IDENTIFYING POTENTIAL MARKERS OF THE SUN’S GIANT CONVECTIVE SCALE

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ABSTRACT

Line-of-sight magnetograms from the Helioseismic and Magnetic Imager (HMI) of the Solar Dynamics Observatory (SDO) are analyzed using a diagnostic known as the magnetic range of influence (MRoI). The MRoI is a measure of the length over which a photospheric magnetogram is balanced and so its application gives the user a sense of the connective length scales in the outer solar atmosphere. The MRoI maps and histograms inferred from the SDO/HMI magnetograms primarily exhibit four scales: a scale of a few megameters that can be associated with granulation, a scale of a few tens of megameters that can be associated with super-granulation, a scale of many hundreds to thousands of megameters that can be associated with coronal holes and active regions, and a hitherto unnoticed scale that ranges from 100 to 250 Mm. We infer that this final scale is an imprint of the (rotationally driven) giant convective scale on photospheric magnetism. This scale appears in MRoI maps as well-defined, spatially distributed concentrations that we have dubbed “g-nodes.” Furthermore, using coronal observations from the Atmospheric Imaging Assembly on SDO, we see that the vicinity of these g-nodes appears to be a preferred location for the formation of extreme-ultraviolet (and likely X-Ray) brightpoints. These observations and straightforward diagnostics offer the potential of a near real-time mapping of the Sun’s largest convective scale, a scale that possibly reaches to the very bottom of the convective zone.

Key words: convection – Sun: corona – Sun: photosphere

Online-only material: color figures

1. INTRODUCTION

The region of the solar atmosphere that is hidden from direct observation by its profound optical depth—the Sun’s convective interior—is an ocean of boiling, bubbling plasma sustained from beneath by a rotating, nuclear furnace. The convective layer that forms the third of the solar interior masks the bottom of the convective zone. The readily amenable granules and super-granules reflect the apparent nested surface scales (with a strong emphasis toward the readily amenable granules and super-granules) reflect the multi-scale organization (or continuous spectrum) of motions present in the Sun’s interior (e.g., Berrilli et al. 2012; Orozco-Suárez et al. 2012; Yelles Chaouche et al. 2012, 2014). As such, the third scale would indeed reflect a slower, longer-lived, convective scale present in the deepest interior (e.g., Nordlund et al. 2009).

In the following sections, we present the application of an analysis technique that was originally designed to investigate the range of connective length scales of the outer solar atmosphere that could be inferred from a simple analysis of photospheric magnetograms—the magnetic range of influence (MRoI; McIntosh et al. 2006). The MRoI analysis demonstrates the presence of a tertiary convective scale, which is ever-present in the magnetogram record of the Helioseismic and Magnetic Imager (HMI; Scherrer et al. 2012) of the Solar Dynamics Observatory (SDO). Furthermore, we see that the magnetic elements that comprise the vertices of this larger scale convective pattern are potential anchor-sites for an ever-present feature of the solar corona—extreme-ultraviolet (EUV) brightpoints (BPs; Vaiana et al. 1973).

2. ANALYSIS

A map of the MRoI is constructed from a line-of-sight magnetogram in a pixel-by-pixel fashion and is defined as the
Figure 1. Full-disk SDO/HMI line-of-sight magnetogram (A) and derived magnetic range of influence (MRoI; B) map from 2010 May 16.

(radial) distance of the pixel over which the total signed flux of the enclosed region is zero. The MRoI is either a measure of magnetic balance, the effective length scale over which we would expect the overlying corona to be connected, or closed. The method was originally conceived to help identify the coronal holes (McIntosh et al. 2006), which, as weak but spatially extended unipolar regions of the photosphere, should have large values of MRoI. Conversely, in magnetically balanced regions, such as the quiet Sun MRoI, values are small (McIntosh et al. 2007; McIntosh 2007). Figure 1 shows the MRoI map (panel B) that is constructed from a “720 s” SDO/HMI line-of-sight magnetogram (panel A) taken at 00:00 UT on 2010 May 16 during a very quiet spell of solar activity. The most striking features in this MRoI map are the extended patches of MRoI values greater than 1000 Mm in value—the orange-red regions, the spatially distributed patches of green, and the blue-purple remainder (see the inset regions of Figure 4 for more detail). It should be noted that the present version of the MRoI does not account for the spherical projection or line-of-sight projection of the line-of-sight field when computing the radial distance of closure. This leads to uncertainties in the MRoI near the limb. Similarly, the fact that the visible disk can be dominated by large spatially distributed unipolar patches—like coronal holes—leads to MRoI values that reach a solar diameter in scale. In this case there is no net-zero-field “closure” available at that largest scale.

