$) | $I_-$ ($\times 10^{11} \text{ Å}$) | $I_{\text{net}}$ ($\times 10^{11} \text{ Å}$) | $I_{\text{imb}}$ ($\times 10^{11} \text{ Å}$) | $I_{\text{imb}}^+ / I_{\text{imb}}$ | $F_{\text{imb}}$ |
|-------------------|-----|----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----|
| 0.317             | 297 | 45             | $14.3 \pm 1.5$  | $-10.46 \pm 1$  | $3.8 \pm 1.8$  | 0.063           | 0.403           | 0.282 |
| 0.634             | 50  | 9              | $11.5 \pm 0.5$  | $-7.2 \pm 0.5$  | $4.2 \pm 0.7$  | 0.156           | 0.681           | 0.474 |
| 1.268             | 10  | 2              | $7.0 \pm 0.6$   | $-1.2 \pm 0.4$  | $5.8 \pm 0.7$  | 0.514           | 0.640           | 0.581 |
| 2.536             | 3   | 1              | $3.9 \pm 0.5$   | $2.1 \pm 0.5$   | $6.0 \pm 0.7$  | 0.580           | 0.663           | 0.541 |

Figure 8. Same as Figure 7, but for NOAA AR 10940. (A color version of this figure is available in the online journal.)
compelling evidence of non-neutralized current patterns in the flaring NOAA AR 2372.

3. Regarding the ARs’ overall current balance, Table 1 suggests that NOAA AR 10930 remains current-balanced regardless of spatial resolution. For all cases, $F_{\text{mb}}$ is 5–25 times larger than $I_{\text{mb}}$. NOAA AR 10940 also appears current-balanced except in case the pixel size becomes $\gtrsim 1^\circ$. Then, $I_{\text{mb}} \sim F_{\text{mb}}$ but with very weak $I_{\text{p}}$ and $I_{\text{c}}$. These weak, insignificant currents practically invalidate any conclusions about $I_{\text{mb}}$.

4. Regarding the non-neutrality factor $I_{\text{mb}}$, it appears that binning consistently increases the coherence of each polarity in terms of sense of electric currents. This is the case for both ARs, although the results are somewhat mired in case of the flare-quiet NOAA AR 10940, where $I_{\text{mb}} \sim I_{\text{mb}}$ for coarser pixel sizes, due to the much weaker—and hence more uncertain—currents involved.

Briefly, we conclude that varying the partitioning threshold and/or altering the spatial resolution does not qualitatively affect our findings of (1) non-neutralized current patterns along PILs and (2) globally current-balanced ARs. Only very restrictive partitioning or very coarse spatial resolution can affect these findings, and only for flare-quiet ARs lacking tight, well-organized PILs. Large partitioning thresholds or severe binning can cause artifacts, such as the disappearance of these weak PILs. PILs, however, are parts of the “topological skeleton” of ARs (Bungey et al. 1996), which means that they are topologically stable features. As such, at least the strongest of them will survive, regardless of thresholding or smoothing. This study shows that non-neutralized current patterns are exclusively related to PILs; apparently the stronger the PIL, the more intense the non-neutralized currents it involves. If well-formed PILs cannot disappear due to thresholding or binning, their currents cannot disappear under these actions, either.

5. PHYSICAL IMPLICATIONS OF OUR RESULTS

We now attempt to establish a qualitative connection between our findings and the observed evolution along well-formed PILs. A crucial aspect of this evolution is magnetic shear. Shear is invariably formed along PILs (e.g., Falconer et al. 1997; Yang et al. 2004) with the effect being more pronounced in stronger PILs. Pending confirmation with larger AR samples, this work also implies that non-neutralized electric currents are also stronger in stronger PILs. A connection between non-neutralized currents and magnetic shear, therefore, appears plausible.

Another notable finding of this study is that partitions of the same polarity tend to have the same sense of non-neutralized currents. This is reflected in the non-neutrality factor $I_{\text{mb}}$ that is $\sim 1$ for the eruptive NOAA AR 10930, despite the large number (hundreds) of partitions for each polarity. The same result in the same AR was recently reported by Ravindra et al. (2011).

