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ANALYSIS OF CORONAL BRIGHT POINTS AT DIFFERENT WAVELENGTHS

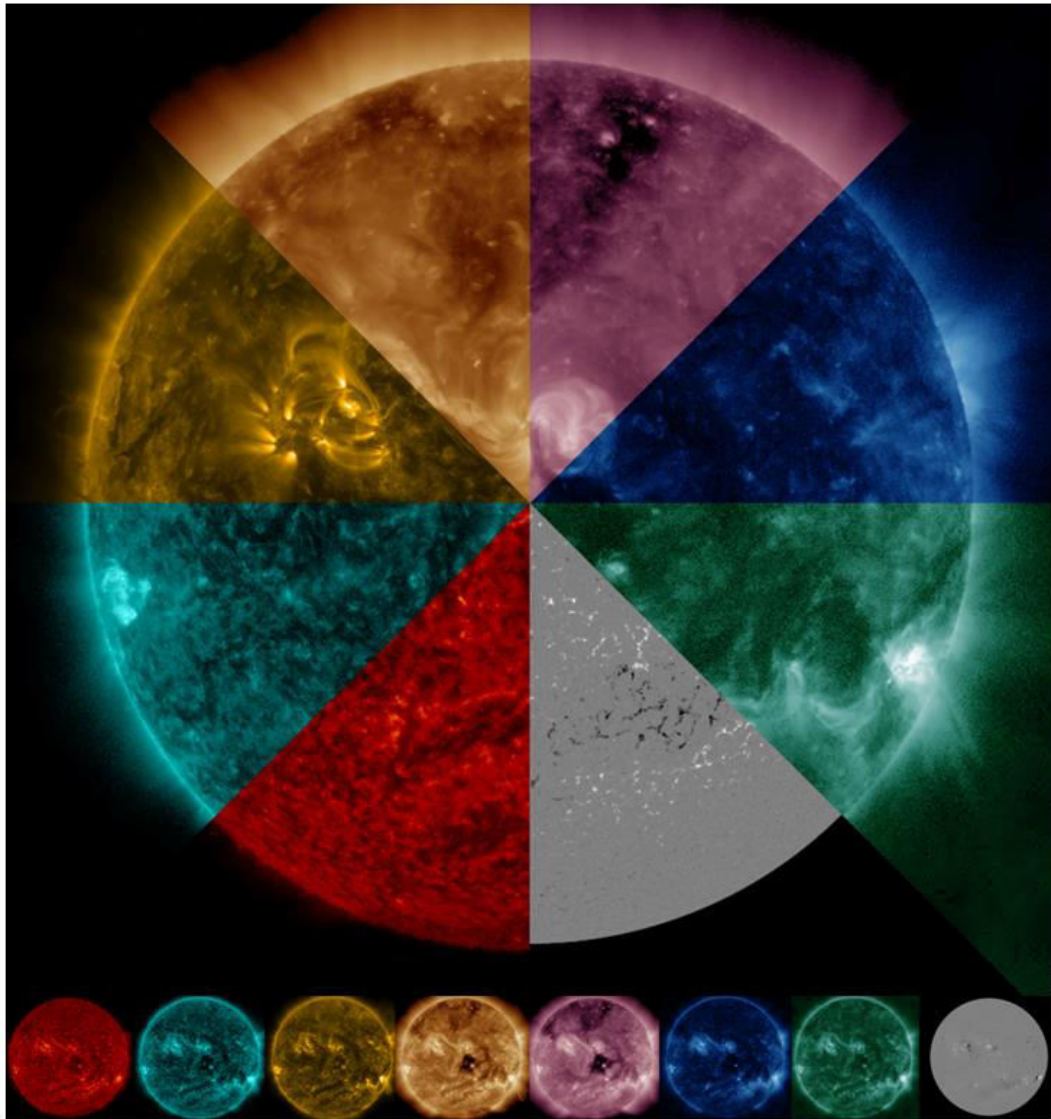


Figure 1: CBPs at different wavelengths (image: <https://helioviewer.org>) 2015-08-13 00:00:00 UTC [78]

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Abstract

Coronal Bright Points (CBPs) are also called X-ray Bright Points (XBPs) and are hot plasma phenomena that are located in the corona of the Sun [24, 38]. A typical CBP seems to be almost isothermal and has a mean temperature of 1.3 MK , which can vary easily between 1.2 to 1.7 MK [1]. CBPs typically emerge at the boundaries of supergranular cells [11, 18, 36] that are caused by convection in the solar interior. Nevertheless, the thermal energy of a CBP is mostly generated in the transition region and in the lower part of the corona, where thousands CBPs are produced simultaneously by magnetic perturbations in the photosphere, that is located at the surface of the Sun. There is strong evidence that CBPs play an important role in heating the corona [34].

The aim of this thesis is to analyze similarities and differences of CBPs and compare them in different wavelengths in the solar atmosphere. We use the IDL SolarSoft library and the Python programming language for our analysis. In total, we analyze a sequence of full-disk images with a cadence of 60 seconds spanning over 12 days from 7 different channels of the Atmospheric Imaging Assembly (AIA) [5, 31] and the Helioseismic and Magnetic Imager (HMI) [54, 56] onboard the Solar Dynamics Observatory (SDO) [44]. To get significant statistics, we select 663 CBPs randomly that have been recorded between 13th of August and 24th of August 2015.

The AIA images and the HMI magnetograms have been spatially aligned and are observed nearly at the same time. One AIA image always corresponds to an HMI observation with a time distance of at maximum 22.5 seconds. We compare only complete sets of observations for each AIA channel with the closest HMI magnetogram, to circumvent the problem that raw data transmitted from the spacecraft are not taken at exactly the same time [42].

All original fits files were Level 1 raw data with 4096 by 4096 pixels and a spatial resolution of 0.6 arcsec. They are processed into Level 1.5 data products. The AIA data were re-scaled (plate scale), rolled and adjusted to the HMI orientation. For the determination of the position of each CBP, the solar differential rotation has been corrected.

After the data reduction, we create segmentation maps of CBPs with our algorithm. We utilize the identified pixels of each CBP to highlight their location on the AIA images and HMI magnetograms [42]. In order to detect a CBP's appearance and disappearance, we investigate variations in the light intensity. If the intensity reaches a specific value higher than the average value plus one standard deviation, this indicates the appearance of a CBP. We identify the disappearance likewise, but in the opposite manner. When we select CBP sequences, we disregard the solar limb, as well as active regions (ARs), including the AR environment of 180 by 180 arcsec [24].

We study the CBP's statistical properties of the lifetime, the temperature, the fluxtubes, the merging behavior, the magnetic-field polarity, the lifecycle of CBPs and the shape, as well as the gaps in CBP sequences due to the algorithm. Thus, we compare the main characteristics of all parameters with each other.

In the literature, three phases in the lifecycle of a CBP are defined. In the „Pre-Interaction Phase“, magnetic regions of opposite polarity approach each other. The generation of a CBP takes place in the „Interaction Phase“, which is driven by reconnection and the subsequent energy release. The decay of a CBP into fragments and their disappearance is called the „Cancellation Phase“ [1]. With this work, we are able to confirm existing statistics from the literature [47]. We find short-lived and strong variations in the light intensity, which supports the conclusion of other studies, where magnetic reconnection is identified as the origin of the CBP heating [24].

Abstract (German)

Coronal Bright Points (CBPs) werden auch als X-ray Bright Points (XBPs) bezeichnet und befinden sich in der Korona der Sonne in einem Hochtemperaturbereich [24, 38]. Die Temperatur eines typischen CBP's scheint fast isotherm zu sein und zeigt eine mittlere Temperatur von 1,3 MK , die zwischen 1,2 und 1,7 MK liegen kann [1]. Die Grenzen der Supergranularzellen sind die Orte, an denen CBPs entstehen [11, 18, 36]. Dennoch wird die Energie des CBP's hauptsächlich in der Übergangsregion und in der unteren Schicht der Korona erzeugt, wo gleichzeitig tausende CBPs in der Photosphäre bzw. auf der Sonnenoberfläche produziert werden. Es gibt also deutliche Beweise dafür, dass sie eine entscheidende Rolle bei der Erwärmung der Korona spielen [34].

Ziel dieser Arbeit ist es, den Vergleich von Ähnlichkeiten und Unterschieden von CBPs bei verschiedenen Wellenlängen in der Sonnenatmosphäre zu analysieren. Die Analyse wird mit Hilfe von Python und dem Softwarepaket der IDL SolarSoft-Bibliothek untersucht. Insgesamt analysieren wir eine Sequenz von Vollscheiben-Beobachtungen mit einer Kadenz von 60 Sekunden über 12 Tage hinweg in 7 Kanälen von Atmospheric Imaging Assembly (AIA) [5, 31] sowie Magnetogramme des Helioseismic and Magnetic Imager (HMI) [54, 56] an Bord von Solar Dynamics Observatory (SDO) [44]. Um eine signifikante Statistik zu erzielen, verwenden wir 663 zufällig ausgewählte CBPs die zwischen dem 13. August und dem 24. August 2015 aufgezeichnet wurden.

Die AIA-Bilder und die HMI-Magnetogramme wurden räumlich ausgerichtet und wurden in etwa zur gleichen Zeit beobachtet. Jedes Bild von AIA hat einen maximalen zeitlichen Abstand zur HMI Beobachtung von 22,5 Sekunden. Wir vergleichen jeweils vollständige Sätze von Bildern der AIA Kanäle mit dem nächstgelegenen HMI-Magnetogramm, um das Problem zu umgehen, dass die Rohdaten vom Satelliten nicht exakt zur selben Zeit aufgenommen wurden [42].

Die originalen FITS-Dateien sind Level 1-Rohdaten mit 4096×4096 Pixeln bei einer räumlichen Auflösung von 0,6 Bogensekunden. Sie wurden zu Level 1.5-Datenprodukten verarbeitet. Die AIA-Daten wurden skaliert, gedreht und an die Orientierung von HMI angepasst. Zur Bestimmung der Position jedes CBP's wurde die solare differentielle Rotation korrigiert.

Nach der Datenreduktion erstellen wir Segmentierungskarten der CBPs durch einen Algorithmus. Wir benutzen die Koordinaten der CBPs, um ihre Position auf den jeweiligen AIA-Bildern sowie den HMI-Magnetogrammen zu markieren [42]. Um das Auftreten oder Verschwinden eines CBP's zu detektieren, bestimmen wir Veränderungen in der Licht-Intensität. Wenn die Intensität über den Mittelwert plus einer Standardabweichung steigt, zeigt dies das Auftreten eines CBP's an. Wir identifizieren das Verschwinden auf dem umgekehrten Wege. Bei der Auswahl von CBP-Sequenzen meiden wir den Sonnenrand sowie aktive Regionen (AR) inklusive einer Umgebung von 180×180 Bogensekunden [24]. Wir untersuchen die statistischen Eigenschaften des CBP hinsichtlich der Lebensdauer, der Temperatur, der Flussröhren, des Verschmelzungsverhalten von CBP's, der Magnetfeldpolarität, des Lebenszyklus von CBPs und der Form, sowie der Lücken in CBP-Sequenzen auf Grund des Identifikationsverfahrens. Anschließend vergleichen wir die Hauptmerkmale jedes dieser Parameter. Die Literatur definiert drei Phasen im Lebenszyklus eines CBP's. In der „Vor-Interaktionsphase“ nähern sich Regionen entgegengesetzter Magnetfelder einander an. Die Entstehung eines CBP's findet in der „Interaktionsphase“ statt, die durch Rekonnektion und deren Energiefreisetzung angetrieben wird. Der Zerfall eines CBP's in Fragmente und ihr Verschwinden wird „Auflösungsphase“ genannt [47]. Wir finden kurze und starke Variationen in der Lichtintensität, womit wir die Schlussfolgerung anderer Arbeiten unterstützen können, welche magnetische Rekonnektion als Ursache der Heizung von CBPs identifizieren [24].

Chapter 1

Introduction

The focus of this master thesis lies in the analysis as well as the comparison of similarities and differences between Coronal Bright Points (CBPs) at different wavelengths in the solar atmosphere. The first observations of Bright Points (BPs) were described by Vaiana et al. in 1973a [65], whereby Sheeley & Golub in 1979 [58] recognized that these BPs seem to be small coronal loops or small bright structures in the solar atmosphere [55].

This thesis aims to track, classify, and compare the CBPs with images and magnetograms observed by the AIA and HMI instruments onboard the SDO spacecraft.

The purpose of the SDO mission is to determine the processes of formation, the structure, and the energy transport of the Sun's magnetic field for a better understanding of the solar wind, total solar irradiance variations, flares, Coronal Mass Ejections (CMEs) and BPs [44, 70]. The observational data allows for the analysis of the CBP lifecycle, in particular, their formation, evolution, and disappearance.

Regarding their shapes, some CBPs appear to be small loops, others are more point-like with surrounding structures, or they show complex forms. A given CBP may appear differently at different times and may change its type due to the evolution of the CBP shape.

To resolve the structure of a CBP, the AIA instrument provides 7 EUV channels for observation, namely 94 Å, 131 Å, 171 Å, 193 Å, 211 Å, 304 Å, and 335 Å with a high spatial resolution of 4k×4k at 0.6 arcsec per pixel. Images are taken with a cadence of 12 seconds for one full-disk image which covers the CBP's temperature ranges from about 10^5 to 20×10^6 K [84].

To measure the magnetic field of CBPs, the HMI instrument delivers Doppler shifts and magnetograms of the full solar disk using the iron absorption line 6173 Å with a high spatial resolution of 4k×4k at 0.505 arcsec per pixel and a cadence of 45 seconds. The scientific goal of HMI is to give insights into the generation of the solar dynamo, the convection zone dynamics, solar magnetic activity, and their disturbances. A special interest of this work is the connection between the photosphere and the corona [54, 56].

In Chapter 1 we give an overview of the Sun's structure, in particular the atmospheric layers. We describe the origin of CBPs in more detail, as well as the coronal heating problem. Chapter 2 deals with observational methods and instruments of SDO, especially AIA and HMI. Furthermore, we describe the algorithm that is necessary for data reduction and automatic CBP tracking. Additionally, we present the classification of CBPs and their visualization by cutouts from videos. Chapter 3 illustrates the statistical results, such as the CBP lifetime, magnetic-field polarity, temperature, fluxtubes, shape, lifecycle, and the merging with another CBP. We compare these properties with each other to see their possible interdependence. We discuss the results in Chapter 4. Chapter 5 gives a conclusion on the magnetic reconnection as an important driver of CBP evolution, including an outlook for further studies. The Appendix A holds essential IDL and Python source codes with comments and a short description.

1.1 Motivation

My first sign of interest in solar physics was the seminar called “Sun and Space Weather“ at Vienna University. There, I got to know my master thesis supervisor Univ.-Prof. Dr. Arnold Hanslmeier, who invited me to the scientific program of the 5th international workshop on small-scale solar magnetic fields and the 6th international workshop on solar and stellar magnetic fields in Bairisch-Kölldorf in Styria.

After that, I got the big chance to start my master thesis at ESTEC as a Stagiaire / Trainee. There, I was able to access and work with a CBP database at ESTEC. It was the most effective way to make progress on the analysis of CBPs. My master thesis is focused on CBPs in the solar atmosphere with AIA and HMI data from the SDO spacecraft.

