1. Introduction

1.1. General information

Coronal bright points (CBPs) are observed ubiquitously in the solar atmosphere in the X-ray and EUV wavelength regimes, with a spatial distribution that becomes more homogeneous and numerous during solar minimum (**?**). Though they only cover about 1.6% of the photosphere (**?**), CBPs and sunspots contribute over 90% of the total magnetic flux (**?**). Over the course of the solar cycle, they can contribute significantly to the global intensity variation of the sun, particularly in the ultraviolet regime (**?**).

CBPs are thought to be composed of bundles of coronal loops, and consist of two components: a bright center and a surrounding darker region (**?**; **?**). Flashes of emission, or "jets" have been observed around these CBPs, with characteristic periods of about one hour (**?**).

1.2. Previous size determination methods

Several techniques for determining the size of coronal CBPs have been employed in the literature. **?** developed an algorithm to locate CBPs in the corona, using size determined by intensity as part of the criteria for distinguishing CBPs from other features, such as top-down views of coronal loops or nanoflares.

1.3. Outline of current project

Here, the size of a single CBP was determined using cross-correlation techniques. The data is described in §2, the results are examined in §**??**, with a subsequent analysis in §**??**, and the primary conclusions are discussed in §**??**.

2. Data

2.1. Download

This study used multi-wavelength data from AIA/*SDO* spanning one hour on June 1, 2012 from 13:00:00 to 13:59:59, at a cadence of 12 seconds. The relevant values for each passband are given in table 1.

The data was downloaded using `vsoget.pro`, a procedure that both queries and/or downloads data from any of the three instruments on SDO. The downloaded data

λ [Å]	log(T) [K]	Ion
94	6.8	Fe XVIII
131	5.6, 7.0	Fe VIII, XXI
171	5.8	Fe IX
193	6.2, 7.3	Fe XII, XXIV
211	6.3	Fe XIV
304	4.7	He II
335	6.4	Fe XVI

Table 1: Characteristic temperatures corresponding to the wavelengths observed in emission in the solar corona (from **?**).

was processed at level 1.0. Double check difference between 1.0 and 1.5 and see if this is important. . .

A grayscale image of the full disk at the beginning of the time series for each pass band is shown in figure **??**. A single CBP was selected from the coronal hole in the upper left region of the solar disk. 100 pixel^2 ($\sim$ 60 arcsecond^2) images of this BP in each passband are shown in figure **??**. As noted by **?** in their study, the CBP structure is most evident for the 131Å, 193Å, and 211Å images.

2.2. Reading and/or restoring of data and header information

The `read_sdo.pro` routine from solar software (ssw) (source?) was used to read the data and headers from the fits files. Since the header information was read into structures, it was necessary to read them at the start of every run since variables in structure form evidently cannot easily (if at all) be saved and restored as `.sav` files. For simplicity, an alternative was not explored since reading headers alone did not take a significant amount of time.

I wrote a code called `bp_read_my_fits.pro` with the option to read data from the fits files or from saved variables (`*.sav`) if the data had already been read and processed (see §**??**), as well as read the headers into a separate variable. The pass bands of interest were entered as an input variable in the form of a string array, e.g. [‘171’, ‘193’]. To provide the most efficient means of reading and organizing the wealth of required information, this code created a separate structure for each pass band into which the desired data range, central wavelength, cross-correlation values, and other pertinent information from the headers was written. In addition to making the task of re-reading data and adding extra header information as quick and simple as possible, this code was written as a general means of reading and organizing any future data, regardless of instrument or location.

2.3. Processing: alignment

Before analysis, an alignment procedure called `align_cube3.pro` was run on each data cube. This involved choosing a reference image (in this case, the image halfway through the time series) for every other image to be aligned to. This procedure corrected for shifts between images due to instrumental effects or the global rotation of the sun.

