DOES HIGH PLASMA-β DYNAMICS “LOAD” ACTIVE REGIONS?

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Received 2006 October 16; accepted 2007 January 24; published 2007 February 13

ABSTRACT

Using long-duration observations in the He ii 304 Å passband of SOHO EIT, we investigate the spatial and temporal appearance of impulsive intensity fluctuations in the pixel light curves. These passband intensity fluctuations come from plasma emitting in the chromosphere, in the transition region, and in the lowest portions of the corona. We see that they are spatially tied to the supergranular scale and that their rate of occurrence is tied to the unsigned imbalance of the magnetic field in which they are observed. The signature of the fluctuations (in space and time) is consistent with their creation by magnetoconvection-forced reconnection, which is driven by the flow field in the high-β plasma. The signature of the intensity fluctuations around an active region suggests that the bulk of the mass and energy going into the active region complex observed in the hotter coronal plasma is supplied by this process, dynamically forcing the looped structure from beneath.

Subject headings: Sun: chromosphere — Sun: corona — Sun: magnetic fields — Sun: transition region

Online material: mpeg animation

1. INTRODUCTION

Recent results (McIntosh et al. 2006, 2007) have provided detailed observational support for the (widely held) hypothesis that the relentless action of magnetoconvection-driven reconnection (e.g., Priest et al. 2002) supplies the bulk of the energy to the solar atmosphere through ejecta that are intrinsically tied to supergranular spatial scales. In discussing their results, derived from Solar and Heliospheric Observatory (SOHO; Fleck et al. 1995) observations, McIntosh et al. (2007) have proposed that the small-scale eruptive phenomena observed are linked to the ubiquitous appearance of “spicules” at the solar limb in eclipse or coronagraph observations (e.g., Secchi 1877; Roberts 1945). The work presented in this Letter was influenced by a movie presented on the SOHO Web site from the Extreme-ultraviolet Imaging Telescope (EIT; Delaboudinière et al. 1995) and shows the Sun “percolating” with passband intensity brightenings in the chromosphere and transition region that occur on spatial scales (commensurate with those discussed by McIntosh et al. 2007). This Letter (and a subsequent paper, i.e., S. W. McIntosh et al. 2007, in preparation) sets out to test the hypothesis presented by McIntosh et al. (2007) with the EIT data used to build this movie and several others like it while offering an interesting, alternative, but logical look at a possible evolutionary lifetime of a supergranular cell (~24 hr). We assume that the bulk of the EIT 304 Å passband consists primarily of emission from He ii formed in the upper chromosphere or low solar transition region at a temperature of ~50,000 K (Mazzotta et al. 1998). However, aside from the strong emission from the He ii 303.78 Å line, there is a contribution to the bandpass emission in an active region from the Si xi 303.31 Å line and the blended emission of Mn xiv and Fe xv at 304.86 Å (all three contaminant lines are formed in the hotter corona at ~1.5 MK) in the ratio 10 : 1 : 0.06 (Brosius et al. 1998). The contribution of He ii emission relative to the emission lines of Fe x/Fe xi (i.e., the contribution from the EIT 171 Å passband in second spectral order at about ~1 MK) is 25 to 1 in an active region and 10 to 1 in the quiet Sun (Brosius et al. 1998).

The 304 Å sequence is augmented by coronal context images from the EIT 195 Å passband and full-disk line-of-sight magnetograms \( B_{\parallel} \) from the Michelson Doppler Imager (MDI; Scherrer et al. 1995) closest to the start of the sequence, 01:12 and 01:36 UT, respectively. Figure 1 shows the context images and subfield pointing for the 2006 March EIT sequence. In Figures 1a–1d, we show the EIT 195 Å coronal image, the first EIT 304 Å image in the sequence, the MDI \( B_{\parallel} \) image, and a smoothed \( B_{\parallel} \) image \( (B_{\parallel})_{20} \); McIntosh et al. 2006, providing information about the net magnetic flux balance on the super-
granular scale (i.e., the magnetogram is convolved with a circular kernel of diameter 20 Mm). We also show the 1200° × 1200° field of view studied (the black square in Figs. 1a and 1b, and the white square in Figs. 1c and 1d). The thin black contour in Figure 1d shows where \( B_1 \) = 0 G, i.e., where the magnetic “neutral” line occurs.

The EIT data sample\(^4\) presented here shows a selected subfield of the EIT field of view that has been tracked, extracted, and co-aligned (to within a half of a pixel) using the IDL solar data mapping software in the SolarSoft data analysis tree (Freeland & Handy 1998).