My traineeship was supervised by Joe Zender and was focused on research on statistical properties of CBPs, to compare them, and find statistical similarities and differences, e.g. of the lifetime, lifecycle, magnetic-field polarity, shape, temperature, fluxtubes or the merging with another CBP. The main idea was to find different types of CBPs and their similarities. Therefore, we expanded the database of CBPs and found a new way to track them. Moreover, we selected 663 CBP sequences randomly and tried to identify their similarities and differences. The main programming languages we used were IDL and Python on Linux.

Coronal extreme UV (EUV) observations of CBPs are available together with co-temporal observations of bipolar magnetic-fields. Connecting these observations may reveal an insight into the evolution of the photospheric magnetic field and the subsequent heating in the corona. The formation of a CBP may be driven by this magnetic activity.

As a result, I gained knowledge about the solar atmosphere, specifically about the corona and the response of the AIA instruments to the different atmospheric layers.

1.2 The Sun's structure

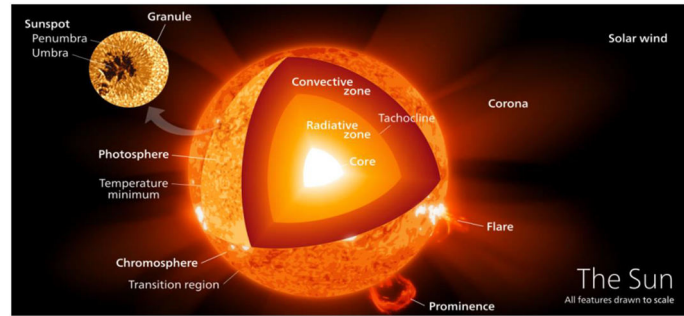


Figure 1.1: The Sun and its six main layers. The three inner layers are labeled here as the core, the radiative zone, and the convective zone, where the tachocline is the interface between these two zones. The three outer layers are called photosphere, chromosphere, and corona that features also flares and prominences [85, 87]. (Image taken from [85].)

For this work, we focus on the solar atmosphere, in particular the corona. The magnetic evolution together with a pressure imbalance is thought to accelerate plasma from the outer corona and thereby producing the solar wind. The distribution of the magnetic flux in the corona is not uniform over the solar surface. In case of a quiet Sun (QS) period, magnetic fields are more radial on the poles and further away from the Sun in the ecliptic. The pole regions appear therefore darker and are called coronal holes. In the active period of the Sun, magnetic fields are more mixed, leading to coronal holes being distributed over the whole solar surface. Sunspots are compact dark regions with strongly dominating magnetic field. The magnetic fields wind up and get twisted because of the faster rotation at the equator, which we call differential rotation (see Figure 2.14). During the solar maximum or high solar activity, we find more sunspots in total. There is a connection between these sunspots and coronal loops. The magnetic flux density in sunspots is so strong that it dominates over the convection, which leads to lower energy transport and hence temperature in the photosphere. This makes sunspots to appear dark [86, 87].

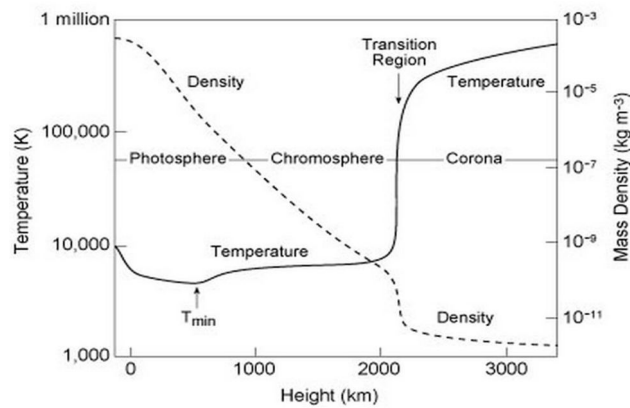


Figure 1.2: Overview of the Sun's atmosphere. The solid line marks the temperature profile while the dashed line describes the density profile. In the photosphere, the temperature drops first from roughly 6,000 K to about 4,000 K. This is located in the minimum temperature region, which is about 500 km above the photosphere. With rising altitude, the temperature is increasing again. The transition region is located between the chromosphere and the corona with a thickness of about 100 km, and features a jump in the temperature from roughly 10,000 K to about 1 million K. In the corona, the temperature is increasing further. However, the density is decreasing continuously, almost in an exponential way, but there is also a significantly stronger decline in the transition region [77]. The corona ranges several solar radii into space. The density of the corona is 10^{-12} times less than in the photosphere and generates even less than 1 millionth of the photospheric visible light [86, 87]. (Image taken from [77].)

1.3 Bright Points

1.3.1 Definition

CBPs (also known as XBP) are small regions of increased magnetic activity that we find all over the solar disk. The very first ones were detected in 1969. During a solar activity cycle of 11 years, there are more CBPs visible at a solar minimum than at the maximum. They are directly bound to small regions of bipolar magnetic-field. According to the literature, the specific definition of CBPs is based on several parameters, e.g. size, temperature, oscillations (periods), and lifetime, see Table 1.1. Table 1.1 is a list of several criteria of CBPs, which have been found in the literature, i.e. their defined size, temperature, oscillation time (period), as well as their lifetime. The numbers of the parameters are varying, which depends on the different spacecraft and their instruments. As can be seen, different instruments lead to varying results that sometimes seem to contradict, even though this is only because of the observational methods used [24, 38].

Table 1.1: Comparison of typical CBP parameter as reported from different sources

size	temperature	periods/oscillations	lifetime
3" – 28" (2 – 20 Mm) (Alipour et al., 2015) SDO -> AIA (0."60 of 12s) [2]	1.1 – 3.4 MK (Kariyappa et al., 2011) [27]	10 – 25 min. (Chandrasekar et al., 2013) [9]	few minutes to a few days 52% -> mean value 12 min. 48% -> mean value 6 hours longest -> 72 hours (Alipour et al., 2015) [2]
5" – 40" (Li et al., 2016) [34]	several MK (1 MK on average) (maximum of 3.148 MK) (Li et al., 2016) [34]	seconds to tens of minutes (typical 90 s) (Li et al., 2016) [34]	hours to days (Schmelz et al., 2013) [55]
10" – 20" (Kariyappa et al., 2008a) Hinode -> XRT (1" of 60s) [25]	2 x 10 MK (Kariyappa et al., 2008a) [25]	few min. to hours (3 min. intensity period for chromospheric BPs) (Kariyappa et al., 2008a) [25]	2 h – 2 days (Kariyappa et al., 2008a) [25]
5" – 20" (Ning & Guo, 2014) SDO -> AIA (0."60 of 12s) [41]	1.2 – 1.7 MK very little plasma emitting above 3MK (Alexander et al., 2010) [1]	quasi-periods between 80 – 100s (Ning & Guo, 2014) [41]	several hours to 2 days (Ning & Guo, 2014) [41]
Few arcsec to tens of arcsec (Karachik et al., 2014) Hinode -> XRT (1" of 60s) [24]	2 – 3 MK (Doschek et al., 2010) [10]	intensity oscillations from 8 to 64 min (Tian et al., 2008) [63]	minutes to days 8 – 9 h average (Karachik et al., 2014) [24]
<15" – 30" (Schmelz et al., 2013) [55]	1.6 – 2.5 MK (Pevtsov et al., 2003) [45]	quasi-periodic 2 – 10 min. with damping time tens of minutes (Tavabi & Koutchmy, 2014) [62]	few minutes to several days 8 – 9 h average (Minenko et al., 2014) [38]
15" – 30" (Minenko et al., 2014) [38]		2 – 5 min. (Pradeep & Kariyappa, 2007) [46]	on average 8 hours (Alexander et al., 2010) [1]
30" – 40" (Tian et al., 2008) TRACE [63]			

Chandrashekhara et al. (2012) [9] show that some criteria for CBP identification need to be added:

Size criterion:

This criterion is relevant for potential CBPs which are smaller than 28 arcsec (20 Mm) and larger than 3 arcsec (2 Mm). On one hand, “bright dots” or “nanoflares” are phenomena that are smaller than 3 arcsec and have a lifetime lower than 45 s [51, 53]. On the other hand, if a feature is larger than 28 arcsec, we consider it as an AR and not as CBPs. Hence, we also disregard any CBP near any AR, for safety [2].

Shape criterion:

It represents the morphological aspect, which includes three types of CBPs: point-like, loop-like, and complex magnetic activity [7, 58]. All types should have a closed contour and should not be elongated or just part of large-scale loop structures [2].

Intensity criterion:

This is another criterion of potential CBPs, where the EUV-light or X-ray intensity level is significantly above average. We use only events that are 1.3 times brighter than the background, because the intensity may vary strongly, according to Subramanian et al. (2010, 2012) [59, 60].

Distance criterion:

The maximum distance between two CBPs to be identified as a “separate event” has to be larger than 60 arcsec. We measure the distance between the brightness maximum of each CBP. If the distance is smaller than 60 arcsec, we consider this as one single CBP [2].

Some structures are not always elliptical and appear more complex. This may be explained by merging CBPs, where they first approach each other and then merge into an elongated shape. As a consequence, they are overlapping and cannot be seen as separate events anymore [42].

In case of merging with another CBP within its lifetime, there are two possible scenarios:

- (1) An “evolving” CBP is when two or more CBPs approach and eventually merge. The lifetime of such an evolving CBP is usually the lifetime of the biggest part before merger [2].
- (2) The “fragmented” CBP dissects from one main CBP into usually two smaller parts or more. We take the lifetime of such a fragmented CBP from the biggest remaining part [2].

According to Kariyappa et al. (2008a) [25], CBPs can be classified in weak, bright, and very strong CBPs. This classification depends on the EUV emission levels, as well as the magnetic field strengths. Class I is characterized by a strong increase of intensity that rises to a minimum of 42 times the background emission of the surrounding corona. Class II is a medium brightness enhancement of at least 13 times the background level, while Class III has an intensity increase below 7 times. Kariyappa et al. (2008a) [25] report that the oscillation period in the intensity is stable and does not depend on the brightness level. Hence the process of heating is assumed to be more or less the same in all three identified classes of CBPs [25].

The reason why it is difficult to identify all CBPs correctly:

With the increasing temperature in the corona, the number of CBPs is decreasing on the solar disk [24, 70]. The CBPs are different in number as well as distribution during solar maximum and minimum. The number seems to be higher at a minimum, and their appearance is more uniformly over the solar disk [55]. Two studies suggest that the number of CBPs show an anti-phase to the sunspot cycle [24, 38]. Their results show a reversed correlation of -0.7, which is in anti-phase to the total number of CBPs on the solar disk versus the sunspot cycle [2, 38]. This can have different causes like the visibility effect due to magnetic activity variations. Thus, during a solar maximum, with more brightness in the corona, it is more challenging to identify the CBP. The literature also mentions that the brighter the CBPs are, the more fluctuations we find in the anti-phase to the solar cycle. If CBPs are fainter, they are more in anti-phase with the solar cycle [24, 38].

Other studies from the period of 2010 to 2014 show that there was an increase in the sunspot number, while the number of flares did not show a significant change. More precisely, they are demonstrating that there is only a negative correlation of -0.2 between the CBP and the flare count [2, 38, 55]. Summing up, we find that the number of CBPs on the solar disk is mostly independent of the solar activity cycle [24, 38].

The formation of CBPs can be divided into two categories. One-third is caused by ephemeral regions (emerging magnetic flux) and two-thirds are related to the cancellation of magnetic fragments (when opposite magnetic polarities encounter and cancel each other) (see Chapter 4) [1, 20]. The understanding of CBPs is not trivial, as can be seen with their complex emergence and cancellation mechanisms. CBPs may appear near magnetic bipoles that are sometimes even not visible. Furthermore, two-thirds of magnetic bipolar regions show no corresponding CBP. Such CBPs do not emerge due to changes in the magnetic field below, but might be form reconnection with the global magnetic field above [1, 21].

Why the detection of CBPs is important and where it is applied:

In the beginning, sunspots were the most used tracer for the differential rotation because they have long lifetimes [3, 6, 22, 40]. There are disadvantages of sunspots since their appearances are quite complex as well as their number is varying during their cycle. At a solar minimum, it is hardly possible to measure any rotation profile since sunspots are rare. Another problem is their distribution, which is mainly concentrated in lower latitudes and cannot be found in higher ones. Whereas for CBPs, this is not the case due to their uniform distribution all over the solar disk at any phases of the cycle. They are located even in the higher latitudes. Although near the solar limb the measurements get inaccurate too and therefore they are ignored in that area (see Subsection 2.3.3). So, there is a limit for good results at $\pm 58^\circ$ latitude measured from the center of the Sun or about $\approx 0.85 R_\odot$ from its radius. It seems that the northern, as well as the southern hemisphere, show the same uniform results and no severe differences among each other, respectively [61]. In contrast to sunspots, CBPs are the better tracers for the differential rotation.

Identifying and tracing CBPs helps to show if the corona has a differential rotation that is similar to the photospheric level. The results show that this is the case and it applies for the entire solar magnetic cycle [26]. The size of CBPs, as well as the solar activity cycle, does not influence the sidereal angular rotation. Another interesting aspect is whether the sidereal angular rotation has effects on long- or short-living CBPs. This can be compared to sunspot data in the photosphere and reveal possible differences. According to the literature, there is no such dependence and they show nearly the same rotational velocity [3, 8, 26].

The differential rotation was measured as well from the bottom of the convective zone up to the photosphere. Below the convective zone, the differential rotation turns into a uniform one, where the rotation angular velocity is constant over all latitudes [61].

Reconnection process:

There are indications of a linear correlation between the magnetic flux density and the EUV and X-ray irradiance near the closed field lines of CBPs [45]. In Figure 1.3 we show a bipolar region with negative (N) and positive (P) flux polarities. With increasing distance δ , the polarities appear more like point sources for magnetic flux.

- (a) The solid semi-circular line in Figure 1.3 indicates the magnetic separator that divides regions of separate magnetic topology. Initially, no field lines are linked to both poles. After some time, field lines from N and P may approach and reconnect, which changes their connectivity.
- (b) After the reconnection, there is new connectivity between the polarities N and P. The remaining field lines also reconnect into a new configuration spanning over the separator.
- (c) The fluxtube is well visible as a loop-like structure after the reconnection, where the separator is located in near the fluxtube. The background field is an arrow and is labeled with B_0 [35].

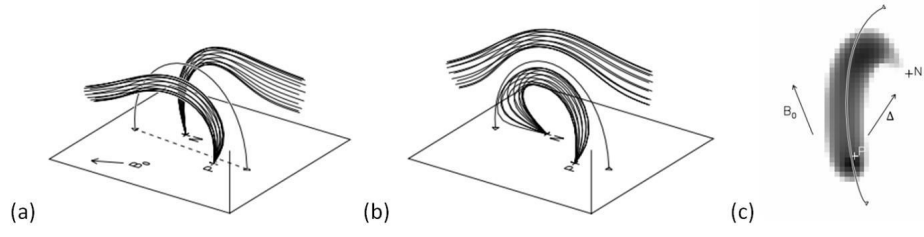


Figure 1.3: A typical reconnection process from the configuration (a) to (b) that may form a CBP (c). The distance between N and P is indicated with δ [35]. (Image taken from [35].)

This model enables a better understanding of large-scale phenomena, like flares and CMEs, as well as of small-scale CBPs, and explosive events in the transition region [34]. CBPs seem to appear preferably for horizontal background fields between 3 and 6 G. About two-thirds of the CBPs occur from reconnection like shown here, while one-third is due to emerging pre-existing fluxtubes [35].