Each shift resulted in the pixels at the edges of the data array to wrap around to the opposite side in both the x and y dimensions. Therefore, it was necessary to run the alignment on a larger two-dimensional data set than just the portion needed for analysis.

The amount by which an image shifted each time was determined by the routine `alignoffset.pro` and returned as a 2xN array (where N = number of images) called "offsets" (in x and y). This procedure was quite mathy and I made no attempt to figure out how it worked. These offsets generally started at 2-3 pixels, then after several runs through the procedure, went down to the sub-pixel level.

The routine `shift_sub.pro`, another mathy code, was then called by `align_cube3.pro` to do the actual shifting of each image, down to sub-pixel accuracies. An interpolated image was returned if the difference was greater than one pixel. If the difference was less than one pixel, the actual values of the offsets determined the amount by which the cube was shifted.

The repetitions were halted as soon as the amount of shift ceased to change by a significant amount (which was determined using the standard deviation so as to account for negative values as the image shifted back and forth). At this point, the data cube was deemed "sufficiently aligned" and ready for analysis.

All three procedures mentioned above were acquired courtesy of Dr. McAteer and Dr. Gallagher.

3. Analysis

3.1. Cross-correlation

3.1.1. General definition

The cross-correlation of two functions gives a quantitative value of how "similar" the two functions are. This similarity is given as a function of the "lag" between the two functions, i.e. the phase shift between the two functions at which a given correlation value occurs. (Source?) Mathematically, the cross-correlation between two functions, f and g, is given by

$$(f \star g)(\tau) \equiv \int f(t)^* g(t - \tau) \mathrm{d}t \tag{1}$$

where τ is the lag between the two functions. If τ is positive, then

In statistical applications, the *normalized* cross-correlation is calculated, giving a rage of possible values between -1 and +1, where a value of +1 means the two functions are exactly correlated, a value of -1 means the two functions are *anti*-correlated, and a value of 0 implies no correlation at all.

The complex conjugate of $f(t)$ in the integral ensures that the peaks/troughs of a complex function will align in a way that contributes positive values to the integral (otherwise the correlation values will be the opposite of what they should be. . . ?).

3.1.2. Application to BP size

The procedure `timelag.pro` normalized the cross-correlation values to account for instrumental effects and the fact that the intensity values from *SDO*/AIA data are not physical. Between -1 and 1 or between 0 and 1 ?? As a result, the absolute intensity values did not have an effect on how well any two given light curves were correlated. Only the relative intensity, i.e. the actual pattern of the light curves was considered. This code took two light curves at a time, which here was two individual pixels, varying in time but static in space.

The array of possible timelags was given as $-\tau/2 \rightarrow \tau/2$, rather than $0 \rightarrow \tau$. This was because, while in principle the two curves are shifted past each other into space where the other doesn't exist (and hence gives a value of zero), the code causes the endpoints of the shifted function to wrap around to the opposite end and be calculated by the initial function as it actually exists in that space. Therefore, the function is shifted forward by half of the full range in τ, and then backward (from the original position) by half of the full range again. This has the effect of maximum correlation values having corresponding timelags that can be either negative or positive. A positive lag means the first function actually "leads" the second by τ, whereas a negative lag means the first function "lags" the second (seems kind of backward, but whatev.)

The array of possible timelags was initially given simply as the image index in the series (0 to 299), but the observation time from the header was substituted later as a more physical shift between each time series.

It should be noted that the full length of the time series (one hour) was chosen to ensure a good buffer around the amount of time over which a disturbance could travel an appreciable distance across the approximate size scale of BPs ("size" being determined from previous literature and based roughly on intensity relative to the background in a single image).

For an initial look at the type of results to be expected, a pixel roughly in the center of the BP was chosen arbitrarily based on the intensity of the initial image in each time series. The cross-correlation procedure was run over the time series of this pixel and every other pixel in the 100 pixel^2 data cube. There are several relationships that can be examined here. The correlation values between two curves as a function of timelag is the standard output from two single functions. One generally sees a bell-shaped curve whose peak y-value occurs at some value τ_{max} on the x-axis. This peak is the maximum correlation between the two curves, and τ_{max} is the lag that occurs between the points where they are most highly correlated.