3. DATA ANALYSIS

The analysis of the EIT 304 Å data presented here is very straightforward, is easily repeatable, and has two parallel threads to explore the temporal and spatial behavior of the observations. In the first thread, we analyze the intensity light curves at each spatial pixel in the de-rotated, co-aligned, and trend-removed [a 10 time-step boxcar-smoothed profile of the intensity; \( \hat{I}(x, y, t) = I(x, y, t) - \langle I(x, y, t) \rangle_t \)] data cube to count the number of significant brightenings over the observing period. Each brightening counts as one instance of an “event” and is defined as a 10% change in the trend-removed ratio \( \Delta \hat{I} = \langle I(x, y, t - 1) \rangle - \langle I(x, y, t) \rangle \). The second thread investigates the spatial dependence of the brightenings through the pixel-by-pixel intensity distribution, \( 
\hat{I}(x = \delta x, y = \delta y, t) \), where \( \delta x \) and \( \delta y \) are each 2 pixels. Using a slightly extended spatial range ensures a higher signal-to-noise ratio level in the time series (5 times the number of points) and ensures that the moments of the intensity distribution, or a curve fit, can be accurately estimated with a high degree of reliability. The accumulation of data explicitly assumes that the plasma in the adjoining pixels is (in some way) physically coupled to that in the pixel being studied.

In Figure 2 we take an example pixel from the 2006 March sequence to demonstrate the quantities used in the analysis. Figure 2a shows the intensity time-series data for the pixel over 20 hr (triangles) and the 10 pixel boxcar trend (gray solid line). In Figure 2b we show the variation of \( \Delta \hat{I} \) over the time period as well as the 10% increase (dot-dashed) line we use to define the occurrence of an “event”; the total number of events in that pixel is then computed as half the number of times the \( \Delta \hat{I} \) profile crosses the 10% increase line. In Figure 2c we show the distribution of intensities for the pixel range, a Gaussian fit (thick gray line) to the distribution, and the four moments (mean, standard deviation, skewness, and kurtosis) of the distribution. We note that the use of skewness and kurtosis in this analysis is very much dependent on having a large enough number of samples to get an accurate intensity distribution (see, e.g., Abramowitz & Stegun 1972, p. 920, and Press et al. 1992). While they are not commonly used, they serve a purpose in the present analysis. We use a simple definition of skewness: it measures whether outliers in the intensity distribution are below (negative) or above (positive) the distribution mean, skewing it to the left or the right, respectively. Similarly, the kurtosis indicates whether the distribution is more or less sharply peaked than a Gaussian (a kurtosis of zero is perfectly Gaussian); a flat value has a negative kurtosis, and very sharply peaked distributions result in a positive kurtosis.

4. RESULTS

Applying the diagnostics discussed above to the EIT 304 Å time-series sample, we can develop an understanding of the relentless nature of the magnetoconvection-driven energy release in the transition region and lower solar corona through the transient brightenings that it produces. In Figure 3 (Plate 1) we present the diagnostic maps for the EIT sequence. Figures 3a–3f show the mean EIT 304 Å intensity, the normalized width of the intensity distribution (width vs. mean intensity), the intensity distribution skewness, the distribution kurtosis, the number of “events,” and the \( (B_1)_{t=20h} \), respectively. In each panel we overplot the EIT 195 Å isointensity contour at 150 DN (e.g., Fig. 1a), and in Figure 3f we show the magnetic neutral line as a thin black contour.

\(^4\) Reduced using the standard package discussed in the EIT User’s Guide (http://umbra.nascom.nasa.gov/eit/).
(e.g., Fig. 1d). The 500′ × 400′ rectangle around the active region (dashed rectangle) is shown for reference.

Figure 3b shows the normalized width of the intensity fluctuation in each sequence. We see that the net width of the intensity distributions is almost uniformly reduced in the coronal holes on-disk (outside the EIT contours) where the mean intensity is also much smaller. There is a prevalent pattern of “rings” in this panel that appear to be of a size commensurate with the supergranular network, visible in Figure 3a. In addition, there are positions of very large normalized widths (“hot spots”; at positions such as [−250′, −325′], [−300′, 50′]) that are cospatial with another set of rings that are clearly visible in Figure 3c (skewness) and Figure 3d (kurtosis). The skewness and kurtosis rings underlie the positions of EUV bright points in the 195 Å image (S. W. McIntosh 2007, in preparation). Filament channels present their own particular signature in the normalized width maps (see, e.g., [−600′ to −200′, −400′ to 0′]) as nearly continuous lines (“snakes”) of low distribution width in the center of the filament outlined with piecewise continuous regions of large distribution width. Active and plage regions (e.g., [0′ to 200′, −100′ to 100′]) are most easily identified in Figure 3e when the number of brightening events detected increases almost 75% above the mean background value (∼35).

