ON THE MASS AND ENERGY LOADING OF EXTREME-UV BRIGHT POINTS

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ABSTRACT

We discuss the appearance of extreme-ultraviolet (EUV) bright points (BPs) in the analysis of long-duration observations in the He II 304 Å passband of the Solar and Heliospheric Observatory Extreme-ultraviolet Imaging Telescope (SOHO EIT). The signature of the observed 304 Å passband intensity fluctuations around the BPs suggests that the primary source of the mass and energy supplied to the magnetic structure is facilitated by relentless magnetoconvection-driven reconnection, forced by the magnetic evolution of the surrounding supergranules. Furthermore, we observe that if the magnetic conditions in the supergranules surrounding the footpoints of the cool 304 Å BPs are sufficient (large net imbalance with a magnetic field that closes beyond the boundaries of the cell in which it originates), the magnetic topology comprising the BP will begin to reconnect with the overlying corona, increasing its visibility to hotter EUV passbands and possibly soft X-rays.

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

Online material: color figures, mpeg animation

1. INTRODUCTION

Recent results (McIntosh et al. 2006, 2007; Jefferies et al. 2006) 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 chromosphere and transition region through thin ejecta that are intrinsically tied to supergranular spatial scales. These observational results were derived from the multimodal analysis of observations from the Solar and Heliospheric Observatory (SOHO; Fleck et al. 1995) and time series analysis of data from the Magneto Optical Filter at Two Heights (MOTH; Finsterle et al. 2004a), and suggest 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). These parallel analyses indicate that the spicular activity is originated by forced magnetic reconnection, which gives rise to the evaporative mass loading and initial energy deposition in the newly created topology. The creation of this new magnetic topology locally modifies the acoustic cutoff frequency (McIntosh & Jefferies 2006) and permits p-mode leakage, propagation, energy dissipation (Jefferies et al. 2006), and mass transport along the inclined field structure (see, e.g., De Pontieu et al. 2004, 2007a, 2007b; Hansteen et al. 2006). In short, the data are consistent with an energy and mass release process that combines driven magnetic reconnection and magnetoacoustic wave leakage and dissipation in one elementary structural unit (at a spatial resolution of ∼5”). It is possible that this unit is a jetlike spicule, and these spicules appear to be systematically distributed over the solar disk in and around the granular and supergranular network. Throughout we will use the term spicule to describe these impulsive jetlike phenomena observed with the provision that we do not have the coverage of other observations (simultaneous observations in Hα or Ca ii) to unambiguously link these jets with classical spicules, fibrils, or mottles. The coupling of the extreme-ultraviolet (EUV) and optical phenomena is clearly complicated and is a topic beyond the scope of this paper, but one that will be explored in a forthcoming paper (S. W. McIntosh et al. 2008, in preparation).

The analysis presented here (like that of McIntosh 2007, hereafter Paper I) was motivated by a movie presented on the SOHO internet site1 from the Extreme-ultraviolet Imaging Telescope (EIT; Delaboudinière et al. 1995). This movie shows the Sun “percolating” with intensity brightenings in the 304 Å (He ii) passband that is formed at the interface between the chromosphere and transition region (Judge & Pietarila 2004; Pietarila & Judge 2004; Paper I). These brightenings occur on spatial and temporal scales that are commensurate with the phenomena discussed in the preceding paragraph, strongly suggesting that they are the result of the same physical mechanism. To that end, an analysis of these 304 Å intensity brightenings provides a means of testing the magnetoconvective energy and mass loading hypothesis that is presented in McIntosh et al. (2007). This paper follows directly from the analysis of Paper I and provides evidence supporting the dominance of high-β forced mass and energy loading in the creation and evolution of X-ray, EUV bright points (BPs; see, e.g., Golub et al. 1974; Habbal & Withbroe 1981; Harvey 1997) and He i 10830 Å “dark points” (e.g., Harvey 1994a; MacQueen et al. 2000).