The purpose of the cross-correlation analysis was to help determine, at the lowest possible resolution, which parts of the BP were moving together as a single physical structure. The timelag at which the highest correlation occurs was expected to be of the same order as the acoustic crossing time. Since magnetism dominates the behavior of waves produced in the solar corona, the speed at which a wave moves through a feature there is expected to be close to that of the characteristic Alfvén speed.

The intensity of each BP compared to the background flux surrounding it can give a visual estimate of its size. The intensity of the first image in each passband is plotted as a function of radial distance from the central pixel in figures **??** and **??**.

4. Results and discussion

Images illustrating the highest cross-correlation value of each pixel and the timelag corresponding to that correlation value are shown in figures **??** and **??**, respectively. A color variation of the correlation images is also shown (figure **??**).

The correlation was given a threshold of 0.5 and rescaled to obtain a better illustration of the structure of the BP. These images are shown in figures **??** and **??**.

4.1. Variation in BP size with temperature

Even though the temperature of the corona increases with height from the transition region to wherever the corona actually ends (need source here), there is not necessarily a direct correlation between temperature and absolute height above the photosphere due to the variety of structures and overall inhomogeneity that exists in the solar atmosphere (source). However, the *relative* height between each bandpass for a given structure is possible to determine, and is relevant to this study.

4.2. Extra emission in 211Å

The 211Å data is particularly notable as it shows strong correlation values at two points to the right of where the BP appears visually in figure **??**. This could be the result of a jet of light emitted from the main structure, or a possible indicator of the main structure splitting into several tubes at the height where the 211 Å emission is strongest. A movie showing all images from this wavelength revealed a flash of emission around the 45th image (t = 45*12 seconds), which matches the timelag at which the high correlation values occurred as shown in figure **??**.

4.3. Crossing time

In the corona, the characteristic wave velocity is expected to be close to the Alfvén velocity, which is on the order of 1000 km s^{-1}. (With a cadence of 12 seconds, do we have enough sampling to do this?)

