Statistical Distribution of Size and Lifetime of Bright Points Observed with the New Solar Telescope

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ABSTRACT

We present results of two-hour non-interrupted observations of solar granulation obtained under excellent seeing conditions with the largest aperture ground-based solar telescope - the New Solar Telescope (NST) - of Big Bear Solar Observatory. Observations were performed with adaptive optics correction using a broad-band TiO filter in the 705.7 nm spectral line with a time cadence of 10 s and a pixel size of 0.0375". Photospheric bright points (BPs) were detected and tracked. We find that the BPs detected in NST images are co-spatial with those visible in Hinode/SOT G-band images. In cases where Hinode/SOT detects one large BP, NST detects several separated BPs. Extended filigree features are clearly fragmented into separate BPs in NST images. The distribution function of BP sizes extends to the diffraction limit of NST (77 km) without saturation and corresponds to a log-normal distribution. The lifetime distribution function follows a log-normal approximation for all BPs with lifetime exceeding 100 s. A majority of BPs are transient events reflecting the strong dynamics of the quiet sun: 98.6% of BPs live less than 120 s. The longest registered lifetime was 44 minutes. The size and maximum intensity of BPs were found to be proportional to their life times.

Subject headings: Sun: activity - Sun: photosphere - Sun: surface magnetism - Physical Data and Processes: turbulence

1. Introduction

Bright points (BPs) observed in the solar photosphere in FeI 6173 Å filtergrams (Muller et al. 2000) and in G-band images (Berger & Title 2001; Ishikawa et al. 2007) are shown to be co-spatial and co-temporal with magnetic elements. However, only about 20% of magnetic elements in intranetwork areas are related to BPs (de Wijn et al. 2008; Ishikawa et al. 2007). Photospheric BPs, therefore, represent a subset of the magnetic elements. The relationship
between BPs and magnetic field seems to be so solid that the former are frequently addressed as magnetic bright points (e.g., Utz et al. 2009, 2010). The mechanism for the formation of BPs is thought to be a convective collapse of a magnetic flux tube (Parker 1978; Spruit 1979) implying strong downflows and evacuation of the flux tube allowing us to look deeper and see hotter plasma. Analysis of statistical distributions of BPs can shed a light on the fundamental properties of smallest magnetic elements.

Another strong reason for enhanced interest in BPs is that they are very reliable tracers of transverse motions of the footpoints of photospheric magnetic flux elements. These motions are thought to be an ultimate source of the energy needed to heat the chromosphere and corona, either via waves or via magnetic reconnection of intertwined flux tubes (e.g., reviews by Cranmer (2002), Cranmer & van Ballegooien (2005), and Klimchuk (2006) and references herein). These and other considerations stimulated numerous studies of transverse (to the line-of-sight) velocities and various applications of the results to the problems of wave generation (Cranmer & van Ballegooien 2005) and reconnection (Cranmer & van Ballegooien 2010 and references therein).

Studies of BPs size and lifetime distributions, however, are rather scanty. Based on Hinode/SOT (Kosugi et al. 2007; Tsuneta et al. 2008) observations, Utz et al. (2009, 2010) studied statistical distributions of G-band BP’s sizes and lifetimes. They used a 5.7 hour data with a pixel size of 0.054″ and 0.109″, and a time cadence of about 32 s. The authors reported a nearly Gaussian distribution of BP’s size, with the peak located near the diffraction limit of the telescope (157 km). For the lifetime distribution, an exponential fit was found.

Now, with the New Solar Telescope (NST) at Big Bear Solar Observatory (BBSO) operational, we attempt to reveal the BPs distribution functions on the basis of more accurate data, which are described in detail in the next session.