In the following section, we will briefly discuss the time series observations and basic analysis of the 304 Å (He ii) passband light curves that form the basis of our study. In § 3 we will investigate the spatial and statistical dependence of the He ii 304 Å intensity light curves in and around a set of sample BPs and a set of BPs identified by automated algorithm (McIntosh & Gurman 2005) designed for that purpose. In § 4 we discuss the results of the analysis, placing them in context with previous investigations relating BPs and spicules (e.g., Moore et al. 1977; Rovira et al. 1999; Madjarska & Doyle 2002), and their connection to the coronal (e.g., Longcope et al. 2001; Brown et al. 2001, 2002) and photospheric magnetic field (McIntosh et al. 2006).

We will see that the mass and energy “loading” of the cool BPs (those visible only in the 304 Å time series) comes from the interaction of the relentlessly emerging and advecting magnetic flux

1 The movie can be viewed at http://sohowww.nascom.nasa.gov/pickoftheweek/old/24mar2006/.
in the vicinity of magnetic dipoles that form its structural core and can therefore explain the appearance of dynamic impulsive heating (e.g., Habbal & Withbroe 1981; Porter et al. 1987; Habbal & Harvey 1988; Habbal & Grace 1991; Rovira et al. 1999; MacQueen et al. 2000; Ugarte-Urra et al. 2004b) and simultaneous observation of running low-frequency (\(\leq 5\) mHz) waves (e.g., Ugarte-Urra 2004; Ugarte-Urra et al. 2004a) in the BP structure. Furthermore, the results of our analysis are consistent with a two-stage BP loading mechanism that can go some way to providing the "necessary and sufficient" conditions (Harvey 1994b) for the production of a hot BP (those observed in hotter EUV passbands and soft X-rays). We infer that forced magnetoconvection-driven reconnection occurs in all cool BPs, but that increased energy supply from the magnetic environment surrounding the BP causes an eventual interaction of the BP magnetic flux with overlying coronal magnetic flux, producing hot BPs.

2. OBSERVATIONS AND ANALYSIS

The results presented in this paper are based on the analysis of a long-duration sequence of EIT 304 Å passband imaging, starting 2006 March 18 20:36 UT and ending 2006 March 21 23:48 UT. The subset of the EIT sequence analyzed here has a fixed cadence of 12 minutes, no missing data blocks (2006 March 19 00:11–23:59 UT) and covers the approximate evolutionary lifetime of a supergranular cell (\(~ 20\) hr; Harvey 1994a). The selected subfield of the EIT data sample used in this analysis (reduced using the standard package discussed in the EIT User’s Guide\(^2\) has been tracked, extracted, and co-aligned using the Interactive Data Language solar data mapping software in the SolarSoft data analysis tree (Freeland & Handy 1998). We estimate (using a cross-correlation

\(^2\) See http://umbra.nascom.nasa.gov/eit/eit_guide/.
algorithm used to obtain subpixel time series co-alignment with TRACE data; e.g., McIntosh et al. 2004) that the data are tracked and co-aligned to within half of a pixel over the period needed, using the middle image (taken at 13:19 UT) as the reference.

The 304 Å sequence is augmented by coronal context images from the EIT 195 Å passband and full-disk line-of-sight magnetograms \((B_{||})\) from the Michelson Doppler Imager (Scherrer et al. 1995) taken closest to the start of the sequence, 01:12 and 01:36 UT, respectively. In later sections we will also use the EIT 195, 171, and 284 Å synoptic images taken at 6 hr intervals over the course of the day (01:00, 07:00, 13:00, and 19:00 UT) to identify visible coronal BPs (McIntosh & Gurman 2005).

Figure 1 of Paper I shows the full-disk context images and subfield pointing for the sequence that we examine here. That figure shows \((a)\) the EIT 195 Å coronal image, \((b)\) the first EIT 304 Å image in the sequence, \((c)\) the MDI \(B_{||}\) image, and \((d)\) a smoothed \(B_{||}\) image \(((B_{||})_{r=20}\); McIntosh et al. 2006), providing information about the net magnetic flux balance on the supergranular scale (i.e., the magnetogram is convolved with circular kernel of diameter 20 Mm). The same figure also shows the \(1200'' \times 1200''\) field of view that is used in the primary study of this paper (black square in panels \(a\) and \(b\), white in panels \(c\) and \(d\)) and shown here in Figure 1.