Karachik & Pevtsov (2011) [23] determine the source regions of the fast solar wind and find that reconnection leading to CBPs is not the main process to drive the solar wind. Reconnection is a source for thermal energy and may cause expanding hot plasma regions in the corona. Therefore, CBPs can be a good indicator for coronal reconnection or may contribute to the coronal heating [24].

Figure 1.4 illustrates the comparison between the intensity of CBPs in the corona (left panel) and magnetic activity at the surface of the Sun (right panel). The blue color is for the quiet Sun, green color indicates low magnetic flux, while yellow and red color indicates higher and strong flux regions.

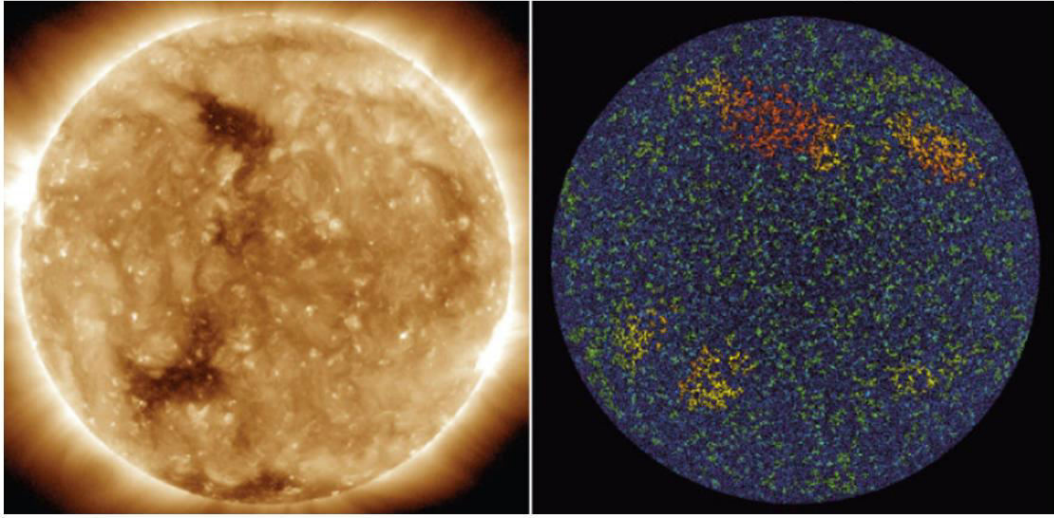


Figure 1.4: Coronal EUV emission (left panel) and magnetic field (right panel) as observed by SDO on May 15, 2010 [76]. (Image: <https://www.sciencedaily.com/releases/2014/04/140417191744.htm>)

It is presumed the existence of two types of CBPs: 1) near ephemeral regions (ER) in the environment of ARs that are mostly oriented in the East-West direction. 2) The other type is found all over the solar disk in quiet Sun (QS) areas, where CBPs are oriented in a random direction [24, 38]. In the following, we focus on CBPs in the QS.

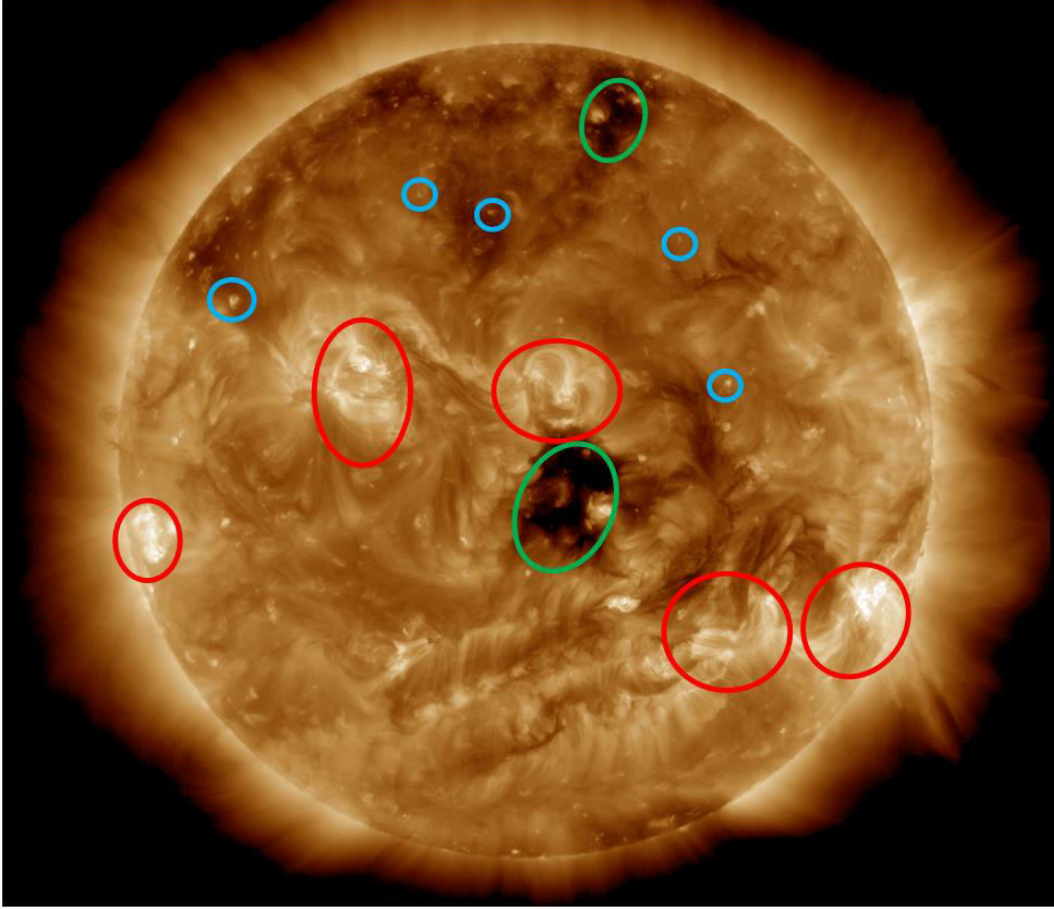


Figure 1.5: Full-disk image from the AIA channel in 193 Å at 2015-08-13 00:00:00 UTC. We mark active regions (red), coronal holes (green), and CBPs in the QS (blue) [78]. (Image: <https://helioviewer.org>)

Reconnection and the evolution of magnetic fields:

Magnetic reconnection causes a reconfiguration of magnetic fields. In the corona, the plasma is tied to the magnetic field and hence is dragged with moving field lines or may move only along the field. Downflows are caused by field lines that move towards the photosphere. Upflows occur when the reconnected field may relax and carries plasma away from the photosphere. They may reach a value of about 300 km s^{-1} . These flows exist in the whole solar atmosphere. Reconnection is likely also the reason why oscillations in light intensity occur for CBPs [34].

Observations suggest that there is a uniform movement of bright structures, which direction is outward from the innermost of a CBP. The brightness of the material diminishes while the plasma moves away from the core. Since the plasma moves freely along the field, it may flow in both directions (bi-directional flows). In the northern hemisphere, we observe northwest oriented flows and southeast flows in the southern hemisphere. The temperature is highest in the core of a CBP and may reach up to 3 MK [34].

We use the AIA 304, AIA 131, AIA 171, AIA 193 and AIA 211 channels. These wavelengths are located in the upper chromosphere, the transition region, and the corona above QS and ARs. There, we expect temperatures of about 0.1 to 1 MK . In the AIA 94 and 335 channels, CBPs are sometimes fainter or not visible at all because these channels are more sensitive for higher or lower temperatures than we find in a CBP [34].

1.3.2 Origin

Magnetic bright points (especially visible in the G-band) are small structures in the photosphere with a diameter of 300 km or less. They can be found in intergranular lanes, more precisely at the edges of granules. They are able to create groups known as bright-point networks and they are pushed by the horizontal motions of the much larger granules [64, 72].

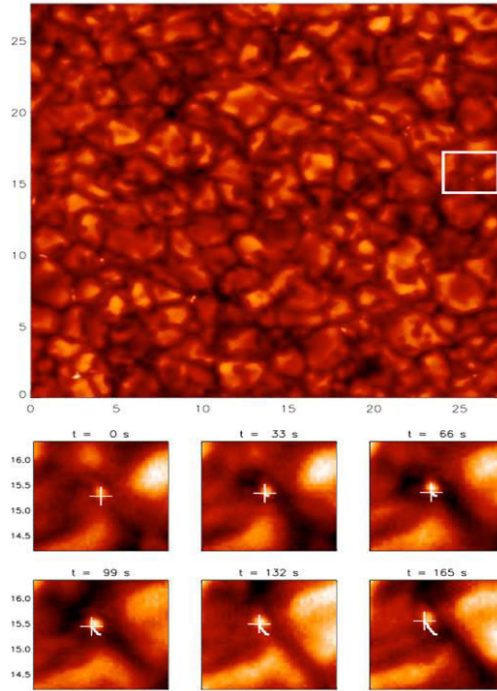


Figure 1.6: Location of a BP in a granulation pattern (uppermost panel) and BP evolution (lower panels). The BP center (white cross) moves horizontally (white line). The coordinates are given in arcsec. (Image taken from [64].)

G-band BPs are located in the photosphere and the rapid motions of their footpoints can bend the magnetic field, which results in magneto-hydrodynamical waves that travel along the magnetic field. Then, nanoflares may be triggered and short-lived reconnection events that release thermal energy. It is still unknown if BPs are created, e.g., by small-scale magneto-convection, due to the global magnetic field, or other phenomena. It is crucial to know the horizontal velocity and the lifetime distribution of BPs to evaluate their energy input to the upper atmosphere. A substantial energy input requires a mean BP lifetime of about 2.5 minutes with a horizontal velocity of $1\text{--}2 \text{ km s}^{-1}$ [64].

90% of the so-called brightness centers of CBPs are located at supergranular cell boundaries, which we hence call “network CBPs” (NCBPs). The emergence of 40% of the NCBPs occur at junctions of this supergranular cell network. The occurrence of the remaining 10% of the CBPs takes place inside of a supergranule and are called “internetwork CBPs” (INCBPs). For both, NCBPs and INCBPs, the horizontal velocity is similar and amounts to $1.6\text{--}1.7 \text{ km s}^{-1}$ [72].

Gošić et al. (2014) [17] show that 54% of all observed INCBPs show magnetic cancellation at the footpoints, while 32% are due to flux emergence. The remaining 14% undergo complex flux changes. In comparison, the majority of NCBPs (60%) show cancellation, whereas 20% show emergence, as well as 20% complex fields [72]. Inside a supergranular cell, about 38% of the magnetic patches eventually propagate towards the cell boundary [17, 72]. The average distance between QS CBPs is similar to the size of supergranules [38, 72] and the CBP horizontal motion is rather random.

1.3.3 Coronal heating problem

Currently, it is not clear why there is such a significant temperature difference of more than one million K between the corona and the photosphere. The photosphere with about $6,000\ K$ is much cooler than the corona with above 1 million K (see Figure 1.2). This high-temperature difference produces strong heat conduction from the corona back to the surface of the Sun. Furthermore, the coronal plasma also radiates energy away through EUV and X-ray emission, which is an additional energy sink in the corona. Since this energy loss of the corona needs to be replenished, there must be an equally strong heating mechanism in the corona. The required energy input to the corona is about $0.1\text{--}1$ kilowatt per square meter. This is only a small fraction of about 2.5×10^{-5} times the solar energy output in the photosphere. Therefore, one cannot solve the coronal heating problem by explaining how energy is transported to the corona, one need to explain also how and why the right amount of energy is dissipated within the corona [86]. Multiple processes have been suggested for trying to solve the coronal heating problem, further detail may be found in Klimchuk (2006) [28].

The recent starts of the NASA mission Parker Solar Probe, as well as ESA's SolarOrbiter, target to these scientific questions [86].

Chapter 2

Methods

2.1 Solar Dynamics Observatory

The launch of the SDO (Solar Dynamics Observatory) was on 11th February 2010 with two imaging instruments onboard, the AIA (Atmospheric Imaging Assembly) and the HMI (Helioseismic and Magnetic Imager) [79]. For the SDO probe several maneuvers were required to reach its intended orbit, which was about 35,800 kilometers high and inclined at 28.5° in a circular geosynchronous orbit to the ground station in New Mexico [84].

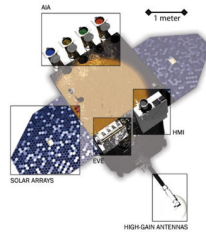


Figure 2.1: SDO is a stabilized probe on 3-axis, which includes three instruments (AIA, HMI and EVE), two solar arrays, and two antennas with high precision. SDO sends data at a maximum downlink rate of 150 Mbps [44,82,84]. (Image taken from [44].)

Tasks / Goals for SDO:

The goals of SDO are the better understanding and prediction of the solar cycle as well as the Sun's activities and variations. This includes small-scale features like CBPs and larger structures like flares and CMEs, which influence Earth's technology and life, the so-called space weather. EUV photons can interrupt communication and navigation technology on Earth through forming a layer of ions by cracking bonds of atoms and molecules in the atmosphere. For these reasons high-resolution images for the observations at the topology of magnetic fields, its formation and evolution are essential. Therefore, SDO measures the inner motions of the Sun to understand how the magnetic field is formed, as well as its upward travelling to the photosphere and how it behaves in the corona in many wavelengths simultaneously. In other words, one seeks to understand how the energy is stored and then released into the corona. Other specific goals are the prediction of more precise temporal and local emergence of active regions and how the solar features are related to the magnetic field. To put this project into action, SDO has to send about 150,000 full solar Sun disk images with high-resolution, as well as 9,000 EUV spectra. These are 1.5 terabytes of data every day or altogether 3-4 petabytes during the planned mission time of 5 years. The transformation of the raw data is able into images, spectra, dopplergrams and magnetograms. Therefore, the mission has been extended for another five years. Thus, a database for long-term studies is created to study the solar features. In addition to that, the SDO data can be added to other spacecraft data (TIMED, TRACE, Hinode and SOHO) and therefore the 22-year solar cycle can be studied [31, 44, 84].

Atmospheric Imaging Assembly (AIA):

The construction of the AIA instrument includes four Cassegrain telescopes. Each of them has a primary mirror of 20 cm and a second one which is active. Their purpose is to observe the chromosphere and the corona and their solar emissions in full-disk with a field of view of 41×41 arcmin at seven extreme ultraviolet (EUV) channels with temperature ranging from 6,000 K to more than 2×10^7 K. The time cadence is 12 seconds with a high resolution of 4096 by 4096 pixel at 0.6 arcsec per pixel.

For isolating specific spectral band passes and provide narrow-band imaging for all four telescopes, AIA has a combination of coatings with multiple layers and foil filters. There are narrow-bands for 10 different wavelengths, whereby seven are found in the extreme ultraviolet (EUV) band at 94 Å, 131 Å, 171 Å, 193 Å, 211 Å, 304 Å and 335 Å. Two of them are found in the ultraviolet band at 1600 Å and 1700 Å and one in the visible light band at 4500 Å. Thereby, the demonstration of the most important features of the solar disk is observable. These EUV channels (except 304 Å) are observing ionized iron (see Table 2.1) and are able to create temperature maps with a full thermal range from 1 MK to 20 MK in the corona. To get the best resolution for observation, all AIA telescopes have apertures with entrance filters. These filters prevent the permeability of visible and infrared wavelengths.