2. Data

Observations of solar granulation were performed with the NST (Goode et al. 2010) with a 1.6 meter clear aperture using a broadband TiO filter centered at a wavelength of 705.7 nm. This spectral line is sensitive to temperature, and it is usually used to observe the sunspot umbra/penumbra (Berdyugina et al. 2003; Reithmuller et al. 2008). When observing granulation with this line, a dual effect presents itself: for granules and BPs the intensity is the same as observed in continuum, whereas for dark cool intergranular lanes, the observed intensity is lowered due to absorption in the TiO line. Thus, TiO images provide
an enhanced gradient of intensity around BPs, which is very beneficial for imaging them.

The FOV of the broadband filter imager is $76.8 \times 0.768''$, and the pixel scale of the PCO.2000 camera we used is 0.0375''. This pixel size is 2.9 times smaller than the Rayleigh diffraction limit of NST, $\theta_1 = 1.22\lambda/D = 0.11'' = 77$ km, and 2.5 times smaller than the FWHM of the smallest resolved feature$^1$ ($\theta_2 = 1.03\lambda/D = 65$ km).

Uninterrupted observations of a quiet sun area near the disk center were performed on August 3, 2010 between 17:06 UT and 18:57 UT. The observations were made with tip-tilt and adaptive optics corrections (Cao et al. 2010). The time cadence of the speckle reconstructed images was 10 s. To obtain one speckle reconstructed image, we took a burst of 70 recorded with 1 ms exposure time, Then we applied the KISIP speckle reconstruction code (Woger & von der Luhe 2008) to each burst. Resulting images were carefully aligned and de-stretched. In the present study, we utilized only the central part ($28.3 \times 26.2''$ of the FOV, where the adaptive optics corrections were most efficient. The resulting data set consisting of 648 images was used to detect and trace BPs. A movie of this data set can be found on the BBSO website$^2$.

On the same day, Hinode/SOT obtained a synoptic G-band image within the time interval of our observations. In Figure 1 we show two images of the same area on the Sun simultaneously recorded with the Hinode/SOT (left) and NST (right). The Hinode image was processed with standard data-reduction Solar SoftWare prep-fg.pro package$^3$. All BPs visible in the Hinode image are present in the NST image. In addition, NST sees much more: small single BPs are clearly visible inside dark intergranular lanes (examine the bottom halves of the images). Moreover, in places where Hinode/SOT detects a single large BP, NST detects several separated BPs (center of the image). Extended filigree features are clearly fragmented into separate BPs in the NST image.

3. Method

To detect and track BPs, we took advantage of the three most important properties of BPs (Utz et al. 2009): small size, enhanced intensity and strong gradient in intensity around BPs. We calculated a BP-mask as follows. First, we smoothed each image (by applying a three-point running average), and then we subtracted the smoothed image from the original

$^1$http://www.telescope-optics.net/telescope-resolution.htm

$^2$http://bbso.njit.edu/nst-gallery.html

$^3$http://msslrx.mssl.ucl.ac.uk:8080/SolarB/AnalysisSoftware.jsp
image. This allowed us to substantially suppress the intensity in granules and only slightly diminish the peak intensity in BPs. Then we applied a thresholding technique to produce a BP-mask. First, we chose the lowest possible value of the threshold, \( th = 85 \) data numbers (DN), so that all BPs outside granules were selected. We then contoured and numerated each BP on an image. The routine was repeated for each image. For comparison, we also ran our code with \( th = 120 \) DN, which allowed us to only select brightest BPs. An example of BPs detection with \( th = 85 \) DN is shown in Figure 2. For each BP, we determined its area, its maximal intensity, and the equivalent diameter, \( d \), of the BP - the diameter of a circle whose area is equal to the BP’s area. Coordinates \((x_c, y_c)\) of the center of the equivalent circle were determined as mean values of corresponding coordinates of all pixels belonging to the BP. Centers of the circles were labeled.