A histogram of the MRoI values from Figure 1 is shown in Figure 2. There are four scales present in the histogram and (for illustrative purposes only) we have associated the three shortest scales with a Gaussian distribution and attempted to simultaneously identify a best-fit (dot-dashed) line. The first component (red) is small in amplitude and, at just above the resolution limit of SDO/HMI at a few megameters, is likely a faint signature of granulation. The second (blue) component of the MRoI distribution peaks around 30 Mm and represents the magnetic scale of super-granulation. The third (green) component of the distribution is smaller in amplitude than that of the super-granules but seems to contain values in the 100–250 Mm range, and there is an excess distribution at very long scales that have contributions from coronal holes and active region plages, as we will see below. While the first two and last component of the distribution are known, or identifiable, the third component of the distribution is composed of the spatially distributed green patches in Figure 1(B) that have the 100–250 Mm scale—a separation length scale that is commensurate with the expected dimension of giant convective cells (e.g., Simon & Weiss 1968; Beck et al. 1998; Miesch 2005). For comparison, we also show the distribution of scale histograms formed from the MRoI analysis of an ensemble of 50 randomized magnetograms (shaded region). Each null MRoI is computed using magnetogram values where the value in each pixel is drawn from an identical distribution to the original SDO/HMI data. The shaded region in Figure 2 reflects the mean frequency and three standard deviations at each spatial scale. While this procedure demonstrates a profound peak of MRoI values around 8 Mm, we see no signature of smaller or larger scales in the randomized maps. This is a strong indication that the scales revealed by the MRoI analysis of the SDO/HMI line-of-sight magnetograms reflect a range of characteristic connective length scales in the Sun’s photosphere.

2.1. Temporal Evolution of the Tertiary Scale

Figure 3 shows the variation of the MRoI length-scale distributions from 2010 May to 2013 August. The inverse color image in the left panel shows that there are persistent features in the MRoI distributions, especially the components centered on ~25 Mm (the red horizontal dot-dashed line) and
Figure 2. Histogram of MRoI values derived from the full-disk map of Figure 1 vs. those of a “null” experiment (see the text). The observed MRoI histogram shows four possible scale ranges: one near the resolution limit of SDO/HMI at a few megameters (red dashed line), the majority of the pixels show a scale of $\sim 30$ Mm (blue dashed line), a third component peaking at $\sim 125$ Mm scale (green dashed line), and a group of scales around 1000 Mm. The shaded ensemble of null MRoI histograms show none of the same characteristic scales. The MRoI has a hard limit of a solar diameter (vertical thin dashed line) imposed.

(A color version of this figure is available in the online journal.)

Figure 3. Temporal evolution of the daily SDO/HMI MRoI histograms from 2010 May to 2013 August. Each vertical slice of the image is an MRoI scale distribution like that shown in Figure 2. Representative super-granular and giant cell scales are drawn as red and blue horizontal dot-dashed lines respectively. The right panel shows the time averaged MRoI histogram (black) and the example from Figure 2 (red) from 2010 May 16.

(A color version of this figure is available in the online journal.)