In the following interpretation of this sequence we assume that the 304 Å passband consists primarily of emission from He \(\text{II}\) formed at a temperature of roughly 50,000 K (Mazzotta et al. 1998). Aside from the strong emission from the He \(\text{II}\) 303.78 Å line, there is a contribution to the bandpass emission in an active region from the Si \(\text{XI}\) 303.31 Å line and the blended emission of Mn \(\text{XIV}\) and Fe \(\text{XV}\) at 304.86 Å (all three contaminant lines are formed in the hotter corona at \(\sim1.5\) MK or above) in the ratio 10:1:0.06 (Brosius et al. 1998). The measured contribution of He \(\text{II}\) emission relative to the emission lines of Fe \(\text{X}/\text{Fe XI}\) (i.e., the contribution from the EIT 171 Å passband in second spectral order at about

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**Fig. 2.**—Distribution diagnostic maps for the 2006 March sequence. We show \((a)\) the normalized intensity distribution width, \((b)\) intensity event count, \((c)\) distribution skewness, and \((d)\) kurtosis maps. Panel details same as in Fig. 1. The black contour in \((b)\) shows the location of the large-scale magnetic neutral line \((B_{||})_{r=20} = 0\ G\), derived from Fig. 1c.
smoothed profile of the intensity) removed [(\(\hat{I}\) in the de-rotated, co-aligned, and trend- (a 10 time-step boxcar-forward, is easily repeatable, and has two parallel threads to expression (and He).

Pietarila (2004) and Pietarila & Judge (2004) have demonstrated that the formation process for the He is characteristic of the upper chromosphere and the low solar transition region. This thermodynamic placement of He makes it a useful proxy of plasma dynamics in and around the “magnetic transition” region where the gas pressure and magnetic pressure of the plasma are in approximate balance: a nexus between the low- and high-\(\beta\) plasma regimes.

2.1. Data Analysis

The analysis of the EIT 304 Å data presented 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 that is measured in units of the (12 minute) intensity “event” count, [(\(c\) skewness, (\(d\) kurtosis, (\(g\) normalized distribution width, and (\(h\) event number map. Each panel shows the four intensity distribution boundaries determined from (\(b\) and the ±25 G magnetic flux contours from the full-resolution SOHO MDI magnetogram (also used to construct the MRoI and (\(B\))\_{r=20} maps).

\(~1\) MK) is 25 to 1 in an active region and 10 to 1 in the quiet Sun (Brosius et al. 1998). Furthermore, the analyses of Judge & Pietarila (2004) and Pietarila & Judge (2004) have demonstrated that the formation process for the He plasma observed in emission (and He 10830 Å in absorption) exhibits dynamic behavior that is characteristic of the upper chromosphere and the low solar transition region. This thermodynamic placement of He makes it a useful proxy of plasma dynamics in and around the “magnetic transition” region where the gas pressure and magnetic pressure of the plasma are in approximate balance: a nexus between the low- and high-\(\beta\) plasma regimes.

3. RESULTS

Figure 1 shows (\(a\) the mean EIT 304 Å intensity over the observing sequence; (\(b\) the EIT 195 Å coronal image; (\(c\) the smoothed \(B\) image (\(\langle B\rangle\)\_{r=20}, providing information about the net magnetic flux balance on the supergranular scale); and (\(d\) the “magnetic range of influence” (MRoI; indicating the distance from a given pixel needed to balance the flux contained there), introduced and discussed at length in McIntosh et al. (2006). Figure 2 shows the intensity distribution diagnostics in the same 1200” × 1200” region: (\(a\) the mean normalized distribution width, (\(b\) intensity “event” count, (\(c\) skewness, and (\(d\) kurtosis maps. With close inspection of Figure 2c and Figure 2d the reader will see a prevalent pattern of circular features, or “rings,” that are visible (at the same location) in the distribution skewness and kurtosis maps. These features are visible in the dashed square regions that are provided as Figures 3 and 4, and are discussed below. Much of the detail present in this figure is not discussed here, but is left for discussion in a future paper (S. W. McIntosh et al. 2008, in preparation).