A similar effect, but at a clearly smaller degree, occurs for the non-eruptive NOAA AR 10940. This coherence of electric currents, more pronounced in more compact ARs with stronger PILs, must be of sub-photospheric origin. Indeed, numerous simulations of magnetic-flux emergence, (e.g., Tortosa-Andreu & Moreno-Insertis 2009; Archontis & Hood 2010; Cheung et al. 2010), all start from a single flux tube with a given twist in the convection zone. Upon emergence in the photosphere, the flux tube undergoes substantial fragmentation. We show here that in the course of such a fragmentation electric currents largely retain their sub-photospheric sense. Strong PILs likely indicate a strongly twisted, perhaps braided (López Fuentes et al. 2003), coherent sub-photospheric flux tube, while weak PILs suggest a loosely formed sub-photospheric tube with only the necessary coherence to survive its emergence in the solar atmosphere.

But how, and why, does magnetic shear occur along intense PILs? For NOAA AR 10930, studied here, Su et al. (2007) concluded that the observed shear is due to sunspot rotation and the east–west motion of the emerging positive-polarity sunspot just south of the negative-polarity main sunspot of the AR. The main PIL of the AR is between these two spots (Figure 1). Here we reveal additional information, namely that strong and systematic non-neutralized currents are formed along the PIL and only there. These currents suggest that the Lorentz force may be the most natural cause of shear. This is already suggested in several works: Manchester & Low (2000) analytically showed that the tension component of the Lorentz force can cause shear in an undulated emerging flux tube. This result was numerically demonstrated by Manchester (2001). Manchester et al. (2004) modeled a Lorentz-force-driven shear with a gradient ranging from photosphere to corona, supporting earlier observations of differential shear in ARs (Schmieder et al. 1996). A systematic modeling of the Lorentz-force-driven shear that demonstrates a coupling between sub-photospheric and atmospheric magnetic fields was performed by Manchester (2007). This author demonstrated by MHD flux emergence simulations that a gradient in the axial magnetic field (along the PIL) during the emergence of an $\Omega$-loop is the cause of the Lorentz force that further causes shear flows leading to magnetic shear. These flows have an amplitude of about half the local Alfvén speed, hence increasing from the photosphere to the corona. These results were supported by Fang et al. (2010) who further found that $U$-loops may be formed along PILs, in agreement with Tortosa-Andreu & Moreno-Insertis (2009). In the sub-photospheric part of $U$-loops, however, they showed that the Lorentz force can unshar the magnetic field lines, contrary to the situation in and above the photosphere.

In an effort to provide a heuristic explanation of the shear-generating Lorentz force $F$ and its physical connection to non-neutralized currents, we write $F$ in terms of magnetic tension and pressure (Jackson 1962), i.e.,

$$F = \frac{1}{4\pi} \left[ (\mathbf{B} \cdot \nabla)\mathbf{B} - \frac{1}{2} \nabla B^2 \right].$$

(15)

The azimuthal component $F_\varphi$ of the Lorentz force in cylindrical coordinates $(r, \varphi, z)$ is given by

$$F_\varphi = \frac{1}{4\pi} \left[ B_r \frac{\partial B_\varphi}{\partial r} + \frac{1}{2r} \frac{\partial (B_\varphi^2 - B_z^2)}{\partial \varphi} + B_z \frac{\partial B_\varphi}{\partial z} + \frac{B_r B_\varphi}{r} \right].$$

(16)

All terms in Equation (16) are due to magnetic tension, with the exception of the term $-(1/(2r))\partial B^2/\partial \varphi$ that is due to magnetic pressure.

We first assume a pair of undisturbed, twisted flux-tube footprints embedded in field-free, plasma-filled space (Figure 9(a)). Obviously there is no strong PIL interfacing between the footprints in this case. We further ignore the (generally nonzero) azimuthal Lorentz force in the flux-tube interior and focus on the outer edges of the tube (dark blue and red rings) where sheath currents reside, and we seek the azimuthal Lorentz force $F_\varphi$ acting in this area. There, the two terms of $F_\varphi$ depending on the radial field component $B_r$ vanish because the field has to be largely azimuthal, with a weaker vertical component $B_z$,
Figure 9. Simplified concept for the occurrence of shear-generating Lorentz forces along lower-boundary PILs in solar active regions. The situation is qualitatively similar for different altitudes, along the normal direction \( z \), until the field becomes space filling. (a) In case of non-interacting flux-tube footprints, hence no well-defined PILs, a lack of azimuthal gradients within and on the interface between the flux tube and the field-free space inhibits a shearing (azimuthal) Lorentz force \( F_\varphi \). (b) In case of interacting, deformed flux tubes, inhomogeneous azimuthal gradients are formed (dark shapes), preferentially enhancing sheath currents along the PIL (dashed line) that become non-neutralized within a given polarity and give rise to an azimuthal, shearing Lorentz force \( F_\varphi \) in the PIL area. In both panels, the field polarity is denoted at the center of each footprint, while red- and blue-color gradients suggest the gradient of \( B \). Spiral curves denote twist in the flux tube, and hence the presence of an azimuthal field \( B_\varphi \). Each footprint is enclosed by its sheath currents (\(-\nabla \times B\)—dark red and blue rings) for the flux tube to maintain coherence.