$\sim 125$ Mm (the black horizontal dot-dashed line). The right panel of the figure compares the temporal mean length scale distribution (black line) with the 2010 May 16 distribution of Figure 2 (red line). These measurements indicate that the $\sim 120$ Mm scale, commensurate with the expected scale of giant cells, is persistently visible in the solar photosphere using the MRoI technique. In addition to the prevalence of the $\sim 30$ Mm and $\sim 125$ Mm scales, we see enhancements at $\sim 240$ Mm and $\sim 420$ Mm (or $2.375$ and $2.625 \log_{10} \text{MRoI}$, respectively) which appear to grow in prevalence as cycle 24 proceeds. A simple assumption would be to associate these scales with the growth of sunspot complexes and coronal holes that are not present, or abundant, in the quiet 2010 spectrum. This interesting realization hints to a subtle solar cycle dependence in the scales, which requires further investigation that is beyond the scope of this Letter but will be explored in a subsequent publication (S. W. McIntosh et al. 2014, in preparation).

2.2. The Tertiary Scale and Extreme Ultraviolet Brightpoints

Brightpoints are small ubiquitous constituents of the Sun’s coronal plasma (e.g., Vaiana et al. 1973). It was originally noted that they are spatially associated with dipolar magnetic configurations (e.g., Golub et al. 1974), however, in a recent investigation, McIntosh (2007) used the MRoI technique to...
demonstrate that BPs typically surround magnetic regions with a magnetic scale that is considerably larger than typical quiet Sun values (~30 Mm).

The upper panels of Figure 4 contrast coronal images and the MRoI. Panel (A) shows the SDO Atmospheric Imaging Assembly (AIA; Lemen et al. 2012) 193 Å image of the solar corona taken at 00:00 UT on 2010 May 16. Panel (B) shows the same image with the BPs identified using the method of McIntosh & Gurman (2005) as black circles, and panel (C) shows the corresponding MRoI map where the BPs are drawn as white circles.

Details of the BPs detection and tracking algorithms are available in the literature (see, e.g., McIntosh & Gurman 2005; Hara & Nakakubo-Morimoto 2003), though we have taken steps to improve the reliability of the detection in subsequent years that will be detailed in a forthcoming article which also presents the 1996–2014 BP record (S. W. McIntosh et al. 2014, in preparation). Following image calibration and cosmic ray removal, we construct a “background” image (I₀) using a 40 Mm × 40 Mm smooth version of that image (I). BPs are defined as spatially small (2–20 Mm) 3σ enhancements of the original image over the background image. That is, we construct a “sigma” image ((I − I₀)/√I₀) that can account for subtle differences of coronal images from instrument to instrument (e.g., say from Solar and Heliospheric Observatory (SOHO)/EIT and SDO/AIA) and provide a significantly more robust BP determination than that originally presented by McIntosh & Gurman (2005). From the resulting histogram of sigma image values, we use one, two, and three standard deviations above the mean value as the thresholds for BP detection—the 3σ detections being the most reliable. After defining the detection thresholds, we isolate contiguous pixel groups in the images, computing their center position and radius of gyration. Only 3σ regions with radii between 2 and 20 Mm are considered as belonging to BPs and are those shown in Figure 4.

On first inspection of Figure 4, we note that the BPs are well separated and that there appears to be a correspondence between regions of large MRoI and BP formation, as first noted by McIntosh (2007). The BPs appear to form in the vicinity of the green (~125 Mm scale) concentrations that are spread over the solar disk. Exploring in a little more detail using the lower row of panels in Figure 4, we highlight the correspondence between BPs, the distribution of quiet Sun magnetism, and the MRoI in more detail than visible in the full-disk images above.

First, we note from panel (D) that BPs do not form around all quiet Sun dipolar field pairs and that they do indeed appear...
to have preferred locations in the immediate neighborhood of the ∼125 Mm scale MRoI (green colored) regions. Hereafter, we will refer to these concentrations of the ∼125 Mm scale as “g-nodes” given their potential connection to the giant convective scale. We should note that a cursory inspection of the magnetogram would not naturally lead one to disentangle the magnetic flux at a super-granular vertex from that of a g-node—to all intents and purposes they are indistinguishable when using the magnetogram alone.