AIA focuses on the entire solar corona, which includes its full thermal range. It also enables a high signal-to-noise ratio for exposure times of 2–3 seconds. In general, AIA tries to observe without any interruptions with a cadence of about 12 seconds for studying energetic transient features. Each of the four telescopes is divided into two sections, where each of them observes in one wavelength channel.

The raw data (called “Level 0 data”) amounts to about 2 terabytes per day (see Subsection 2.3.4). In addition to that, the data of AIA and HMI Level 0 is processed by means of data pipeline systems. Consequently, these Level 0 data are converted into Level 1 and 1.5 for scientific use.

For Level 1 data processing, the dark current is considered due to the CCD read noise. Actually, the dark current of the CCD cameras is insignificant if the exposure time is just a few seconds and their temperature is -65°C or even lower. Furthermore, the AIA images are corrected by a flat-field. After that, two algorithms ensure that single pixels are corrected. The first one finds and corrects “bad” pixels, which properly show hardly any reaction towards the light, but they make up only a small part of 0.1%. By using interpolation of the values from the pixels next to them, they can be compensate. The second one tries to find and replace the “spikes” by means of the median value of the pixels next to them. Spikes are appearing when energetic particles interact and produce high-energy photons, whereby the CCD cameras are able to detect them. Then the position of the AIA images has to be changed. At the top, the solar north of the array is situated, whereby the roll angle is crucial. To produce Level 1, it is important to know that almost all these data depends on the time, e.g. pointing information, camera gain ($e^- \text{ DN}^{-1}$), “bad” pixels, flat field.

For Level 1.5 data processing a plate scale, roll and telescope coalignment modification is required, which allows implementing AIA to display movies. Therefore, the preparation begins with Level 1 data, where the position of the pictures is changed so that solar North is at 0° . The orientation of the four telescopes is made before starting since a correction in orbit is not possible. However, between these telescopes, there is a small residual roll angle, which is removed using the star tracker signal. So, the probe can change position to the solar North of 0° . At the next correction, the plate scale has to be corrected to reach the 0.6 arcsec per pixel. It is the reason due to not identical focal lengths of each telescope and they have small deviations. The bore-sight pointing is defined with 20 arcsec before launch. HMI magnetograms are also available at Level 1.5, exactly like AIA data. Therefore, these HMI data require the same resolution as AIA. So, they are rescaled down to match the AIA scale of 0.6 arcsec. Thus, they agree with the roll and alignment of AIA. Thereby the HMI resolution is minimal reduced [31, 44, 84].

Helioseismic and Magnetic Imager (HMI):

The HMI instrument is a filtergraph and consists of several filters. The equipment includes, e.g. a filter for front-window, a system for the stabilization of images, a five-stage Lyot filter, an instrument for polarimetry, two Michelson interferometers and cameras with high resolution.

HMI studies the inner of the Sun with its process and origin of variability and connection between magnetic activity and solar surface. Especially, several components have to be observed to comprehend these effects and the possible cause of solar dynamo. Therefore, HMI determines also motions and polarization to analyse oscillations and the composition of magnetic fields in the photosphere. There are several fields, in which the HMI is in use, e.g. mapping and probing the solar convection zone, where a possible magnetic dynamo produces its energy. It is also known as helioseismology, where measurements of solar oscillations are affected. This is useful to examine the inner structure of the Sun and the interaction of its rotation, its magnetism and its turbulent convection zone. At its base, there is a region with rotational shear. Based on convective flows, it is called tachocline and possibly responsible for the dynamo. These flows cause twists in the fluxtubes and result in shifting footpoints of magnetic structures in the photosphere, which are also found in the corona. These configurations are not stable, and eruptions occur, which influence the Earth's atmosphere. It has a massive impact on the evolution of magnetic fields. Hence, it includes the generating process at the base of the convective zone and their emergence at the surface. In other words, the present magnetic fields at the surface are newly distributed again.

There are the two mechanisms which might cause stressed magnetic fields, the shear motions and the already emerged shear stressed ones. It is still unknown which one is the more dominant and how the process of supplying the energy is connected with the eruptions. Therefore, HMI enables dynamical and magnetical observations within the shear layer called tachocline. Detailed observation of full-disk images is possible with high-resolution, combined with steady recording process, and hence allows sensitive measurements of variations. Other relevant fields are the measurements of the magnetic field in the photosphere and their brightness to perceive the link between magnetic and convective behavior as well as the resulting variations of irradiance. In addition to that, it will supply information about the spatial magnetic and convective distribution connected to the variable irradiance as well as the variations of shape and radius of the Sun.

Through Vector magnetic-field analysis, the topology and vertical electric current can be measured. These measurements are crucial for better knowledge of how flares develop. Therefore, observations are needed for tracking magnetic changes in the field as well as in the electric current. HMI needs an adequate spatial resolution for tracking to see all changes, especially the time before and after flares. For producing these measurements with full-disk, it is essential that HMI is equipped with high cadence and accuracy. The magnetic field's variation is connected with all solar features, e.g. solar wind, coronal holes, CMEs and flares. Since these features are originating from the inner of the Sun and get through the atmosphere, it is very important to examine the correlation between them. They are caused by variability, which drives global change.

HMI observes the full disk with the longitudinal and vector magnetic field and measures the Doppler-shift in the photosphere for the Fe I line at 6173 Å. The Zeeman Effect is essential to measure Stokes parameters in the Fe I line. Hence, the line-of-sight magnetic field or also called LOS magnetogram, as well as the vector magnetogram, are possible to determine in full-disk.

95% of the dopplergrams could be restored where 99% of them are complete. The HMI's cadence for LOS magnetograms is every 45 seconds. It has a resolution of 4096 by 4096 pixel at 0.505 arcsec, and the noise level prevails of about 25 m s^{-1} and 17 G . However, the time steps of vector magnetograms are every 12 minutes and their measurement of polarization has only a deviation of about 0.3%. So, HMI might be able to reveal magnetic processes within the surface of the Sun.

In this way, magnetograms with these settings will contribute better insights to several models for coronal magnetic fields and solar wind forecasting as well as for comparable studies.

Summing up, it can be said, that every 3.75 seconds a full disk image is created which results in a 45-second cadence when measuring intensity, Doppler and magnetic field. Consequently, for vector magnetic field measuring the cadence is every 90 or 135 seconds.

The difference between HMI and AIA cameras is illumination. The HMI cameras are lighted up at the front-side while the AIA cameras are lighted up at the backside. The detectors are able to recognize 200,000 electrons. Their dark current is negligible (see AIA) due to their temperature of less than -50°C . It is cooled indirectly by radiators on the top of the CCDs [44, 54, 56, 84].

AIA & HMI:

In Figure 2.2, the observing area covers all from the solar surface to the Sun's corona, where each wavelength underlines another part of the atmosphere [2]. In the chromosphere and transition region, AIA 131 and AIA 304 can be found. For the quiet corona, AIA 171 is observable. The active parts of the corona are better recognizable in the AIA 193, AIA 211 and AIA 335 channels, whereas for the flaring corona AIA 94, AIA 131 and AIA 193 are the best observing wavelengths. For this thesis, we do not use the AIA 1600 and AIA 1700 wavelengths due to they are not suitable. The reason is the hardly notable radiation at the photosphere and lower chromosphere and their shallow temperature of only 10^4 K . As a result, the radiation in the ultraviolet bands is too weak. Summing up, it can be said that all CBPs consist of multiple structures of temperatures [34].

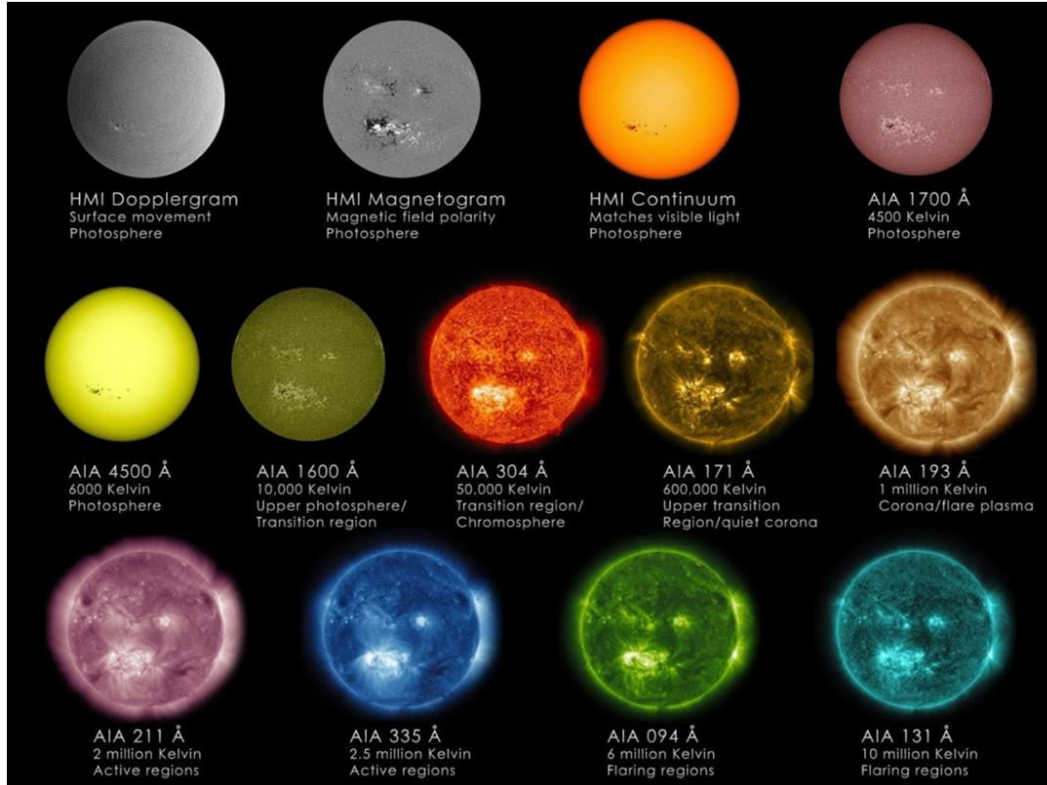


Figure 2.2: These instruments (AIA and HMI) make it possible to see images of the Sun in 13 different wavelengths in ultra-high-definition with their characteristic emission temperatures [79]. (Image taken from [79].)

AIA has four multilayer telescopes taking frames at six channels that are concentrated on certain iron, which are shown in Table 2.1. These lines include Fe VIII for 131 Å, Fe XI for 171 Å, Fe XII for 193 Å, Fe XIV for 211 Å, Fe XVI for 335 Å and Fe XVIII for 94 Å and He II for 304 Å. Additionally, two channels have hotter lines too, which are related to flares, namely 131 Å and 193 Å. The temperature seen in Table 2.1 is logarithmic and ranges from about 0.4 to 20 MK [55]. Table 2.1 also shows a list of each bandpass with their primary ions and each wavelength has one or two of them.

Table 2.1: List of different bright point temperature with its respective primary ion

Wavelength	Temperature $\log(T)$	Primary Ion
304 Å	4.7 MK	He II
131 Å	5.6 MK (7.0 MK)	Fe VIII, (XXI)
171 Å	5.8 MK	Fe IX
193 Å	6.1 MK (7.3 MK)	Fe XII, (XXIV)
211 Å	6.3 MK	Fe XIV
335 Å	6.4 MK	Fe XVI
94 Å	6.8 MK	Fe XVIII

Figure 2.3 shows the resolution of different instruments, where the image resolution of STEREO is just half and SOHO even just a quarter of the AIA ones indeed. Likewise, the cadence of AIA is much higher with one image every few seconds whereas at STEREO there is one image every 3 minutes and even every 12 minutes at SOHO. The big difference is clearly seen in Figure 2.3 [81].

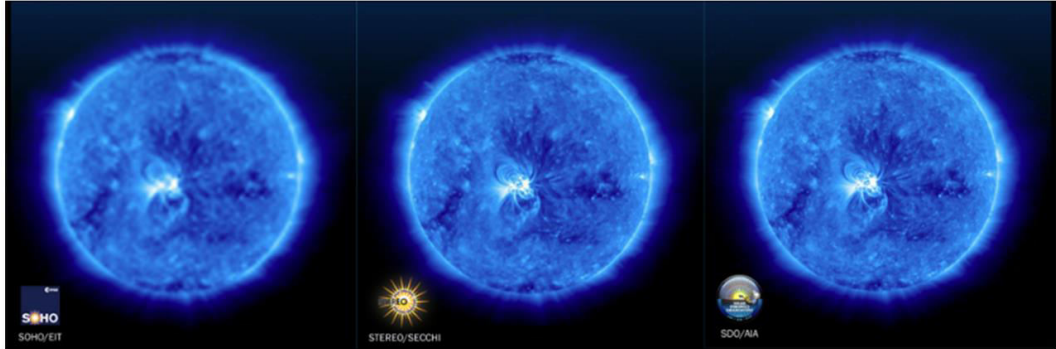


Figure 2.3: Comparison of different spacecraft resolution with SOHO (left), STEREO (middle) and SDO/AIA (right) [81]. (Image taken from [81].)

TRACE is 10 times slower imaging the Sun in full-disk than AIA. AIA is equipped with 2 times more coronal channels than TRACE and SOHO/EIT, respectively. Besides, AIA images the whole solar disk instead of just a small cutout. TRACE, as well as SOHO/EIT has even 16 times less pixels in its images than each of the AIA telescope. Compared to TRACE, AIA has an adequate cadence that is 10 times higher. In comparison with EIT onboard of SOHO, AIA is about 700 times faster. This results in an improvement factor of 400 to 22,000 concerning information rate. In other words, AIA processes much more data. As a comparison, AIA processes in three days the same amount that TRACE has in its whole mission of 12 years. Also, the cadence of SOHO's MDI magnetograms is one magnitude slower than the HMI onboard of SDO. XRT onboard of Hinode and EUVI onboard of SECCHI have CCD cameras with 2000 by 2000 pixels at 1 and 1.6 arcsec, respectively, whereas AIA provides 4096 by 4096 pixels at 0.6 arcsec [31].

Extreme Ultraviolet Variability Experiment (EVE):

The EVE instrument is a spectrograph and has a EUV Spectrophotometer (ESP), which is equipped with a quadrant photodiode. It is able to work in real-time and flares can be easily detected on the Sun. EVE measures EUV wavelengths and their fluctuations. In particular, these are measurements in the most variable part of the solar spectrum, which lies between 10 Å and 1050 Å and 1216 Å, respectively. For this purpose, EVE's cadence is 10 seconds. It consists of two Multiple EUV Grating Spectrographs. The MEGS-A measures EUV wavelengths from 50 to 370 Å with a resolution of 10 Å. The other MEGS-B measures EUV from 350 Å to 1050 Å with the same resolution. So, EVE's measurements are in the range of extreme ultraviolet (EUV) and soft X-ray (XUV). The CCDs of EVE are lighted up at the backside, the same as the AIA ones. Their resolution is 1024 by 2048 pixels, and their noise level is low due to the cooling down to about -70 °C. Through the grid design and different angle of incidence, the spectrograph achieves much higher sensitivity. One of the goals is the improvement of understanding how the connection between EUV variations and magnetic variations works. The radiation is not identical stable all over the solar cycle of 11 years. These changes have effects on heating the Earth's atmosphere and communication systems such as GPS (Global Positioning System). Such accuracy and temporal resolution in terms of spectral irradiance is unique and currently only measurable by EVE. The wavelengths of AIA and EVE are comparable due to their overlapping. [44, 70, 84].