Figures 3e and 3f demonstrate the presence of a very distinct ring signature in the skewness and kurtosis diagnostic maps. In concert with the kurtosis and skewness rings present in Figures 3e
and 3f we see that a significant enhancement in the normalized distribution widths (Fig. 3g) that sit on the line geometrically bisecting the two magnetic flux concentrations that mark the footpoints of the BP (shown as black [negative] and white [positive] contours from the full-resolution SOHO MDI magnetogram at a level of 25 G, respectively). We can see that the BP structure (in 195 and 304 Å; Figs. 3a and 3b) is outlined by these rings. The prevalent connection of the skewness and kurtosis ring signature (cf. Fig. 2) may provide some insight into how BPs are loaded with mass and heated. Recall, from Paper I, that we have interpreted increases in distribution skewness and kurtosis as being with mass and heated. However, these brightenings may not always be of large enough magnitude in and around these bright structures to constitute the detection of an event (Fig. 3h shows a very weak enhancement in the number of events surrounding the magnetic dipole in the ring location).

We know that some portion of the emerging magnetic flux in the interior of the supergranular cells, whose vertices comprise the BP’s magnetic footpoints, is advected toward the boundary connecting them. It is likely that the advecting flux elements are forced to reconnect with the magnetic topology in whatever way they can, impulsively changing the intensity surrounding the BP and creating the skewness and kurtosis rings while they load mass and thermal energy into that topology (cf. the quiet-Sun heating and mass loading proposed by Jeffries et al. 2006; McIntosh et al. 2007; De Pontieu et al. 2007b). In addition, the global flow field will continue to push and pull the BP footpoints at random, giving an additional magnetic energy impulse to the complex system as the supergranular cells are relentlessly being created and destroyed. The BP will continue to consume the emerging/advected flux that is heading in its direction, heating and loading until it stops emitting and dies. In much the same way that the BP is born, its death is most likely to occur when the footpoint magnetic flux eventually cancels (see §3.1). Because the BP footpoints are located at vertices of the same, or neighboring, supergranular cells they are separated by, at most, a supergranular diameter (∼20 Mm). Therefore, the lifetime of the BP will depend on the evolutionary lifetime of the separating cells. If they collapse, the BP footpoints will coalesce and eventually cancel each other’s magnetic flux. Conversely, if the intermediate supergranules do not collapse, then the BP will continue to exist and be loaded by the advecting flux surrounding it. A detailed understanding of BP lifetimes can be undertaken with a much larger data set (McIntosh & Gurman 2005), but is beyond the scope of this paper and left for future work (S. W. McIntosh & A. R. Davy 2008, in preparation).

From Figure 4 we make an important distinction about the physical connection between BPs and skewness/kurtosis rings. While each skewness/kurtosis ring has a bright 304 Å emission and a magnetic foundation (at least a dipolar structure) at its core, not every skewness/kurtosis ring has a “hot” EUV BP associated with it (i.e., bright emission in a “true” coronal passband, e.g., EIT 171, 195, 284 Å, or soft X-rays). This fact has already been noted in the BP literature (e.g., Porter et al. 1987; Harvey et al. 1993; Harvey 1994a, 1994b), where it was clearly demonstrated that not all “ephemeral active regions” have hot BPs associated with them. Comparing the panels of Figure 4, we see that the brightest emitting regions in Figure 4a (that overlie magnetic dipoles) have associated bright 304 Å emission in Figure 4b. Furthermore, these locations also have large MRoIs and (at least) a moderate $\langle B_{||} \rangle_{r=20}$. Of the seven locations with skewness and kurtosis rings [centered on (−330, −250), (−340, −310), (−310, −310), (−250, −320), (−250, −220), (−220, −360), and (−250, −240)] five have bright coronal emission associated with them [(−330, −250), (−340, −310), (−310, −310), (−250, −220), and (−250, −240)].

There are two regions where no coronal BPs exist even though the dipoles are in place and there is (reasonably) bright emission in the 304 Å passband [(−220, −360) and (−250, −320)]; these regions are examples of small BP “cavities.” The rings in these regions occur where the MRoI is small in one or both footpoints and the $\langle B_{||} \rangle_{r=20}$ is low in the vicinity of the BP. We believe that the presence of cavities tells us a great deal about the mass and energy loading of the individual dipoles, and that it must be related to the magnetic conditions in and around the dipole (see above and Harvey 1994a)—not all of these rings/dipoles receive the same mass and energy flux, and so we observe the fact that not all (EIT detected) BPs occur in all coronal passbands, or different
temperature images see different numbers of BPs (McIntosh & Gurman 2005). In § 3.2 we will compare the locations of skewness/kurtosis rings in Figure 2 with the BP locations automatically detected in the three other EIT passbands to study the properties needed to create a BP cavity.