We then traced the detected BPs from one image to another. When in image \( i \), inside the radius of \( d/2 \) around the \((x_c, y_c)\) pixel, we find a pixel labeled as a center of a BP in the \( i + 1 \) image, we assigned the two found objects to be the same BP visible on two consecutive images. This approach allows us to trace sub-sonic displacements of BPs of radius larger than 3 pixels. For smaller BPs we cannot trace large displacements (velocities larger than 4-5 km s\(^{-1}\)). It was undesirable to choose more broad than \( d/2 \) for the radius for searching the response object in the next image because BPs are frequently located very close to each other. When a BP merged with another BP, or when we could not find a BP
Fig. 2.— NST TiO image taken at 17:08:15 UT (left). The right panel shows the same image with detected BPs denoted by yellow pixels. The image size is 16.9″ × 13.9″.

in four consecutive images, we concluded that this BP ceased to exist. We thus were able to determine the lifetime of each tracked BP. The diameter, $D$, of each BP was determined by averaging over the lifetime equivalent diameter, $d$. Below in this paper, by ”BP” we mean an object observed at several consecutive images, but not a single spot of enhanced brightness observed in a single image.

When tracking BPs, we discarded all events with the area smaller than 2 pixels, all events detected at only one image, as well as events with maximal intensity below the mean intensity of the image. All these restrictions resulted in total of $N = 13597$ tracked BPs in case of $th = 85$ DN threshold and $N = 7148$ BPs for $th = 120$ DN.

4. Results

Figure 3 shows the probability distribution functions (PDFs) for the diameter, $D$, lifetime, $LT$, and maximum intensity, $I_{\text{max}}$, of BPs. In the left panels, results for two runs are shown: the black lines correspond to $th = 85$ DN and the red lines to $th = 120$ DN. The right panels show PDFs only from the $th = 85$ DN run. For all the PDFs in the figure, the difference between the two runs is small: for higher threshold the relative number of large-size events slightly decreases, and the relative number of brighter events slightly increases. The lifetime distribution does not appear to be affected by the threshold at all. The reason for this might be the very sharp gradient of intensity around BPs, so that the change in the cutoff level has little effect on the size of the selected BP. This is in line with Utz et al.
(2009), who reported that a change in the cutoff level by 30% results in change of sizes by only about 10%. Further, in the text, we only discuss the PDFs obtained for the \( th = 85 \) DN threshold.

The PDF of diameters displays a nearly linear behavior in the linear-logarithmic plot (Figure 3, a). The monotonous increase is present down to the diffraction limit, \( \theta_1 \), of NST. The saturation and the turnover of the observed PDF at scales smaller than \( \theta_1 \) (to the left from the dashed vertical line) might be caused either by the fact that the NST does not purely resolve elements smaller than 77 km, or that elements much smaller than 77 km do not exist. For comparison, in the same panel we show the BP size distribution as derived from Hinode/SOT G-band images by Utz et al. (2009). In spite of a drastic difference in the shape of the PDFs derived from the two instruments, physically, they are consistent. The Hinode PDFs also saturate at scales corresponding to the diffraction limit of the instrument, which is 157 km for SOT observations in the G-band.

From these results, we may conclude that the real minimum size of magnetic BPs (or magnetic flux tubes) has not yet been detected in observations with modern high resolution telescopes. As to the maximum size of BPs, the upper boundary for it seems to exist: as soon as BPs defined as those located inside intergranular lanes, the diameter of BPs cannot be larger than characteristic width of the intergranular lanes, which varies in a range of 150-400 km.

To determine the analytical fit for the distribution functions, PDF\((u)\), where \( u \) denotes \( D, LT, I_{max} \), we applied three different approximations: exponential, power law, and log-normal. The exponential function can be written as

\[
PDF(u) = \exp(-\beta u + c_1),
\]

where \( \beta \) and \( c_1 \) are free parameters, while the power law approximation can be presented as

\[
PDF(u) = 10^{c_2} u^\alpha
\]

with free parameters \( \alpha \) and \( c_2 \). The log-normal distribution function (the logarithm of \( u \) is normally distributed, e.g., see Aitchison & Brown 1957; Romeo et al. 2003; Abramenko & Longcope 2005) is

\[
PDF(u) = \frac{1}{us\sqrt{2\pi}} \exp\left(-\frac{1}{2} \left( \frac{\ln(u) - m}{s} \right)^2 \right),
\]

where \( m \) and \( s \) are the mean value and the standard deviation of \( \ln(u) \).