Temperature response:

Figure 2.4 shows the comparison of temperature response between all instruments with each other. The temperature response of the instruments is quite similar and underlines the 171 Å passband's stability. This means that the appropriate function of temperature response remains stable within the ~ 10 Å wide band despite the changes with temperature. Within that width, it is possible to find more than one spectral line. However, due to different heights in the corona, there are significant changes in their temperature and density towards their contribution to the spectrum. So, this results in different spectra. It can also be seen in Figure 2.4 that TRACE has the lowest response and AIA the highest because of the iron-illuminated CCD detector's low efficiency. Another difference is the response shape of AIA, which is different from the others too. This is caused by the large aperture size of AIA, and it has a more developed technology than the others (see in AIA & HMI above) [49, 50].

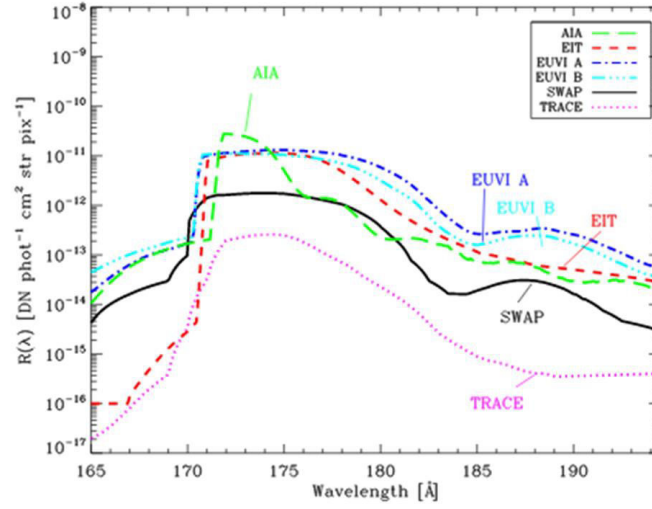


Figure 2.4: The temperature response of wavelengths from different spacecraft is compared with each other. These spacecraft are SDO/AIA (green), SOHO/EIT (red), STEREO/EUVI A (blue), STEREO/EUVI B (pale blue), Proba-2/SWAP (black) and TRACE (purple). $R(\lambda)$ specifies the sensitivity of the instrument's emission at a specific wavelength and is given in units of $\text{DN phot}^{-1} \text{cm}^{-2} \text{str pix}^{-1}$. The sensitivity is conditional of a combination of instrumental parameters like resolution and aperture size [49, 50]. (Image taken from [50]).

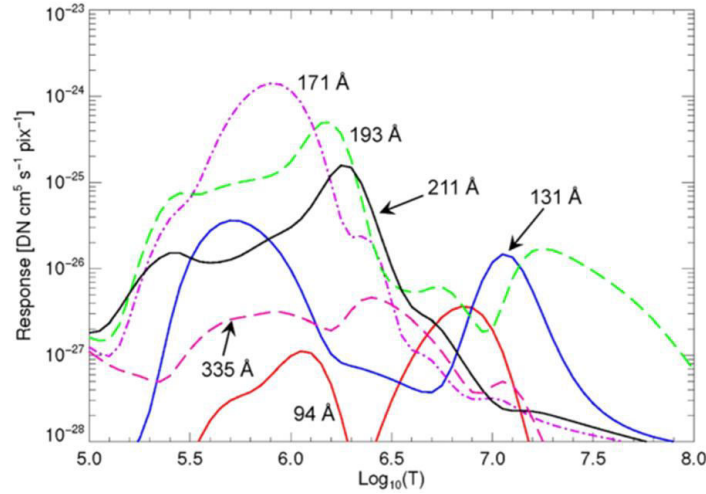


Figure 2.5: The six EUV channels of AIA's temperature response function, which are dominated by iron, namely 94 Å (red), 131 Å (blue), 171 Å (purple), 193 Å (green), 211 Å (black) and 335 Å (pink). These emission lines are computing from the effective-area functions. Therefore, the responses of solar emissions are calculated by a CHIANTI model. It is considered that the correction factor is applied to the helium dominated 304 Å intensities 20 times. For this reason, the He-II line at 304 Å is not useful for DEM analysis due to it is not very representative [5, 31]. (Image taken from [31].)

If the sensitivity of an instrument's emission at a certain temperature has to be determined, the multiplication of this wavelength response function (as mentioned in Figure 2.4) with an appropriate solar spectrum is required (see Chapter 5) [49, 50].

2.2 Algorithm diagram

We show an overview of the main programming languages IDL and Python. These routines are used on Linux, which we show in Figure 2.6 and describe in detail in Section 2.3.

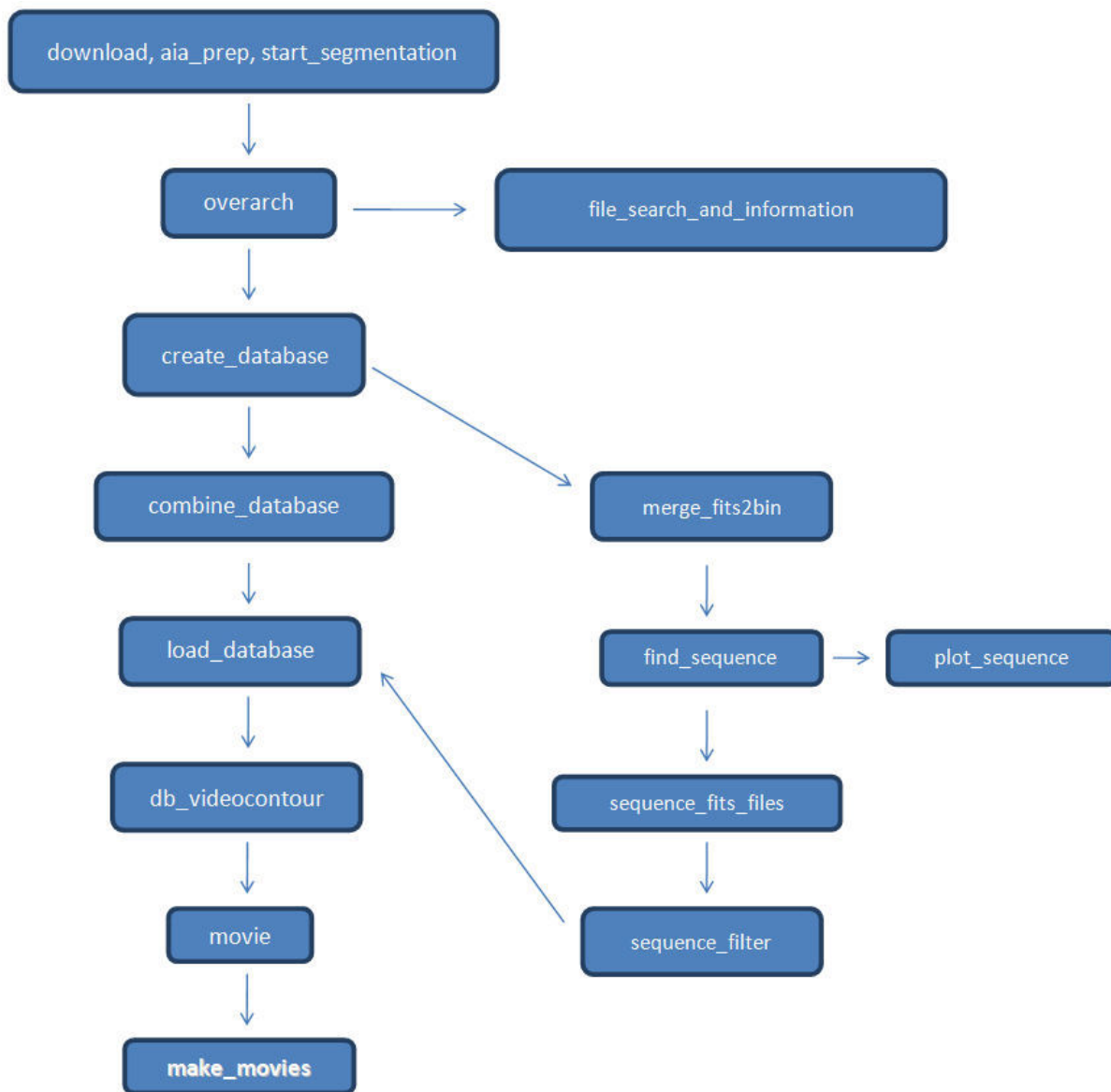


Figure 2.6: Flowchart of IDL routines (left) and Python routines (right), see detailed description in the Appendix A.1 and A.2.

2.3 Data Reduction and Algorithm Processes

2.3.1 SolarSeg Software Pipeline

The beginning of SolarSeg was made by J. Zender in 2013 with the help of G. Giono's internship work in 2012. M. Bergmann continued this work in 2015. He changed and improved some existing pipeline procedures and created the HMI segmentation algorithm of detecting the CBPs. He mapped it onto HMI magnetograms and AIA 171 images as well as BP segmentation. This algorithm recognizes whether a potential CBP candidate is a CBP or has to be sorted out. A. Otto created a database of 10 days in 2016.

The SolarSeg is analyzing data taken by PROBA2 and SDO from May 2010 to the current day. It tries to investigate the responsible reason of the solar irradiance variability and how significant the influence is on the different features of the Sun such as AR, BP, CH, QS as well as the interaction of different layers. The goal of this pipeline is to find out if these interactions change with time and what causes flares or CMEs for better understanding of solar wind and space weather. The programming language for SolarSeg is an analyzing and visualizing data software called IDL, which is based on a vector oriented in multidimensional arrays. SolarSoft is essential for solar physical work on IDL due to useful libraries and routines. Using the SPoCA software suite for creating maps based on the SDO instrument's channels AIA 171 and AIA 193, they applied onto HMI magnetograms. These maps include coronal holes and active regions as well as the quiet Sun [4].

2.3.2 Preparation of the data

The downloading data are fits files from the spacecraft SDO (Solar Dynamics Observatory) with its instruments AIA (Atmospheric Imaging Assembly) and HMI (Helioseismic and Magnetic Imager). We select channels for this work, which are the following wavelengths, namely 94 Å, 131 Å, 171 Å, 193 Å, 211 Å, 304 Å and 335 Å, as well as the magnetograms of HMI. Concerning, 171 Å plays an essential role in segmentation due to the best temperature response (see Section 2.1 temperature response). The downloaded images have a resolution of $4k \times 4k$, and the cadence of SDO usually is 12 seconds. Although there is significant amount of disk space, 60 seconds are enough to get good results too and the chance of gapless available data is higher (see Subsection 2.3.4). Nevertheless, we used Level 1 of downloaded data files, which means that only data reduction of flat-fielding, get rid of spiking as well as reducing of dark current is implemented. Further transformation is necessary, e.g., focusing on the center of the Sun. This means that all the images have the same coordinates and show the same location on the Sun. Another one is normalizing the images to DN/pixel to prepare the images to Level 1.5. After that, we compressed the Level 1.5 images to .fits.gz to save disk space. The following procedures of IDL codes are needed for a run-through, namely "download", "bpt_aia_prep" and "bpt_compress_fits" (more details in the Appendix A) [4].

2.3.3 Mapping of bright points

For segmentation, we used the HMI magnetograms, which contain the measured magnetic flux densities. These magnetic flux densities are separated by the direction in a positive and a negative one. Every value below 20 is set to zero after neutralization of the background. After that, there are two algorithms created for finding high magnetic flux density like sunspots and finding small magnetic flux density like CBPs.

The flux measurement takes place at 6173 Å, and every pixel can be calculated to obtain the magnetic flux density by means of the Zeeman-effect.

Further, we used images of 193 Å channel, due to their remarkable clear appearance in contrary to other wavelengths. This helps with the assistance of two algorithms, one for identifying significant high-intensity regions such as active regions to exclude them from the segmentation map and the other for searching small dots with high intensity, namely CBPs.

After that, a CBP's shape and diameter are measured and sorted out by these criteria, whether it is a CBP or not. In detail, all CBPs smaller than 200 pixels and bigger than 15,000 pixels are not identified as CBPs and will be deleted. The remaining CBPs are compared to an ellipsis where the ratio between the axes is 2.5, whereby the major axis is not exceeding 200 pixels. These remaining CBPs are considered as the real CBPs now, and the others were removed (see Subsection 1.3.1). The following procedures of IDL codes are needed for a run-through, namely “make_segmented_bp”, “segment_aia” and “make_bp_map”, which all make it possible to input the AIA 193 original and its header. For characterization, a CBP's value is 200, whereas the excluded regions like active regions have a value of 100. After that, the resulting images show an image with CBP and active area regions.

The next step utilizes the fits header. The pixel of the center of the solar disk is found as well as the radius in pixel. A mask is generated to avoid distorted or deformed CBP results from solar limb, so all CBPs outside of the 95% radii are excluded [4]. All these steps are visualized in Figure 2.7.

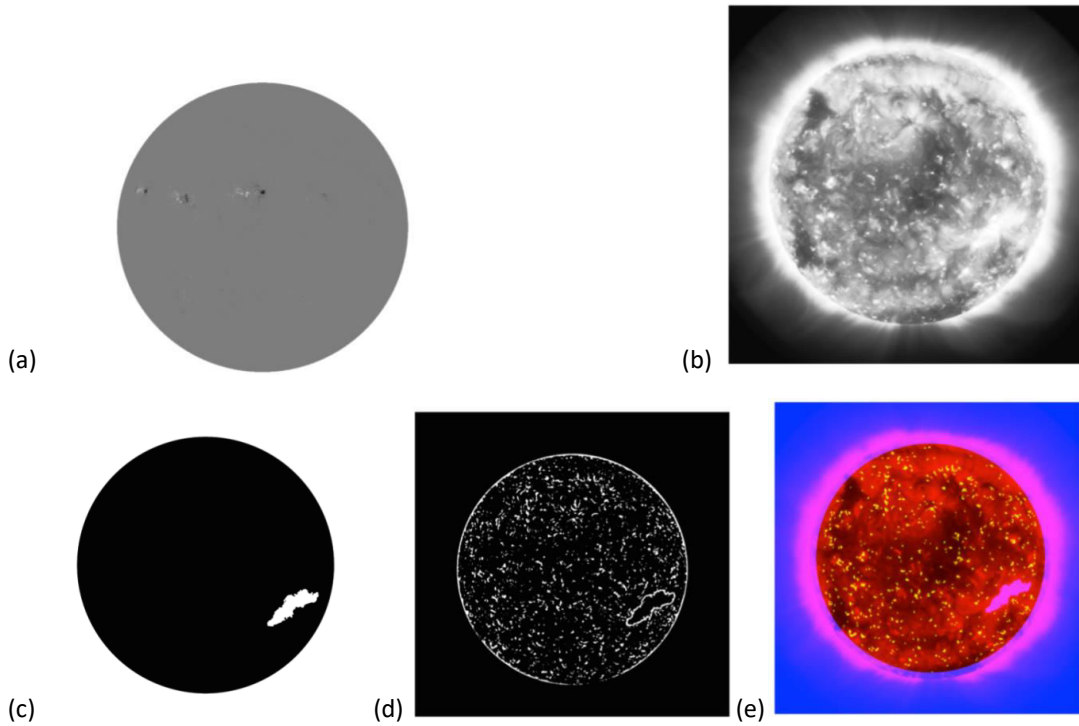


Figure 2.7: a) This is an example of hmi.M_720s.20110730_000000_TAI.fits [4]. The map is showing the surface of the Sun with its magnetic field. The black dots show the magnetic field lines, which move away from the observer (negative polarity), whereas the white dots show the magnetic field lines move towards the observer (positive polarity) [80]. (Image taken from [4].)

b) This is an example of AIA 193 AIA20100513_000000_0193.fits.gz for easier CBPs searching [4]. (Image taken from [4].)

c) This is an example for visualizing active region, which has excluded area marked in white [4]. (Image taken from [4].)

d) Mask of potential CBPs in white and excluded area in black [4]. (Image taken from [4].)

e) Finished map after sorting out by size and diameter. So, real CBPs are left in yellow, the excluded area is blue and pink and the original AIA 193 image in the background for comparison is red [4]. (Image taken from [4].)