3.1. The Evolution of One 304 Å Bright Point

We have seen in the preceding figures and paragraphs that the EUV BP has a very particular statistical signature (as far as our analysis is concerned). Figure 5 provides evolutionary snapshots, from birth to death, of one single 304 Å BP extracted from 3 day EIT sequence at 6 minute cadence, starting at 23:58 UT on 2006 August 16 and ending at 23:43 UT on 2006 August 18 (this sequence will be studied in some detail by S. W. McIntosh et al. [2008, in preparation]). This EIT sequence is very useful for looking at the detailed evolution of the BP and also has the benefit of 1 minute cadence full-disk MDI magnetogram observations, for the large part August 17. With these data we can monitor the evolution of the BP over its lifetime with respect to the magnetic field creating and feeding it. In Figures 5a–5f we show the instantaneous EIT 304 Å intensity and the nearest MDI magnetogram to that time (the MDI data shown are the result of a 6 minute average of the full-disk 1 minute magnetograms); the thick black and white contours represent magnetogram levels of −25 and 25 G, while the thin contours are ±10 G, respectively. For comparison with the frames presented in Figures 5a–5f we show the evolution of the mean brightness light curve and the total magnetic flux of the available MDI magnetograms over the whole 60″ × 50″ region surrounding the BP in Figure 5g, shown as a solid line and joined dots, respectively. The online version of this paper has a movie illustrating the lifetime of the BP shown.

In Figure 5a there are four main flux elements in the region around the BP that is beginning to form. As the large negative flux concentration at the top of the panel migrates southward
and the large positive concentration on the left migrates eastward the net magnetic flux in the region approaches zero (~04:00 UT). The emission around the BP has already begun to increase significantly as we move into Figure 5b and the migrating negative flux is canceling rapidly, evolving to a tripolar magnetic configuration, and the BP is detected in EIT 195 Å image (~1.5 MK plasma) at 07:13 UT, reaching peak 304 Å brightness about then and staying there through Figure 5c. Eventually, some 6 hr later, in Figure 5d, the tripolar configuration has whittled down again to a north-south dipole configuration with the coalescing of the evolving positive flux elements and some significant removal of negative flux through cancellation. By 20:00 UT (Fig. 5e) most of the negative flux has been canceled and the region is taking on a distinctly unipolar look; by 23:00 UT you would not know that a BP had ever existed in the region.

Over the course of 24 hr we have monitored the interaction of the magnetic flux in the region and the supergranular flow in which it is anchored, as it creates and destroys an EUV BP. This is a very typical evolutionary path for a BP, where lifetimes of ~20 hr are commonplace (e.g., Harvey 1994a), tying their life span directly to the magnetic aggregation process driven by the converging supergranular flow patterns (e.g., Crouch et al. 2007).

In Figure 6 we take a closer look at the BP and the fluctuations of the (trend removed) 304 Å intensity at four points in the region (one in a footpoint [green]; one near the apex of the structure [red]; and two points in the surrounding plasma [blue and yellow]—see inset image of the BP). The purpose of this figure is to demonstrate the range of variation in the 304 Å emission in and around the BP, and to give us a feel for the influence these variations have on the distribution diagnostics that are the focus of this paper, and are shown for this BP, in Figure 7. In the BP apex time series (red) we can see the time when the BP is reaching “maturity” (around 05:00 UT) where the intensity fluctuations significantly increase in amplitude, but are not much higher than the mean intensity there (~4000 DN) producing a broad distribution that has a kurtosis near zero and small positive skewness. In the quiet Sun surrounding the BP (blue and yellow) we see little evidence of the massive He ii brightenings that are visible in the BP apex (or footpoint) time series. However, there are a number of places in these time series where the change in intensity is just above the mean quiet-Sun intensity (~300 DN) and is probably significant enough in number to increase the skewness and kurtosis of the intensity distribution there. These intensity changes are, most likely, caused by the migration of the various flux elements that comprise the BPs structural core over its many phases of existence. The BP footpoint time series (green) is a hybrid of the evolution observed in the quiet-Sun and BP apex cases, slightly higher enhancements in skewness and kurtosis (over the BP apex), and a relatively broad intensity distribution. Therefore, we see that the evolution of the magnetic flux (anchored in the high-β plasma flow), which comprises the structure of the BP results, is consistent with the production of enhanced skewness and kurtosis in the intensity distributions that surround the bright point.