We applied the above approximations covering the largest possible interval, \( \Delta \), where the fit was performed with a minimum reduced \( \chi^2 \) test. Results are presented in Figure 3 and the parameters of the fits are listed in Table 1.
For the BP size distribution function, PDF(D), is a log-normal fit since it has the lowest $\chi^2$ while the fitting interval is the largest. The mode of the log-normal distribution, $e^m$, occurs at $D = 64$ km, which is lower than the diffraction limit. It is not excluded that observations with even higher resolution will show the mode at even smaller scales. What is obvious now is that the size distribution is not scale-free, since the corresponding power-law fit is applicable over only a narrow range. Moreover, the power-law $\chi^2$ is the worst.

The lifetime distribution function (Figure 3, c, d and Table 1, 3rd column) can be fitted very well by all three approximations, however, differently for different intervals. Short-lived BPs are better approximated by the power-law fit, while medium lifetime BPs (500 - 1200 s) better obey an exponential law. When we include long-lived BPs, the log-normal fit seems to be the best suitable for all observed BPs that live longer than 100 s. Note that the longest living BP in our data set was observed during 44.2 minutes, which is less than half of the length of the data set.

The maximum intensity distribution function (Figure 3, e, f; Table 1, the right-most column) can be equally satisfactorily fitted with an exponential or power law with the best $\chi^2$ test favoring the power law. At the same time, the log-normal fit is not suitable at all for PDF($I_{max}$). Inside the range of approximately 3800 - 4500 DN, the function is flat indicating a nearly uniform distribution of BPs with the maximum intensities in this range. Note that this is an interval of typical intensities found inside granules. Recall that we discarded all BPs with $I_{max} < \langle I \rangle \approx 3400$ DN, so that the saturation of the PDF($I_{max}$) at 3800 - 4500 DN is not related to the BP selection routine. The flat range of PDF($I_{max}$) might be caused either by insufficient sensitivity of NST to weak BPs, or by a real deficit of weak BPs.

The regression plots of the diameter and maximum intensity of BPs versus their lifetime (Figure 4) show the presence of a direct proportionality: BPs that live longer, tend to be larger and brighter.

5. Conclusions

A two-hour data set of quiet sun granulation obtained with highest to-date spatial and temporal resolution (77 km diffraction limit NST images with a time cadence of 10 s) was analyzed to obtain statistical distributions of size, lifetime and maximum intensity of photospheric BPs. An NST TiO image was compared with co-temporal and co-spatial image from Hinode/SOT obtained in G-band.

NST BPs are co-spatial with those visible in Hinode/SOT G-band data. This result allows us to take advantages of observations with the TiO filter, in contrast to the G-band
filter: the adaptive optics system and the speckle reconstruction code are more efficient when observing at longer wavelengths. We see a clear improvement caused by the higher resolution of the NST: in cases where Hinode/SOT detects one large BP, NST detects several separated BPs. In addition, NST detects numerous small and weak BPs which are not visible in the Hinode/SOT data. Extended filigree features are clearly fragmented into separate BPs in the NST images. The majority of BPs have a circular shape, however, some of them are elongated.

We found a weak positive proportional relationship between the lifetime, on one hand, and the BP’s size and intensity, on the other hand. So that brighter and larger BPs tend to live longer.