Figure 5 demonstrates the apparent relationship between g-nodes and BPs (panel (A)). The g-nodes are identified from the MRoI maps using a modification of the BP detection algorithm—employing it to isolate only the 100–200 Mm scale concentrations. In general, we see that BPs recurrently form in the immediate vicinity of g-nodes, but not all g-nodes have neighboring BPs (panel (B)). The general proximity of BP and g-node suggests that one “pole” of the BP’s magnetic root is a g-node while the other is most likely a super-granular vertex of opposite magnetic polarity. This picture is supported by the average spatial separation of g-node and BP being ∼18 Mm (panel (C); red distribution), which is smaller than a typical super-granular diameter, while g-nodes are considerably further apart (∼62 Mm; blue distribution). This preferred scale of BP formation supports observations that not all magnetic dipoles have associated BPs (e.g., Figure 4(D) and Golub et al. 1974). Finally, we note that g-node detection in coronal holes is significantly impaired by spatially extended regions of large MRoI as shown by the red masked regions of the figure. Future versions of the MRoI analysis will address this long length scale masking.

3. SUMMARY

Our observations have demonstrated that length scales of the order 30 Mm and 100–250 Mm are readily discernible from the MRoI diagnostics of photospheric line-of-sight magnetograms. This is possible because our MRoI technique infers the connective length scales of the outer atmospheric plasma from the photospheric magnetograms—a departure from the conventional (largely spectral) scale analysis (e.g., Nordlund et al. 2009).

We anticipate that using a technique like MRoI to study numerical simulations of magneto-convection (M. Rempel 2014, in preparation) may help us to understand the correspondence between apparent connective scales demonstrated herein and the apparently scale-free environments inferred from other analyses of high resolution, small field-of-view simulations and observations (e.g., Nordlund et al. 2009; Berrilli et al. 2012; Orozco-Suárez et al. 2012; Yelles Chauouche et al. 2012). This pair of scales is visible throughout the record of SDO/HMI line-of-sight magnetograms and the latter appears to be commensurate with the implied depth of the solar convection zone from calculations and helioseismic measurements (e.g., Simon & Weiss 1968; Gilman 1975; Wilson 1987; Beck et al. 1998). Therefore, we infer that the 100–250 Mm scale apparent in the MRoI maps identifies a pattern that is consistent in magnitude with that expected from giant convective cells. An extension of this work noted that EUV BPs appear to form preferentially around the magnetic vertices of this scale, features that we have dubbed g-nodes. The connection between these magnetic concentrations and EUV (and X-Ray) BPs has possibly been evident for some time. Golub & Vaiana (1978) noted that the longest-lived BPs rotated at rates equivalent to much deeper rooted magnetic objects than surface phenomena. Furthermore, it is possible that an archival survey of observations can be used to infer the presence of BPs and g-nodes that may trace back to the pioneering work of Karen Harvey and others linking ephemeral active regions, BPs, the torsional oscillation, and other phenomena connected to the solar cycle (e.g., Wilson et al. 1988; Harvey 1992).

The methods highlighted above offer the potential for a near-real-time mapping of the Sun’s largest convective scale. This scale, driven by the rotation of the convective plasma ocean (Gilman 1975; Wilson 1987; Miesch 2005), was also recently uncovered using Dopplergrams from SDO/HMI during the same very quiet epoch of solar activity (Hathaway et al. 2013). Understanding, and possibly combining, these new analysis techniques (also including the recently discovered, and potentially related, “coronal cells”; Sheeley & Warren 2012) could yield a significant breakthrough in the understanding of
the solar interior and solar cycle. An investigation combining the SOHO and SDO epoch observations is forthcoming (S. W. McIntosh et al. 2014, in preparation).

4. CONCLUSION

We have seen that the quiescent photospheric magnetic field is composed of multiple connective scales. The observed scales range from a few megameters to those that are 100–250 Mm in scale. We expect that the latter of these scales belongs to a spatially large, deep, and hence slowly overturning convective flow—one that possibly reaches to the bottom of the convection zone. Furthermore, it would appear that photospheric line-of-sight magnetograms (and Dopplergrams) carry information about these nested scales in a non-trivial spatial mixture. It follows that the two cannot be easily disentangled without employing a technique like the MRoI. However, the ready visibility of a giant convective scale and its relatively straightforward identification could have a significant bearing on our ability to probe the variations of the deep solar interior and its long-term evolution.

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