Overall, we see that there is a striking correspondence between the number of events counted (Fig. 3e) and the variation of the \( \langle B_1 \rangle_{-20} \) (Fig. 3d). From the discussion in §§ 4 and 5 of McIntosh et al. (2007), we would expect this to be the case if magnetoconvection-driven reconnection were responsible for their appearance; flux emerging into a region of larger imbalance would increase the probability of immediate reconnection. The same connection to patterning induced by magnetoconvection-driven reconnection can be attributed to the quiet-Sun distribution width rings. They occur almost exclusively at the interior of the supergranular boundaries and bear an uncanny resemblance to the loci of highest reconnection probability in the cartoon representation of the reconnection process (Fig. 12 of McIntosh et al. 2007). In this Letter we focus on the intensity diagnostic patterns observed in the vicinity of an active region and offer a new insight into the mass and energy loading of active regions from their base, leaving other features for a future publication (S. W. McIntosh et al. 2007, in preparation).

In what follows, we assume that the emission in the 304 Å bandpass, outside of the brightest active regions’ pixels, is dominated by He ii; we believe this assumption is justified both by the response of the EIT multilayer coatings (Delaboudinière et al. 1995) and by the spectroscopic measurements of quiet- and active-Sun intensities (Brosius et al. 1998). Similarly, we assume that the constant driving of the emerging magnetic flux by the convective flow in the high plasma-β will not switch off unless the flow itself is suppressed, i.e., in a sunspot spanning at least one or two supergranular cells in diameter. From additional context images supplied on the SOHO Web site or on the Active Region Monitor, there is a complex of very small sunspots underlying the active region, but these spots are not of sufficient size to impede the flow significantly outside the spots themselves.

Figure 4 shows the maps of the intensity distribution diagnostics in and around a relatively simple-looking active region complex (NOAA AR 10860 and AR 10862). The panels of Figure 4 show the mean EIT 304 Å intensity, the 195 Å image, the event location, and the \( \langle B_1 \rangle_{-20} \) maps for the active region.

We see that the spatial distribution of events (Fig. 4c) shows two lobes of intense activity where the number of events increases considerably (∼60 events pixel⁻¹) over that of the quiet Sun (∼45 events pixel⁻¹) and the supergranular cell interiors in particular (∼35 events pixel⁻¹). The event pattern is visibly correlated to the structure and amount of imbalance in the opposing polarity lobes of the active region itself, with a measurable drop overlying the \( \langle B_1 \rangle_{-20} \) neutral line (Fig. 4d) despite the bright emission over the same location in Figures 4a and 4b. The location of the events tells us a great deal about how mass and energy are transported into the active region and plage complexes. This correspondence may also shed light on why neighboring coronal loops (anchored in the same active region) have apparently different mass loads and temperatures (e.g., Klimchuk 2006 and most TRACE observations). Figures 4e and 4f display enhanced distribution kurtosis and kurtosis in regions that bisect the major magnetic neutral line [100′, 0′]. We speculate that this highly impulsive but small (not a large number of events) magnitude intensity change in the bright emission above the sunspots has a significant contribution from the coronal emission contaminating the the EIT 304 Å passband (see the movies accompanying Fig. 3), but we acknowledge that information is really limited and that this must be verified by modeling and more detailed observations in the passband, such as discussed by Judge & Pietarila (2004), Pietarila & Judge (2004) and Thomas & Davila (2001; the EUNIS sounding rocket).

5 DISCUSSION AND CONCLUSION

If we assume that we are indeed observing the impulsive mass loading and thermal heating caused by magnetoconvection-
driven ejecta that are trapped below the coronal loop arcades (an extreme case of the quiet-Sun heating and mass loading presented in McIntosh et al. 2007), then most of the activity takes place in the largest regions of $\langle B_i \rangle_{\sim 2.0}$. We would expect this to be the case when the emerging flux is almost immediately forced to reconnect in those locations because the net reconnection rate must increase as $\langle B_i \rangle_{\sim 2.0}$ increases. Similarly, the magnitude of the reconnection event (the energy input into the system) will be greater at those locations, as there is a larger reservoir of magnetic imbalance to exploit, and the drop in the event production rate around the neutral line to the quiet-Sun value appears to add weight to this argument. The increased variation of the field inclination in the evolving high-$\beta$ magnetic field will also result in an increased “leakage” of $p$-modes in and around the active region (Jefferies et al. 2006), and these $p$-modes contain an energy flux that may well dwarf that of the forced reconnection that initiated their propagation along the field lines.