Finally, the finished maps are available for the algorithm segmentation of CBPs called “bpt_start_segmentation” in IDL to simplify the CBP detection (more details in the Appendix A). For a better visualization than the original images, the solar background gets black (value 0), the active regions, as well as the area outside of the solar disk, get grey (value 100) and CBPs get white (value 200) as shown in Figure 2.8 [42].

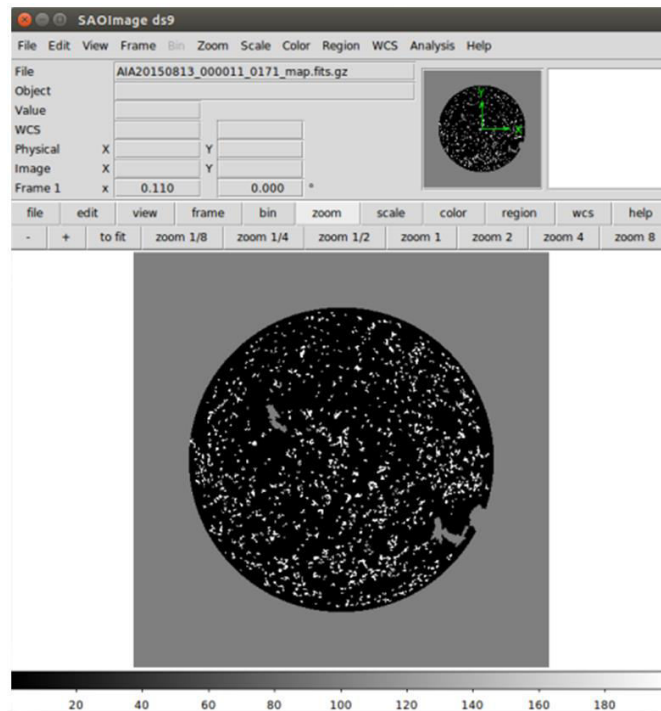


Figure 2.8: This is an example of AIA20150813_000011_0171.maps.fits.gz for simplifying CBP detection with the background (black), the active regions and everything outside the solar disk (grey) and CBPs (white), which is visualized with the program SAOImage DS9.

We combine the IDL routine “bpt_overarch” with the download, preparation and segmentation for receiving faster results (more details in the Appendix A).

The procedure “bpt_file_search_and_informationlvl15andmaps” in Python we create is looking after every image that is found, downloaded, prepared and segmented. In other words, it is easier to get an overview of how many and whether the data is correct or not. We describe this Python routine in Figure 2.9 (more details in the Appendix A).

```

/home/ikraus/Environments/Isabella/bin/python /home/ikraus/Untitled Folder/bpt_file_search_and_informationlvl15andmaps.py

```

Date	AIA94_lvl15	AIA131_lvl15	AIA171_lvl15	AIA171_maps	AIA193_lvl15	AIA211_lvl15	AIA304_lvl15	AIA335_lvl15	HMI_lvl15
20150813	1440	1440	1440	1440	1440	1440	1440	1440	1440
20150814	1440	1440	1440	1440	1440	1440	1440	1440	1440
20150815	1440	1440	1440	1440	1440	1440	1440	1440	1440
20150816	1440	1440	1440	1440	1440	1440	1440	1440	1440
20150817	1440	1440	1440	1440	1440	1440	1440	1440	1440
20150818	1440	1440	1440	1440	1440	1440	1440	1440	1440
20150819	1440	1440	1440	1440	1440	1440	1440	1440	1440
20150820	1440	1440	1440	1440	1440	1440	1440	1440	1440
20150821	1440	1440	1440	1440	1440	1440	1440	1440	1440
20150822	1440	1440	1440	1440	1440	1440	1440	1440	1440
20150823	1440	1440	1440	1440	1440	1440	1440	1441	1440
20150824	1440	1440	1440	1440	1440	1440	1440	1441	1440

Process finished with exit code 0

Figure 2.9: The resulting algorithm for proving if there are all Level 1.5 fits files without any gaps and missing files. So, there is one image every minute, which results in 1440 images per day (more details in the Appendix A).

2.3.4 Database

The range of the database is from 13th August 2015 till 24th August 2015, so we could use A. Otto's database from 15th August 2015 till 24th August 2015 and add two additional wavelengths, 211 Å and 335 Å. Then we expand it for two more days.

Details:

Period: 12 days (2015-08-13 – 2015-08-24)

Resolution: 4096×4096 pixel (0.6"/pixel)

Wavelengths: 94 Å, 131 Å, 171 Å, 193 Å, 211 Å, 304 Å, 335 Å and HMI

Frames: 1 frame/min $\rightarrow$ 1,440 frames/day $\rightarrow$ 17,280 frames for 12 days

Downloads for 1 frame:

$\rightarrow$ 11.4 MB (download)

$\rightarrow$ 134.2 MB (prepared uncompressed)

$\rightarrow$ 29.4 MB (prepared compressed)

$\rightarrow$ 16.8 MB/147 KB (segmentation uncompressed/compressed)

Downloads for 1 day (1,440 frames):

$\rightarrow$ 341.6 GB

Downloads for 12 days (17,280 frames):

$\rightarrow$ **4.01 TB**

Duration for 1 day database:

Download: 8h (20s/frame)

Preparation: 6h (15s/frame)

Compression: 4h (10s/frame)

Segmentation: 96h (240s/frame)

create 1 day $\rightarrow$ 20h (414,7 MB)

By combining databases $\rightarrow$ **5 GB** (.sav file)

General information:

AIA and HMI data contain images, full-disk maps and spectra. They are provided by the Joint-SOC (JSOC) at Stanford University in FITS formatted files ¹.

AIA data are available as Level 1.5 images as well as Level 1.0 data images wherein they have to be edited with routines in IDL through SolarSoft package ². Nearly the same also applies for HMI maps like dopplergrams and magnetograms, but they are only available as Level 1.5 images [44].

¹<http://jsoc.stanford.edu/ajax/lookdata.html>

²<http://www.lmsal.com/solarsoft/>

In Figure 2.10 we show the header of the database and in Figure 2.11 one table for one database day as examples.

```

File Edit Tools Help

Search for: [ ] Find Case sensitive? No

SIMPLE = T / Written by IDL: Wed Sep 21 00:51:10 2016
BITPIX = -64 / IEEE double precision floating point
NAXIS = 2 / Number of data axes
NAXIS1 = 36 / Number of positions along axis 1
NAXIS2 = 1384947 / Number of positions along axis 2
EXTEND = T / FITS data may contain extensions
DATE = '2016-09-20' / Creation UTC (YYYY-MM-DD) date of FITS header
COMMENT FITS (Flexible Image Transport System) format is defined in 'Astronomy
COMMENT and Astrophysics', volume 376, page 359; bibcode 2001A&A...376..359H
COMMENT A. Otto - 24.5.2016 & I. Kraus - 19.9.2016
XTENSION= 'BINTABLE' /
TFIELDS = 36 /
TTYPE1 = 'image_number' /
TFORM1 = 'I' /
TTYPE2 = 'bp_number' /
TFORM2 = 'I' /
TTYPE3 = 'xcen' /
TFORM3 = 'I' /
TTYPE4 = 'ycen' /
TFORM4 = 'I' /
TTYPE5 = 'latitude' /
TFORM5 = 'I' /
TTYPE6 = 'longitude' /
TFORM6 = 'I' /
TTYPE7 = 'box_center_x' /
TFORM7 = 'I' /
TTYPE8 = 'box_center_y' /
TFORM8 = 'I' /
TTYPE9 = 'box_width' /
TFORM9 = 'I' /
TTYPE10 = 'box_height' /
TFORM10 = 'I' /
TTYPE11 = 'distance_active_region' /
TFORM11 = 'I' /
TTYPE12 = 'aia94_maximum' /
TFORM12 = 'I' /
TTYPE13 = 'aia94_total' /
TFORM13 = 'I' /

```

Figure 2.10: A cutout of an example of its header for one day from the database.

	1	2	3	4	5	6
1384947	1.4390000000E+03	9.6300000000E+02	3.4867053223E+03	2.0362407227E+03	2.2861239910E+00	2.6916656494E+01
1384946	1.4390000000E+03	9.6200000000E+02	3.4857919922E+03	1.9879472656E+03	5.4175817966E-01	2.6740345001E+01
1384945	1.4390000000E+03	9.6100000000E+02	3.4586884766E+03	2.1829555664E+03	7.7897157669E+00	2.5533454895E+01
1384944	1.4390000000E+03	9.6000000000E+02	3.4524357910E+03	2.2537446289E+03	1.0354613304E+01	2.5860509872E+01
1384943	1.4390000000E+03	9.5900000000E+02	3.4233413086E+03	2.0900000000E+03	4.7448902130E+00	2.2067981720E+01

Figure 2.11: This is a cutout of an example of a table for one day from the database.

Bold black column: entries, 1. column: image number, 2. column: bp number, 3. column: xcen, 4. column: ycen, 5. column: latitude, 6. column: longitude, etc. (see fitsheader in Figure 2.10)

So, for each image number, we find about 900 to slightly more than 1,000 CBPs. There exist more than 1.3 million entries for one day, i.e. for 12 days, there are 16,938,990 entries.

According to the literature, a study in 2015 from Alipour et al. suggested that there are located on average about 572 CBPs at any given time with a density of about $1.9 \times 10^4 \text{ Mm}^{-2}$ on the solar disk. Both values were detected using the 193 Å wavelength (see Section 2.1 temperature response) [2].

Problems to expand database:

First, our goal was to expand the database from 1st August 2015 to 16th September 2015 to get a more extensive period of tracking CBPs. Unfortunately, not all dates were available due to a lot of gaps (more than 100 frames were missing or not usable).

Two reasons were responsible for that:

1) The first reason was an Earth eclipse from 25th August 2015 to 9th September 2015 due to the circular geosynchronous orbit of SDO around Earth (see SDO JSOC Calendar ³)
So, in the end, these dates cannot be used for the statistical work.

2) The second reason was a Delta-V maneuver on 12th August 2015 (see SDO JSOC Calendar ⁴)
So, in the end, these dates were useless as well.

There were only data to expand the database from 13th August 2015 to 14th August 2015 without any gaps. After some research, we found out that this is the most extended continuous period without any missing or any unusable fits files and any significant active regions in 2015.

Why it is so crucial of not allowing gaps?

The leading reason is that there should be no gaps in the algorithm otherwise it would not work anymore.

1) Even if there are some data available during these time gaps mentioned above, they are not useful at all due to the atmosphere of the Earth which is shown in Figure 2.12.

2) Even if there are some data available, e.g. 1 min after this time gap, they are still too bad due to the atmosphere of the Earth. It is clearly seen, even if we would accept the time gaps, the following data also would not be good and helpful which is shown in Figure 2.13.

These are the reasons why we currently created a database of 12 days ranges from 13th August 2015 to 24th August 2015.

Interruptions:

There are several interruptions such as calibration of instruments. This calibration is a particular calibration set for every single instrument separately and regularly like flat fields on a daily base, and roll and off-point maneuvers which have an influence on all instruments at the same time.

As the geosynchronous orbit of the probe has an inclination of about 28°, eclipses occur like the Earth eclipses which are twice a year around Vernal and Autumnal Equinoxes. At these two periods, AIA cannot observe because the Earth is located between the probe and the Sun. Therefore, a loss of about 44 hours per year occurs. In standard operation, AIA manages to observe about 95% of the time consistent with a cadence of typically 10 to 12 seconds.

Furthermore, Moon transits happened once to four times a year, the Mercury transited in May 2016 and in November 2019 as well as the Venus transit in June 2012. These events are not bad for science or lost data. They are useful as calibration improvements that everything together lasts about 100 hours each year.

Moreover, the high radiation of the Earth's outer parts of the radiation belt, where the probe's orbit is situated, is very harmful. The probe is sheltered through additional shielding for reducing against the illumination of ionizing radiation [31, 44].

³aia.lmsal.com/public/SDOcalendar.html

⁴aia.lmsal.com/public/SDOcalendar.html

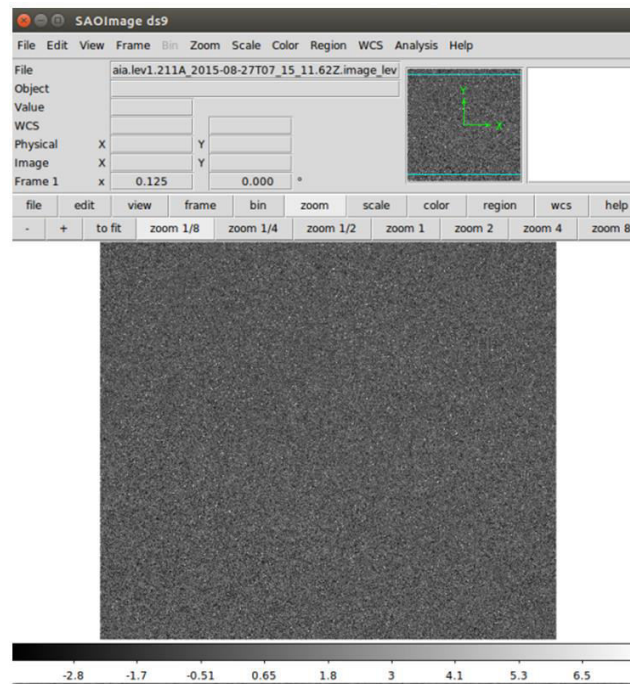


Figure 2.12: Example of unusable fits file due to Earth eclipse, which is visualized with the program SAOImage DS9.

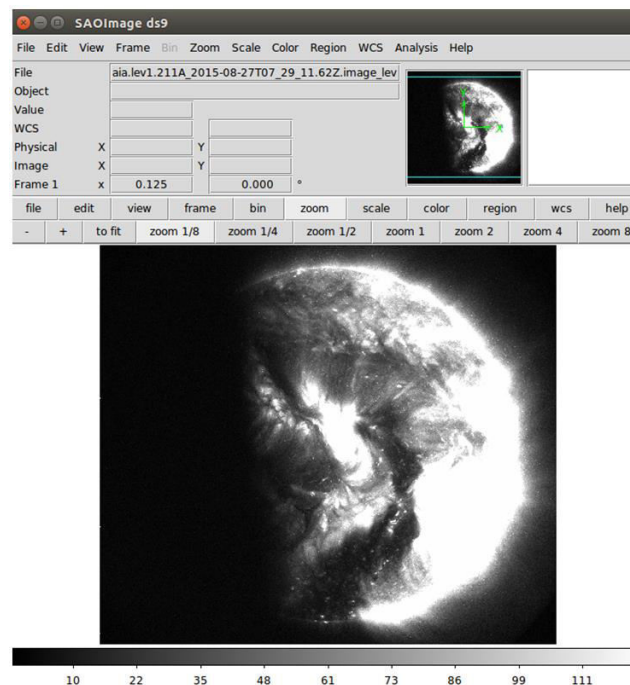


Figure 2.13: Another example of unusable fits file due to Earth eclipse, which is visualized with the program SAOImage DS9.