We now assume a pair of interacting flux-tube footprints that deform due to this interaction, forming a strong PIL between them (Figure 9(b)). The field will still have to be predominantly azimuthal on the interface in this case, too, so Equation (17) can still be used. However, (i) the vertical field component \( B_z \) is no longer non-vanishing; in fact, it can be quite strong along both sides of the PIL, and (ii) enhanced, PIL-localized azimuthal field gradients build up in the deformation area, even in this simplified, axially symmetric (with respect to the PIL) case. These gradients preferentially enhance sheath currents along the PIL. These currents cannot be neutralized any more within a given polarity. Evidently, then, \( F_\varphi \neq 0 \) along the PIL (but not on it, because \( B_z = 0 \) there) unless the two terms in the parenthesis of Equation (17) cancel each other. This resulting azimuthal Lorentz force is purely due to magnetic tension.

Cancellation of the derivative terms may conceivably happen, but in general it is not the case, and it is certainly not true in case of asymmetries in the magnetic-flux distribution within a given
footprint. Nonzero azimuthal Lorentz force will cause shearing motions along the PIL that will further give rise to magnetic shear, as demonstrated in numerical simulations. Qualitatively, this result is similar for all interacting opposite-polarity flux tubes.

In the actual solar photosphere, however, the plasma $\beta$-parameter is high enough for MHD to compete with the hydrodynamics of the non-magnetized plasma. This dense plasma, therefore, should exhibit an inertia to the action of the Lorentz force that can only be overcome locally, where strong fields give rise to powerful azimuthal Lorentz forces (Equation (17)). An intuitive PIL field strength that, if exceeded, should allow $F_\beta$ to move the plasma, is the equi-partition value $B_{eq}$ needed for $\beta = 1$. Assuming typical photospheric values for convective flows and mass density, or for number density and the effective temperature, one finds $B_{eq} \sim 800$ G. In NOAA AR 10930 the field strength around the PIL always exceeds 1.5 kG and, in many cases, it is higher than 2 kG (Figure 1). In this case it is clear that $\beta < 1$ in the PIL area, hence $F_\beta$ should be powerful enough to move the plasma. In NOAA AR 10940, the PIL field strength ranges between a few hundred G to $\lesssim 1.5$ kG. In this case, therefore, despite some non-neutralized currents, the azimuthal Lorentz force may not be able to shear plasma and magnetic field considerably. This rough interpretation qualitatively agrees with the observational facts for both studied ARs.

In a symmetric case such as the one of Figure 9(b), Equation (17) clearly implies an opposite orientation of $F_\beta$ in the two sides of the PIL that leads to an opposite sense of shear flows. In case of strong asymmetries, however, the competition of the two tension terms in the parenthesis may result in the same sign of $F_\beta$ in the two PIL sides, and hence in a similar sense of shear flows. Asymmetries can be simply thought of as severe flux imbalance and/or different field morphologies of the partitions deformed along the PIL. For the studied NOAA AR 10930, for example, inspection of continuum and magnetogram movies implies that velocity shear mainly acts in the counterclockwise direction in both sides of the PIL. Figure 1(b) shows clearly that the PIL area is strongly asymmetric. Even in case of similar shear orientation, however, asymmetries lead to strong velocity gradients across the PIL that give rise to strong relative motions in the two sides of the PIL. Albeit in a more complicated manner, therefore, the end result of strongly asymmetric shear flows is qualitatively similar with that of the symmetric case. The directionality of the shear is determined by the direction of $B_\beta$ that is due to the dominant sense of twist in the flux tube. The consistency of the shear-flow orientation for the lifetime of the PIL corroborates our findings that there indeed exists a dominant sense of twist in interacting opposite-polarity flux tubes.