3.2. Comparing Rings Locations with Automated EUV BP Detection

We have seen above that not all BPs that are visible in 304 Å have a counterpart in the considerably hotter 171, 195, or 284 Å EIT passbands, i.e., there are BP cavities. This is a correspondence first noted by (Harvey 1994b), who stated in her conclusion that “the emergence or cancellation of magnetic fields in the photosphere is not in itself a necessary and sufficient condition for the occurrence of an XBP,” a X-ray, or very hot BP. Fortunately, we
have a tool to automatically detect BPs in the hotter EIT passbands (McIntosh & Gurman 2005) that can be readily applied to all of the other EIT images taken on 2006 March 18. The detected BP locations can then be compared with the distribution and magnetic field diagnostic maps to see if a specific pattern appears; this pattern may shed some light on the necessary condition to produce a hot BP.

On 2006 March 18 there were four images each in the 171, 195, and 284 Å EIT passbands taken around 01:00, 07:00, 13:00, and 19:00 UT—the typical EIT “SYNOP” cadence. Since we have no information in the distribution diagnostics about when the skewness and kurtosis rings developed we must look at all of the BPs detected on that day to make our comparison. The left column of Figure 8 (top to bottom) shows the detected 171, 195, and 284 Å passband images taken around 13:00 UT, while the right column of panels show the corresponding BP detections for the whole day. Again, particularly in 171 and 195 Å, we see the cavities where very few BPs exist. The 284 Å passband has a contribution from transition region (S v) network emission and may lead to a previously unnoticed large number of additional detections in that passband from a modification to the detection algorithm. All of the EIT images and BP locations are rotated to the midpoint of the 304 Å time series 13:19 UT. We do not show the BP locations in the active region, just northwest of disk center (circled in the panels). Similarly, we acknowledge that the sparse 6 hr SYNOP observations may mean that we miss some hot BPs that occur, appearing and disappearing between images. This is not likely to be many, as the mean BP lifetimes are ~20 hr, but the amount missed can be estimated by comparing BP appearance rates and lifetimes at particular latitudes and longitudes, at different cadence of EIT images, using studies such as that of McIntosh & Gurman (2005).

There are regions in the panels that show locations where there are very few, or no hot BPs, over the 24 hr period searched. These locations, such as the lower left corner running diagonally upward toward disk center, are exactly what we mean by a BP cavity: BPs in 304 Å, but not in 171, 195, or 284 Å. All of the visible cavity regions appear to have another thing in common: they have very weak quiet-Sun coronal emission. The apparently weak emission has a bearing on the reduced number of BPs detected if the analysis of McIntosh et al. (2006) is correct, as it reflects the energy (and mass) input for quiet solar corona and its dependence on the background magnetic footprint ($B_\parallel$).

Figure 9 allows us to compare the event map (Fig. 9a) and normalized distribution width map (Fig. 9c) with the detected BP locations (Figs. 9b and 9d, respectively). The colors of the BPs shown in the right-hand panels illustrate the EIT passband in which they were detected: blue from 171 Å, green from 195 Å, and yellow from 284 Å. We notice immediately that the detected BP locations occur over regions where there are a large number of events (Fig. 9b), and the cavities occur in locations where there are small numbers of events. This is also consistent with the analysis of Paper I, where it was noted that the brightest emission in the 304 Å passband occurs in regions where the number of detected events are largest and the $B_\parallel$ is large (cf. with Figs. 1a and 1c). We also see, from Figure 9d, that the BPs are offset from the distribution width (quiet-Sun supergranular interior) rings, which is not surprising when the magnetic footpoints of BPs are at the vertices of the supergranulation pattern. The places where the normalized distribution width are largest, as we have seen in Figure 3g, are additional markers of hot BPs.