We create the IDL routine “bpt_create_database” that creates one database for each day that includes the segmented file maps with active regions and CBPs. The maps are made from Level 1.5 AIA and HMI files that are already calibrated (more details in the Appendix A). So, for each CBP in each image the coordinates of each pixel as well as the heliographic ones, the intensity of brightness for the wavelengths namely 94 Å, 131 Å, 171 Å, 193 Å, 211 Å, 304 Å and 335 Å and the magnetic field’s strength are defined, measured and stored in the database. Further, there are just coordinates for each CBP instead of reading full images which makes the algorithm much faster. Through the algorithm, we create an image number and identification number for easier finding.

The database starts at midnight, and 24 hours later it ends.

Next, we generate the routine in IDL called “bpt_combine_database”. Through this routine, it is possible to link the day by day databases together and get one big database which includes all 12 days in the end (more details in the Appendix A). In avoiding wasting too much space disk, which means reducing the resulting data from about 4 TB to 5 GB, we save the output suffix of the CBP database as “.sav” and “.fits”.

This combination of databases is necessary due to the purpose of tracking since a CBP could exist longer than one day or a CBP appears in the night and disappears the next morning. It has to be considered that the image number is continued and not started at the beginning every day anew. After that, we produce the routine called “bpt_load_database”, which causes the database to load faster to facilitate tracking the CBPs (more details in the Appendix A). Now it was easier to create a video, as the database had to load only once. Otherwise, it would have taken too much time to load it for each video separately.

2.3.5 Find and Filter sequences

For finding sequences we use the Python routine “merge_fits2bin”, which means that the result is the same as combining database in IDL to run the next Python routine called “bp_find_sequence” (more details in the Appendix A). We utilize another Python routine to visualize these found sequences, which plotted the normalized total intensity against the lifetime (see Figure 3.2 – 3.5), namely “bp_plot_sequence” (more details in the Appendix A).

We decide to search only long-living BPs with a lifetime of at least 60 minutes due to the cadence of 60 seconds. More precisely, it results in at least 60 images for observing and analyzing, enabled by the Python routine called “bp_sequence_fits_files” (more details in the Appendix A). Less than 60 minutes could lead to insufficient knowledge about a CBP’s evolution process.

We require additional filters for being sure to get the best out of the potential CBPs candidates, namely the Python algorithm called “bp_sequence_filter” (more details in the Appendix A). Since in the literature, the size of a CBP varies (see Table 1.1), this routine only considers CBPs smaller than 50×50 pixels (2,500 pixels), which seems to be a good standard (see Subsection 1.3.1 size criterion). Moreover, CBPs will be filtered, if they are too close to an active region due to their probable influence. This threshold is 300 pixels away from the center of an active region. Another limit is the size change from one image to another, which is at a maximum of 30%.

2.3.6 Tracking and creating videos

We require several IDL routines to track and create videos of CBP sequences. One of them is the routine called “bpt_db_videocontour” which manage the tracking of the CBPs in accordance with the differential rotation of the Sun (more details in the Appendix A). With this routine, the definite shape of CBPs gets visible through the segmented HMI maps. Consequently, every CBP receives an ID number which makes it easier to identify them. If the identification of the first image, where the CBP is visible, worked out, the routine retries to find the same CBP with this ID number again in the following image and so on. In other words, the tracking algorithm works with the correctly found coordinates for each time step and not by images anymore. Therefore, it is crucial to determine the accurate location on the solar disk to understand how the time influences the position changing due to solar rotation. Also noteworthy is the image number, which indicates the exact time an image is created.

This is a bit challenging as in the meantime, the Sun continues its differential rotating, which means that the tracking algorithm has to track these CBPs with their right speed. If the speed of the algorithm is too slow or too fast, the selected CBPs are not trackable and not visible in the videos. Thus, corrective action called the “coord_helio.cart” gets included, which means that the computation from the latitude and longitude pair of the CBP is the $x\ y$ for each time instance. This is possible under the condition of assuming that the heliographic coordinate system of the Sun has the same differential rotation speed as the CBPs – in every detected wavelength. It turns out that the differential rotation in the photosphere is needed for a reliable tracking of CBPs in the lower corona. Therefore, using heliographic coordinates is the right assumption in this work. Actually, CBPs seem to be valuable as tracers for solar rotation (see Subsection 1.3.1).

The cause of the Sun’s differential rotation is the heat transportation in the convective zone as well as the resulting Coriolis force through the rotation of the Sun. At the Sun’s pole, the duration of one rotation is slower, which is about 33.5 days or $10^\circ/\text{day}$ than at its equator, which is about 25.6 days or $14^\circ/\text{day}$. The mean speed of one period of rotation is about 25.7 days and is shown in Figure 2.14 [61, 83, 87].

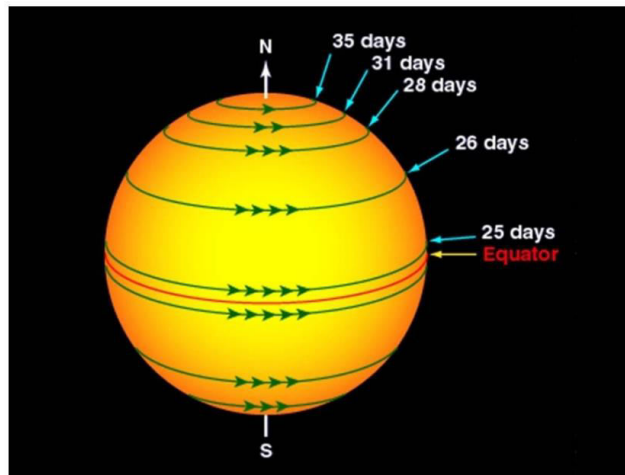


Figure 2.14: An overview of differential rotation of the Sun [83]. (Image taken from [83].)

The final routines we use in IDL are called “bpt_movie” and “make_movies”. At “bpt_movie” all videos are listed, and 663 randomly selected sequences are found and usable for statistics. At “make_movies” (see in the Appendix A) the final videos are automatically created (see Section 2.5). With all these procedures (see Subsection 2.3.2 – 2.3.6), the tracking of CBPs shows their behavior and evolution as well as what happens before a CBP appears and what happens after a CBP disappears again.

2.4 Classification

We show some criteria for selection in Figure 2.15 to define a CBP sequence. They comprise several features, e.g. fluxtube, magnetic polarity, temperature, merging CBPs within their lifetime, shape, lifecycle, lifetime, algorithm gaps, B/D/A, which means whether the sequence is a complete sequence or not (all explanations in Chapter 3).

Filename	Fluxtube (wavelength visible in Å)						Polarity (positive/negative Pole)													
	304	131	171	193	211	335	94	positive	negative	both	none									
AIA_2015-08-13T00:01:11.34_img1_bp25	1	0	0	1	1	1	0	0	0	equal	0									
AIA_2015-08-13T00:01:11.34_img1_bp33	0	0	0	1	1	0	0	0	0	negative dominated	0									
AIA_2015-08-13T00:01:11.34_img1_bp42	1	1	1	1	1	1	0	0	1	0	0									
AIA_2015-08-13T00:01:11.34_img1_bp51	1	1	1	1	1	1	0	0	0	negative dominated	0									
AIA_2015-08-13T00:01:11.34_img1_bp62	0	0	1	1	1	1	0	0	0	equal	0									
Temperature (wavelength visible in Å)						Shape		Lifetime in h												
304	131	171	193	211	335	94	roundish/sim	loop-like/curve	comp	0-3	3-6	6-9	9-12	12-15	15-18	18-21	21-24	24-28	28-32	32-36
1	1	1	1	1	1	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0
0	1	1	1	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
1	1	1	1	1	1	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0
1	1	1	1	1	1	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0
1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	1	0	0	0	0	0

Figure 2.15: A cutout of classification examples of all found CBP sequences.

In Figure 2.16, we visualize some examples of the criteria for getting a better understanding of the differences.

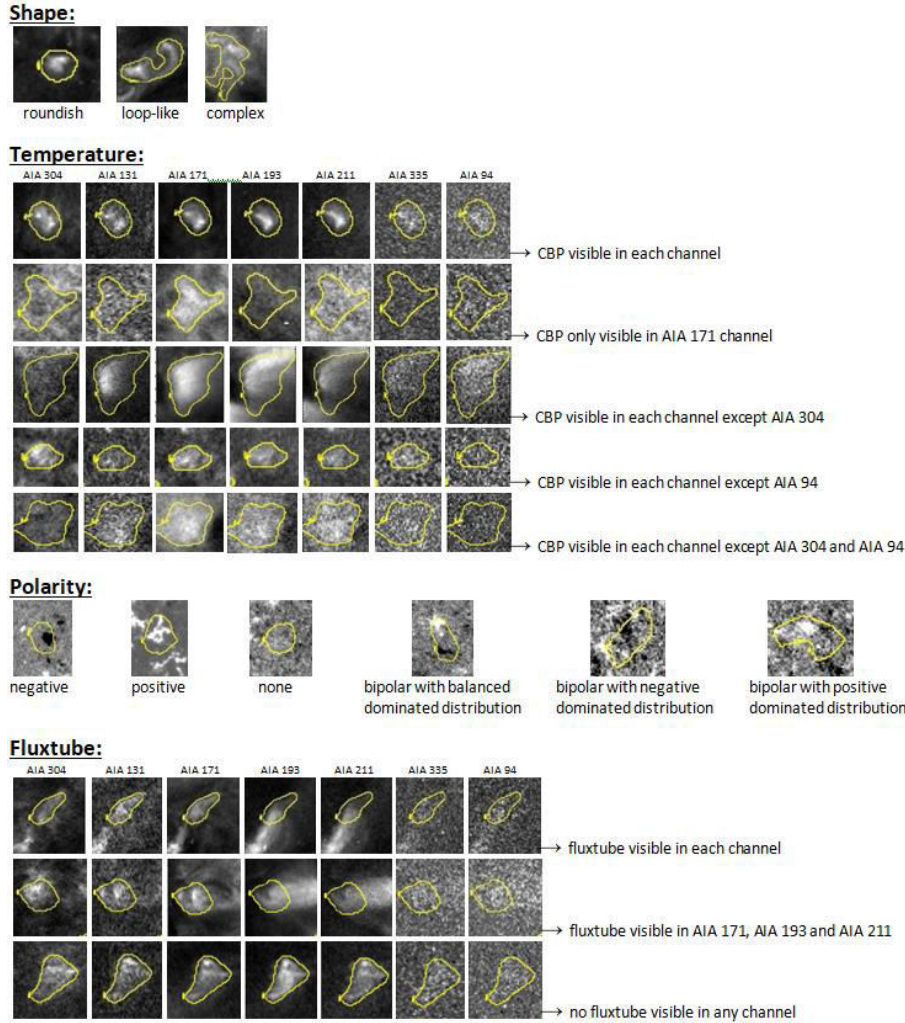


Figure 2.16: An overview of the different criteria, e.g. shape, temperature and fluxtube (left to right: 304 Å, 131 Å, 171 Å, 193 Å, 211 Å, 335 Å, 94 Å). Polarity is visible in HMI channel.

2.5 Videos

In Figure 2.17 – 2.19, we show the analysis cutouts of a CBP with time. In the respective top panel of each figure, the red circle demonstrates the location of the investigating object. In the bottom panels, we visualize seven wavelengths with different temperature and the HMI. Additionally, on the right side, we count and calculate the gaps during the CBP's life span in percent. Below the gaps the duration of the CBP's lifetime can be seen.

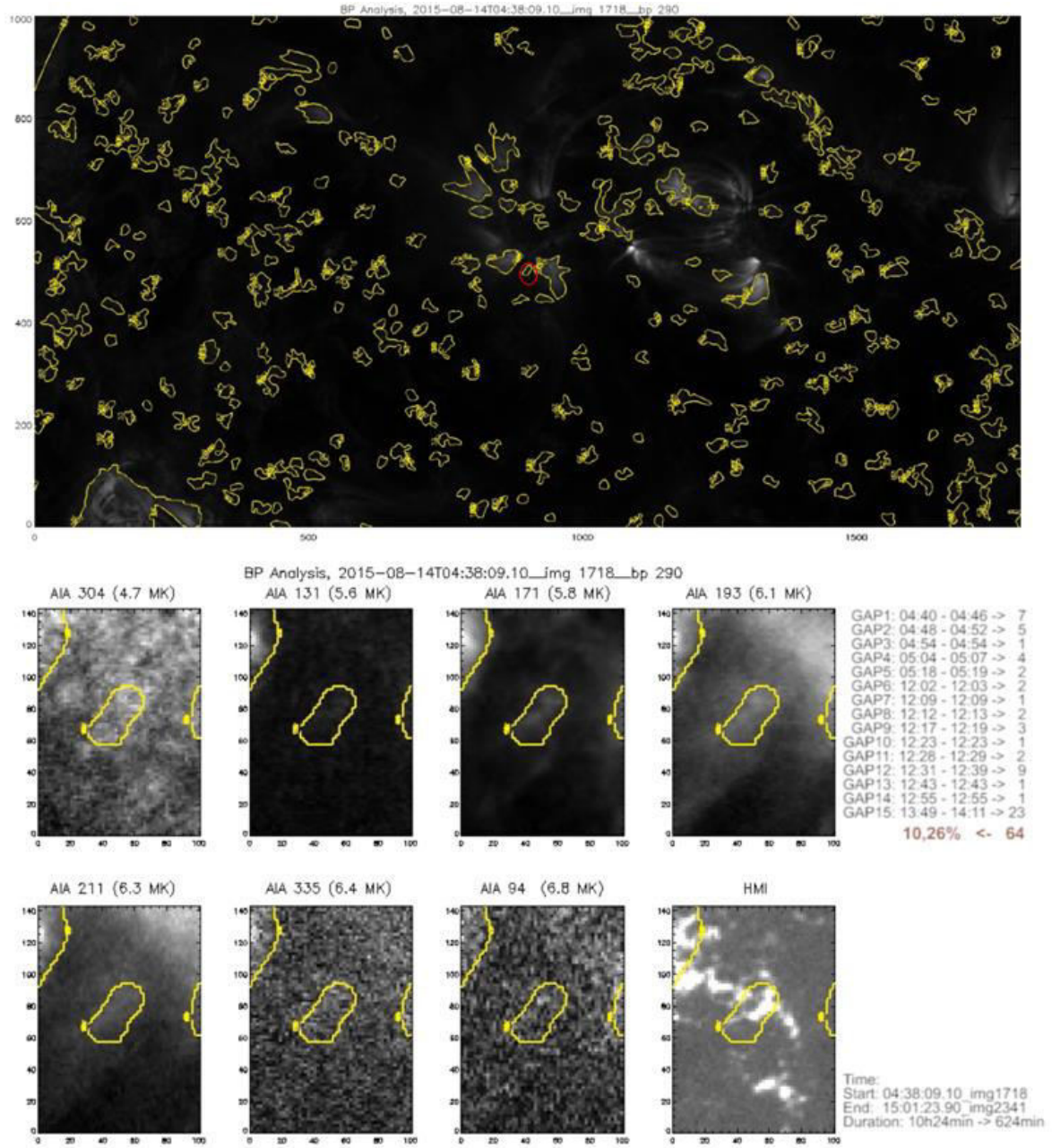


Figure 2.17: Example of a CBP in each wavelength (304 Å, 131 Å, 171 Å, 193 Å, 211 Å, 335 Å, 94 Å and HMI) at its first emergence. The temperature in million K is a logarithmic scale. Video of the CBP evolution is available online: <https://doi.org/10.5446/49482>

In the literature, CBPs consist of a halo and a bright core. The pixels in the core have more than 50% brightness of the maximum. On average the size, of such a total area of a CBP is about $130 Mm^2$, while the bright inner core is about half of this area, which means $60 Mm^2$ [2]. According to Zhang et al. (2001) [73], there are $110 Mm^2$ for the total area on average. Concerning the total solar disk surface, it turns out that 2.6% is highlighted by the total area of CBPs, which makes up 1.3% for the bright inner cores and agrees with Zhang et al. (2001) [73]. The shown example in Figure 2.18 is in good agreement with the literature [2].