The net result of the footprint-dominated energy release discussed here is that we will observe coronal loops within the active region (and plage) complex where there is contrast in the thermal and mass load based on the contrast in the magnetic flux available where they are anchored. Furthermore, we believe that the hotter (low-$\beta$) corona may well be sustained by an entirely different physical energy release (e.g., nanoflaring; Parker 1988) where the energy (and mass) is subsequently (and efficiently) redistributed by thermal conduction along the lines of force. In this case we have a “two-stage” heating process for the active Sun (as in the scenarios advocated by Klimchuk 2006 and Aschwanden et al. 2007). There is a dominant hydrodynamic forcing of the plasma that initiates the mass and energy loading from the chromosphere and a secondary process that acts to redistribute the small percentage of the mass and energy along the magnetic fibers that compose the low-$\beta$ portion of the active region. The second stage, intrinsically tied to individual lines of force and their interaction, should help us resolve the apparent spatial thickness of low-$\beta$ coronal loops (López Fuentes et al. 2006; DeForest 2007).

Furthermore, the results presented here may offer some perspective on the anomalously high UV/EUV helium emission observed on the Sun compared to theoretical models (Jordan 1975). We note that the combination of magnetoconvection-forced reconnection ejecta and leaking $p$-modes in a class of chromospheric spicule provide evidence in support of Judge & Pietarila (2004) that spicule-forced neutral helium diffusion across the chromospheric magnetic topology is the significant contributor to quiet-Sun helium emission. In addition, Judge & Pietarila (2004) argue that the influence of the “photoionization-recombination” mechanism (Zirin 1975) of overlying coronal radiation is negligible for the He ii 304 Å emission that is formed in the hybrid physical region at the boundary of the chromosphere and transition region. Mauas et al. (2005) come to the same conclusion for active region UV/EUV helium emission. The other proposed helium emission enhancement mechanism, “velocity redistribution” (from nonthermal plasma motions in the line formation region; e.g., Andretta et al. 2000), is the result of “transient ionization” (Pietarila & Judge 2004). Is it possible that this rapid transient ionization is the result of impulsive heating of the plasma as would happen locally in the forced reconnection ejecta we study in this Letter? This question will be addressed at greater length in S. W. McIntosh et al. (2007, in preparation).

To conclude, we have offered an interesting insight into the dynamic loading of (active region) coronal loop arcades from the high-$\beta$ region in which they are tethered. In fact, we observe that the relentless loading is driven by the same mechanism responsible for the quiet Sun and coronal holes, and while these have a clear topological difference on the global scale (“open” vs. “closed” flux), an active region highlights the degree of energy input into the system from its footprint; we have seen that it scales as the degree of imbalance in the local magnetic field grows. Unfortunately, we cannot use the data presented in this Letter [which discusses the exact microphysics of how the dynamically forced loop footpoints in the active region transport their mass and energy into the structures observed in the hotter (low-$\beta$) coronal plasma] to answer, unambiguously, the question posed in the title of this Letter, but the detailed observations to be made by Hinode and EUNIS (e.g., Brosius et al. 2007) will go a long way toward resolving this picture.

The material presented in this Letter is based on work carried out at the Southwest Research Institute and supported by grants from NASA (SOHO: NNG05GQ70G; SEC-G: NNG05GM75G; SR&T: NNG06GC89G) and the NSF (ATM-0541567) issued to the author.

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Fig. 3.—Distribution maps for the March 2006 sequence. From left to right and top and bottom, we show the mean intensity, normalized intensity distribution width, skewness, kurtosis, event location, and \(\langle B_{\perp}\rangle_{x,y,z}\) maps. In each panel, we show the EIT 195 Å 150 DN intensity level; in panels e and f, we show the magnetic neutral line \(\langle B_{\perp}\rangle_{x,y,z}=0\) G. The dashed rectangle isolates the active region shown in Fig. 4. The online edition of this Letter provides a movie of the entire 304 Å time series analyzed. The $500^\circ \times 400^\circ$ region around the active region (dashed rectangle) studied in this Letter is shown for reference.