The proposed mechanism of Lorentz-force-driven shear along PILs is, of course, qualitative—careful quantitative studies are necessary for all aspects of it to be clarified at sufficient detail. The study of Török & Kliem (2003) first showed numerically that as soon as shearing motions are generated in the PIL area, non-neutralized currents inevitably build up in the corona. Shear in that study was generated by placing bipolar flux concentrations—twisted by photospheric vortex flows—progressively closer to each other; the closer the concentrations, the larger their non-neutralized total current. Further, Török et al. (2011) recently analyzed the evolution of electric currents in an emerging flux-rope simulation. As predicted earlier by Longcope & Welsch (2000), these authors also found that the electric current in the coronal part of the emerging flux rope is, indeed, essentially non-neutralized, although the physical mechanism underlying this effect has yet to be clarified. Works like the above substantiate our findings for non-neutralized currents in AR PILs while our proposed mechanism, at work in case opposite-polarity photospheric flux concentrations approach close enough to interact, provides a physical context for this effect.

6. SUMMARY AND CONCLUSIONS

Using solar magnetic field measurements of the highest available spatial resolution, we have studied in detail the electric current patterns of the photospheric magnetic configurations in two solar ARs: a flaring/eruptive AR and a flare-quiet one. Our main objective was to determine whether emerging and/or evolving ARs inject significant non-neutralized electric currents in the solar atmosphere through the photospheric boundary. We show that such currents are injected solely and exclusively along the photospheric magnetic PILs that accompany the dynamical formation and evolution of ARs. In our limited sample of two ARs we find that stronger PILs imply more intense non-neutralized currents. This result is robust and insensitive to magnetic field thresholding and the spatial resolution of the studied magnetograms, but has to be confirmed by future studies with larger AR samples.

Despite current non-neutrality in particular locations within ARs, our study confirms that ARs as a whole are current-balanced magnetic structures. This means that non-neutralized currents injected on one side of a PIL are roughly counterbalanced by non-neutralized currents of the opposite sense that are developed on the other side of the PIL.

An additional finding, in agreement with recent results (Ravindra et al. 2011), is the coherence in the sense of electric currents within a given polarity. We have quantified the effect by means of a dimensionless parameter dubbed the global non-neutrality factor (Equation (14)). We find that this effect is more pronounced in the eruptive AR we study, but it is also present in the non-eruptive region (Figures 4(a) and 6(a) and Tables 1 and 2), despite the considerable flux fragmentation in the photosphere. We conclude that this effect is of sub-surface origin, which stands in agreement with the results of multiple numerical simulations that show substantial fragmentation of a single buoyant flux tube in realistic simulations of emerging ARs (e.g., Cheung et al. 2010).

Our findings seem to put a nearly twenty-year-old debate to rest: amidst claims ranging between no injection of net electric currents in the solar atmosphere, per Parker’s (1996b) isolated flux-tube picture (see the Introduction), and injection of net currents in each and every magnetic-flux emergence episode, we demonstrate that injection of significant net currents does occur but it is as rare—as or as frequent—as the appearance of intense PILs in the solar photosphere. In this case only, Parker’s assumption of isolated flux tubes breaks down and Melrose’s (1991, 1995) proposition of non-neutralized photospheric currents becomes valid. It is obviously beyond the scope of this work to argue about the detailed nature of the sub-photospheric origin of these currents (i.e., the $[E, J]$- versus the $[B, u]$-paradigm). However, we do argue that strong non-neutralized currents occur exclusively in case of emerging magnetic footprints of opposite polarities that are close enough to interact, i.e. to “feel” each other and deform as a result of this interaction. Deformation implies preferential enhancement of return currents sheathing these flux tubes at the deformed areas. Because shear currents
are perpendicular to the axes of the tubes, these perturbations imply the exertion of a Lorentz force that, via magnetic tension, generates shear along the PIL, in terms of both shear flows and magnetic shear. The more enhanced the shear currents developed in more flux-maximally, tight PILs, the stronger the Lorentz force and the resulting shear, provided that the magnetic field strength in the PIL area is greater than the equipartition value (plasma $\beta < 1$), so that the Lorentz force can overcome the hydrodynamic inertia and move the plasma (Section 5).

The direction of shear flows is typically opposite in the two sides of the PIL (Equation (17)). The magnetic shear angle reflects the sense of twist of the interacting flux tubes; for the studied NOAA AR 10930, negative magnetic polarities associate to positive (non-neutralized) currents and vice-versa (Figures 3 and 4)—this implies a left-handed sense of twist in the region. An opposite situation (right-handed twist) in eruptive ARs, as demonstrated by previous (e.g., Nindos & Andrews 2004; LaBonte et al. 2007; Georgoulis et al. 2009) and recent (e.g., Tziotziou et al. 2012) works. Undoubtedly, much remains to be revealed, but efforts should focus on putting together as many pieces of the solar eruption puzzle as possible in the most meaningful physical interpretation possible. We intend to undertake such efforts in future studies.

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