Figure 10 compares the distribution skewness (Fig. 10a) and kurtosis (Fig. 10c) maps with the detected BP positions. We can clearly see that a (very) large number of the hot BPs do occur over skewness and kurtosis rings, while there are locations where skewness and kurtosis rings exist, but hot BPs do not. This could either be caused by the lack of interaction (and reconnection) between the magnetic topology of the BP and the overlying coronal magnetic field (discussed by Harvey 1994b), or indicate that...
Fig. 8.—Comparing the EIT SYNOP images (taken around 13:00 UT 2006 March 19) with the detected EUV (hot) BPs (dots) over the whole 24 hr period studied. From top to bottom we show the 171 Å with emission peaking at a temperature of about 1 MK, 195 Å (1.5 MK), and 284 Å (2.0 MK). Each panel shows the coronal hole boundaries (white solid contour determined from the 195 Å image) and the dot-dashed circle surrounding the active region—we do not show the BPs detected in the circled region. [See the electronic edition of the Journal for a color version of this figure.]
the 6 hr sampling of the EIT images causes us to miss some BPs that occur in the time frame studied. The data analyzed lead us to believe that it is the former of these two possibilities: not all rings have hot BPs, while all hot BPs have skewness and kurtosis rings associated with them. Why? We have seen above that BP cavities occur in locations of reduced (weaker than average quiet Sun) coronal emission, but we must also consider the magnetic conditions at the root of the cavity and whether or not it will have the magnetic energy available to allow a hot BP to appear.

Figure 11 illustrates the correspondence between the detected BP locations and the underlying magnetic field conditions: the $|B_{ijr}|_{r=20}$ and MRoI. We are instantly drawn to the fact that the large majority of BPs occur in places where both the absolute value of the $|B_{ijr}|_{r=20}$ and MRoI are large, greater than $\sim 3$ G and $\sim 100$ Mm. Furthermore, these comparative images indicate that very few hot BPs overlie magnetic neutral lines (regions of low $|B_{ijr}|_{r=20}$ and MRoI). These are likely locations for BP cavities, regions where the magnetic field closes locally and has very little net imbalance. As we have suggested above (according to the results of McIntosh et al. 2006, 2007; Paper I), the corona above these regions is not very extended (low MRoI as a result of local magnetic closure) and does not receive as much mass or energy supply as the regions where the MRoI and $|B_{ijr}|_{r=20}$ are large. The correspondence of BP cavities with regions of low MRoI and low imbalance lends further credibility to the deduction of Harvey (1994b); these regions of cool, weak corona cannot supply the additional mass and energy that is needed to generate and support the existence of hot BPs.

4. DISCUSSION

In the preceding sections we have observed that a simple analysis of EIT 304 Å passband image time series gives rise to several prevalent patterns in the derived diagnostics. This paper has concerned itself with the pattern that is closely associated with the appearance of EUV BPs: rings of enhanced distribution skewness and kurtosis. These rings span the vertices of one (or more) supergranules and occur as a consequence of abrupt emission changes in the region immediately around the BP. We have also

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**Fig. 9.**—Comparing the event number map (top) and normalized distribution width (bottom) with the detected hot BP locations. The color of the dots indicates the EIT passband in which they were observed: blue (171 Å), green (195 Å), and yellow (284 Å).
noticed that the supergranular convective flow evolution governs the brightness fluctuations as the network vertices in these convective cells coalesce (or pull apart) as part of the natural flow evolution, or similarly as magnetic flux is being relentlessly driven to the boundary of the cells. In this case the appearance of BPs in the 304 Å passband is consistent with convection-forced magnetic reconnection at the interface between the chromosphere and transition region (the likely formation region of the \( \text{He}\ ii \); e.g., Judge & Pietarila 2004; Pietarila & Judge 2004; Paper I).

We have noted that BPs have been linked with dynamic, magnetically forced phenomena (Moore et al. 1977; Habbal & Withbroe 1981; Habbal & Harvey 1988; Porter et al. 1987; Habbal & Grace 1991; Rovira et al. 1999; MacQueen et al. 2000; Madjarska & Doyle 2002; Brosius et al. 2007) like those invoked by McIntosh et al. (2007) to explain energy delivery to the quiet-Sun and coronal hole plasmas as a result of relentless magnetoconvection-forced reconnection objects that look like (UV/EUV) spicules. Incidentally, the same forced reconnection should result in the leakage of \( p \)-modes into the closed magnetic system (e.g., De Pontieu et al. 2004, 2005, 2007a; McIntosh & Jeffries 2006; Hansteen et al. 2006; Jeffries et al. 2006) and explain the observation of propagating 3 and 5 minute waves in BPs (e.g., Ugarte-Urra et al. 2004a).