The distribution function, PDF(D), of the BP’s size extents down to the diffraction limit of NST (77 km). The saturation and the turnover of PDF(D), visible at smaller scales, might be caused by the fact that NST does not resolve properly elements smaller than 77 km. This result is consistent with PDFs derived from Hinode/G-band data (Utz et al. 2009): the Hinode PDFs also saturate at the diffraction limit of the instrument. The best approximation for the observed PDF(D) is found to be a log-normal fit with a mean value $m = 4.157$ and a standard deviation $s = 0.382$ of $ln(D)$. The log-normal fit performs better than the exponential and power laws over the entire range of diameters above 67 km. The mode of the log-normal distribution, $e^m$, occurs at $D = 64$ km, which is lower than the diffraction limit. Unlike the power law, the log-normal distribution is not scale-free, therefore, there is a limit on a minimal size of an elementary flux tube. However, the real minimum size may not have been achieved yet from observations with modern telescopes. The log-normal nature of the size distribution implies that the fragmentation and merging processes are important mechanisms contributing into evolution and dynamics of BPs (e.g., Abramenko & Longcope 2005). Frequent fragmentation and coalescence are clearly visible in the data set movie\(^4\).

The observed distribution function of the BP’s lifetimes can be best fitted with a log-normal approximation. The NST lifetime distribution function qualitatively agrees with that reported by de Wijn et al. (2005) inside the overlap interval, while Utz et al (2010) reported an exponential distribution for the lifetime of Hinode BPs in the interval of 2-12 minutes. In our study, the overall slope of the PDF(LT) in this particular 2-12 minutes interval is nearly the same as reported by Utz et al. (2010), however, it appears that the power law is the best analytical fit inside this particular interval.

About 98.6% of all BPs live less than 120 s (12 time steps). This remarkable fact was

\(^4\)http://bbso.njit.edu/nst-galery.html
not obvious from previous studies because an extremely high time cadence was required. The fact indicates that the majority of BPs appear for very short time (tens of seconds), similar to other transient features, for example, chromospheric rapid blue-shift events (RBEs), Rouppe van der Voort et al. (2009). The most important point here is that these small and short living BPs significantly increase dynamics (flux emergence, collapse into BPs, and magnetic flux recycling) of unipolar network areas. These unipolar fields make it difficult to invoke reconnection between the emerging and pre-existing flux as an explanation for the RBEs. However, the fact that the network field is more dynamic than expected may allow to apply the component reconnection approach. The magnetic field is fragmented into flux concentrations with well defined interfaces between them known as current sheets. Random motions of BPs, as well as often appearance/disappearance of new flux concentrations, will change the spatial distribution of the current sheets thus leading to component reconnection and to release of energy.

It is interesting that we did not find a power law to be the best fit inside a whole available scale interval for any of the tested parameters. Two reasons for that might be advanced. First, a reign of the power law inside the interval from zero to infinity is impossible unless the analyzed field is a computer-generated monofractal. Second, a power law implies self-similarity - scaling with the same index - inside the entire range where this law reigns. This means a monofractal structure of the field, and, therefore, an absence of multifractality. At the same time, processes and structures formed in a natural way possess different scaling indices for different scale intervals; in other words, they are multifractals. As broader range of scales becomes available for observations, the stronger is the deviation of the observed distributions from a pure power law.

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REFERENCES


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<th>$LT, \text{ s}$</th>
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Fig. 3.— PDFs of the BPs diameter \((a,b)\), lifetime \((c,d)\), and maximum intensity \((e,f)\). Left column shows the data for both runs: for the mask threshold of 85 DN (black), and 120 DN (red). Straight thick blue lines in all left frames show the exponential fit to the data points calculated inside a range between the vertical thin blue lines. In all the right frames, the log-normal and power-law fits were applied inside intervals, \(\Delta\), covered by the purple and green lines, respectively. In the frames \(a,b\), the vertical dashed segment shows the position of the Rayleigh diffraction limit of NST for observations with the TiO filter. Blue and green double curves show the distribution of BPs size from Hinode G-band observations as reported by Utz et al. (2009): blue (green) line for the pixel size of 0.109\(\arcsec\) (0.054\(\arcsec\)).
Fig. 4.— BPs lifetime plotted versus the BPs diameter (*left*) and maximum intensity (*right*). Dashed lines connect the mean values calculated inside each bin of the lifetime distribution function, PDF($LT$). Straight solid lines are the best linear fit to the dashed line points.