5. Conclusion

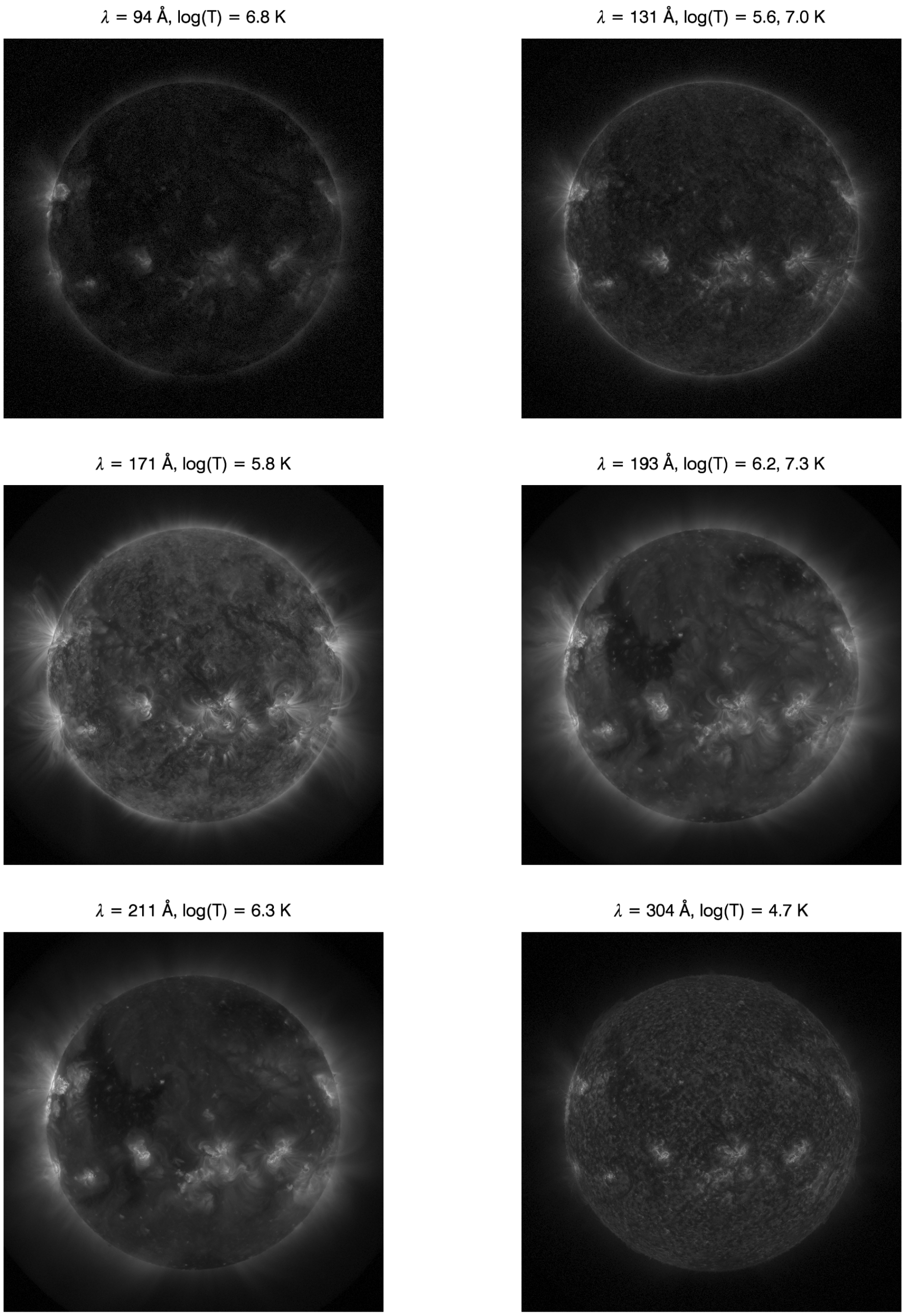

Fig. 1.— Full disk showing the relative intensity at the start of the time series for each AIA bandpass used in this study. These images show the square root of the exact data values for better visualization of the features.

bp_all.png

Fig. 2.— Images of the BP in six different AIA wavelengths. The pixel coordinates are given relative to the full disk shown in figure **??**. The location of the BP appears to shift from one bandpass to next, which may indicate a structure that is not completely straight, or a possible shift in the data itself. As with figure **??**, these images show the square root of the original data values.

cc_all_grayscale.png

Fig. 3.— Images showing the highest cross-correlation value for each pixel.

cc_all_color_cutoff.png

Fig. 4.— Cross-correlation images scaled to show only values higher than 0.5.

tt_all_color_cutoff.png

Fig. 5.— Timelag corresponding to the cross-correlation values higher than 0.5.

im_211.png

Fig. 6.— Images from the 211 Å bandpass only, around the times when the two jets of light appeared in the upper right region of the main body of the BP.

closeup_211.png

Fig. 7.— Timelag at 211 Å “zoomed in” around the two jets of light.

intensity_1.png

Fig. 8.— Intensity of each pixel is plotted as a function of radius for each passband. I have no idea what's going on with the 94Å data.

intensity_2.png

Fig. 9.— Same as figure **??**, but with half the radius range cut off to better view the values around the main BP.

cc_tt_plot.png

Fig. 10.— The highest cross-correlation value of each pixel is plotted as a function of its distance from the center pixel. The color indicates the timelag corresponding to the maximum cross-correlation for that pixel.

cc_tt_plot_scaled.png

Fig. 11.— Same as figure **??**, but with two thirds of the timelag cut out at both ends.