We have discriminated between these cool (visible in the 304 Å passband) and hot EIT BPs (visible in the 171, 195, or 284 Å passbands; detected using the method of McIntosh & Gurman [2005]). We have noted that not all cool BPs have an associated hot BP, as was also noted by Harvey (1994a) and others. That is, while all cool BPs have skewness and kurtosis rings associated with them, not all rings have hot BPs overlying them. In addition, we have noted the presence of regions in the hot corona where very few hot BPs occur and have dubbed them “BP cavities.” These BP cavities are cospatial with locations in the corona where the quiet-Sun emission is reduced, but to the level found in a coronal hole. This last point indicates that the global magnetic field topology in the BP cavity is closed (low \( \langle B_{\|} \rangle \) and low MRoI) and that the energy supply to the coronal plasma surrounding the 304 BP is generally reduced (e.g., McIntosh et al. 2007). It is not unreasonable, therefore, to expect that this reduction in global energy input is an important factor in

Figure 10.—Comparing the distribution skewness (top) and kurtosis (bottom) with the detected hot BP locations. Dot colors same as in Fig. 9.
explaining why some cool BPs do not become hot BPs. To this end, we propose that (both cool and hot) BPs are subject to a two-stage heating process: one forced by the constantly evolving magnetic flux elements rooted in the high-β convective flow, as we have discussed above, and a second stage, which only appears to be significant when the BP is immersed in an energetic magnetic environment \((\langle B_j \rangle_{r=20}, \text{moderate to high MRoI})\) in the latter case, following the presented analysis and that of Paper I, stage one will be very vigorous, continuously dumping mass and energy into the BP. As the stage one loading progresses, the BP will expand vertically and begin to interact with the energetic corona that surrounds it (stage two), amplifying its brightness in a manner described by Longcope et al. (2001) and Brown et al. (2001, 2002).

Unfortunately, it remains to be seen if the enhanced distribution widths at the BP apex (e.g., Fig. 3g) are the direct signature of the stage two connection between the overlying corona and the expanding BP; this is an issue that we also intend to follow up in future work. Similarly, we have seen that the evolution of BPs is a very complex magnetic interaction with a basis that hinges on the supergranular evolution and magnetic flux aggregation on that spatial scale (e.g., Crouch et al. 2007). We can say then that the dynamic evolution of the individual supergranular cells is itself the controlling factor in establishing BP lifetimes.

Finally, in § 3.1 we demonstrated the complex evolution of a typical BP from birth to its eventual death as a monopolar object. Using this BP as an example we can speculate on what might happen to a similar BP that it is now anchored in a coronal hole (a open magnetic region with high MRoI and nonnegligible magnetic imbalance, nonzero \(\langle B_j \rangle_{r=20}\)). We allude to the possible conversion of coronal hole BPs into polar plumes (e.g., DeForest et al. 1997; DeForest & Gurman 1998; Wang 1998). We propose that this is the natural consequence of the BP’s evolution from a dense, bright dipolar to a bright, effectively monopolar, strawlike coronal structure (typical magnetic network elements in coronal holes are not bright in the EUV, while plumes are; e.g., McIntosh

![Fig. 11.—Compare the supergranular averaged magnetic field strength \((\langle B_j \rangle_{r=20}; \text{top})\) and MRoI (bottom) with the detected hot BP locations. Dot colors same as in Fig. 9.](image)
et al. 2007). The evolution from BP to plume occurs because one BP footpoint is constantly being eroded by the imposed net imbalance of the coronal hole itself, launching compressive waves and dense plasma into the fast solar wind. It is precisely the evolution of the single BP and its impact on the energetics of the solar wind and corona that are of interest for Hinode (Ichimoto et al. 2005) and subsequent flights of the EUNIS sounding rocket (Thomas & Davila 2001; Brosius et al. 2007). In particular, the instrument suite of Hinode will be able to monitor the evolution of the photospheric magnetic field simultaneously with the reconnection of separator reconnection (e.g., Longcope et al. 2001; Brosius et al. 2007). Further increasing the plasma temperature at which it becomes visible.

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