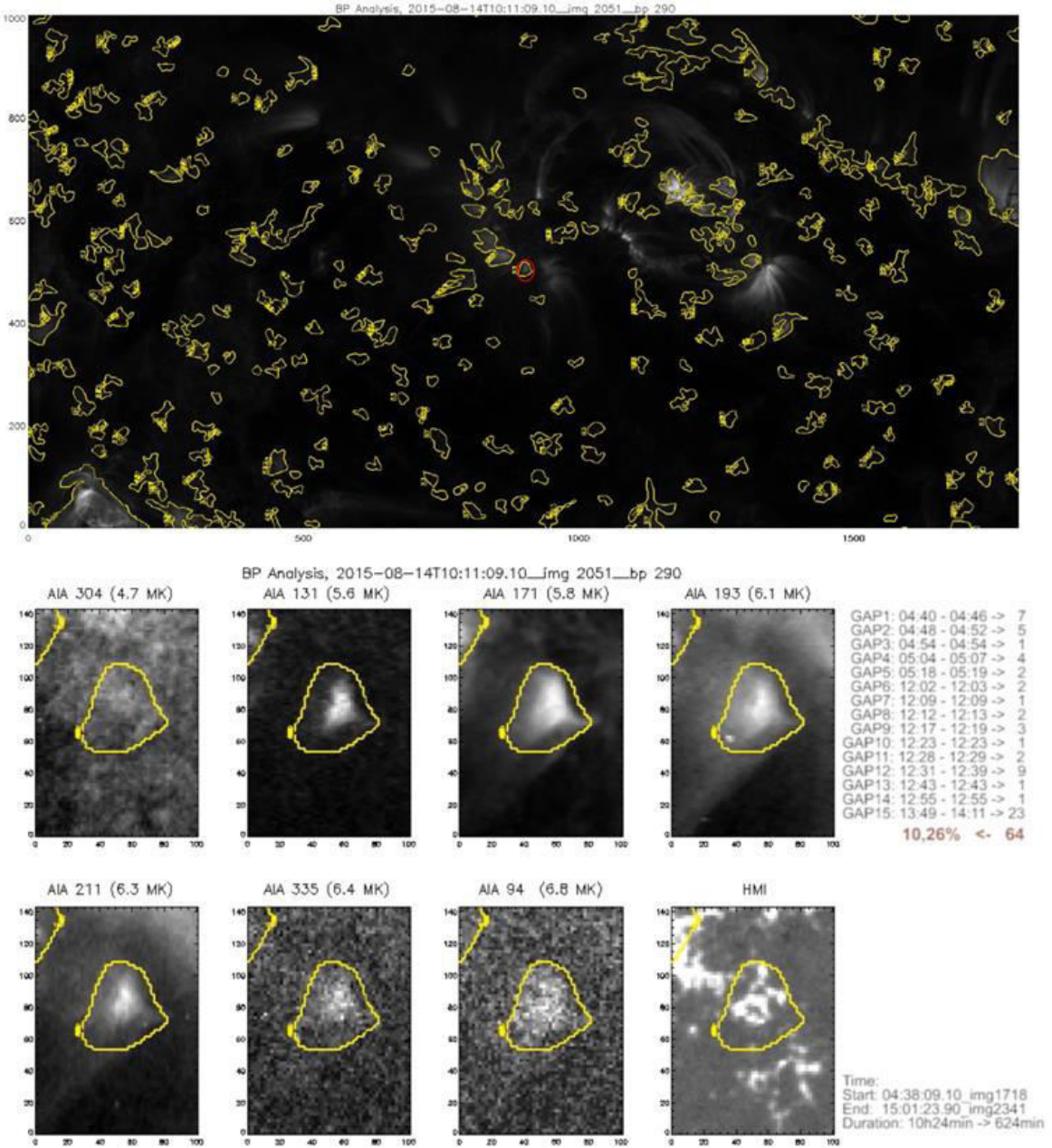


Figure 2.18: Example of a CBP in each wavelength (304 Å, 131 Å, 171 Å, 193 Å, 211 Å, 335 Å, 94 Å and HMI) in the middle of its evolution. The temperature in million K is a logarithmic scale. Video of the CBP evolution is available online: <https://doi.org/10.5446/49482>

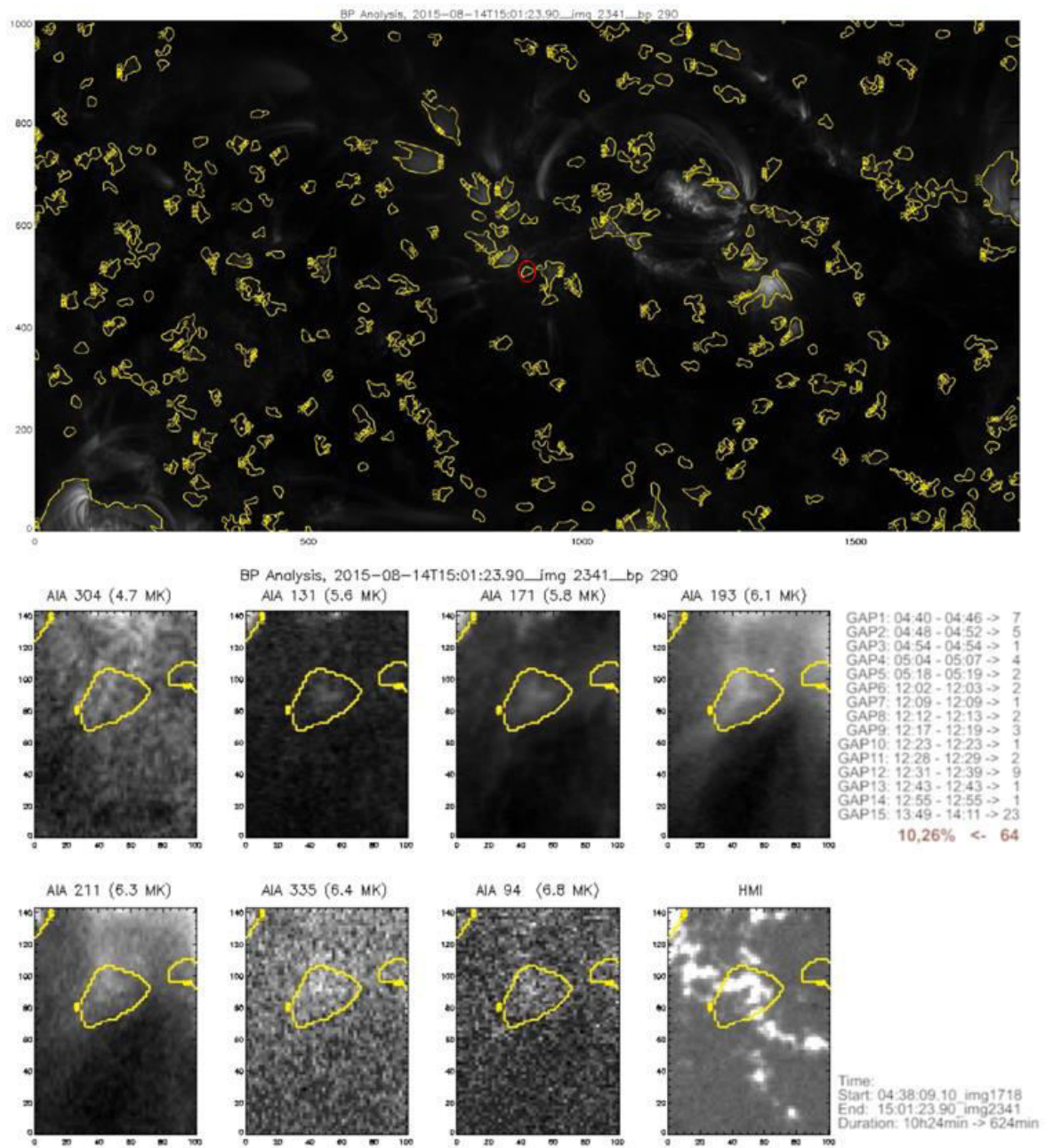
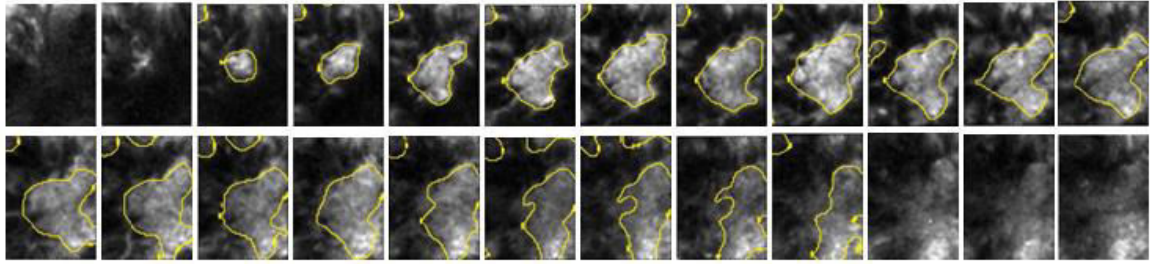


Figure 2.19: Example of a CBP in each wavelength (304 Å, 131 Å, 171 Å, 193 Å, 211 Å, 335 Å, 94 Å and HMI) at the end of its evolution. The temperature in million K is a logarithmic scale. Video of the CBP evolution is available online: <https://doi.org/10.5446/49482>

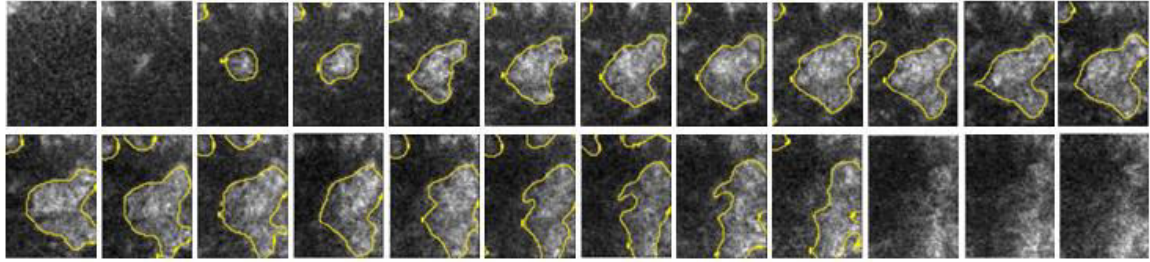
Example of CBP videos: (2015-08-14T11:07:24.10 – 2015-08-14T14:57:38.90)

In general, we show that magnetic evolution can be defined as two or more mixed magnetic field poles (bipolar), which are independent and approach each other after some time. According to the literature and as well as can be seen in Figure 2.20, the conclusion of the eye-tracking results in elementary, point-like features or cluster-like ones. The cluster-like ones have more than one bright kernel. Especially in the case of Figure 2.20, we find that this CBP starts with a simple shape and evolve into a complex one, which is quite rare (see Section 3.9 and Chapter 4). The assumption is that CBPs are resulting from magnetic reconnections, but it is difficult to identify which specific magnetic poles are responsible for that. The bipolar magnetic-field is demonstrating an increase as well as a decrease and is often fluctuating in between for only small periods.

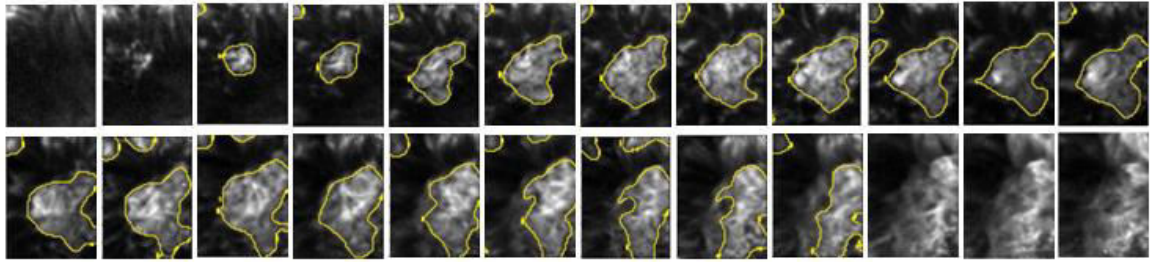
AIA 304:



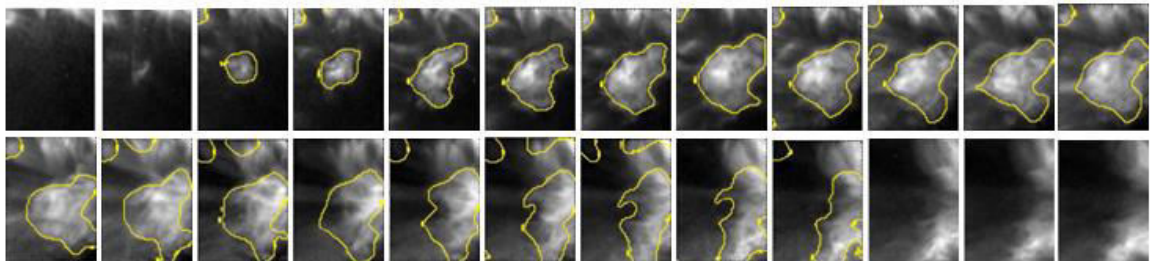
AIA 131:



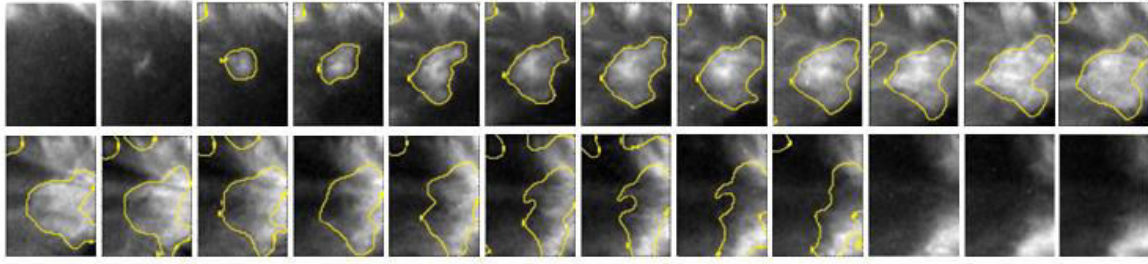
AIA 171:



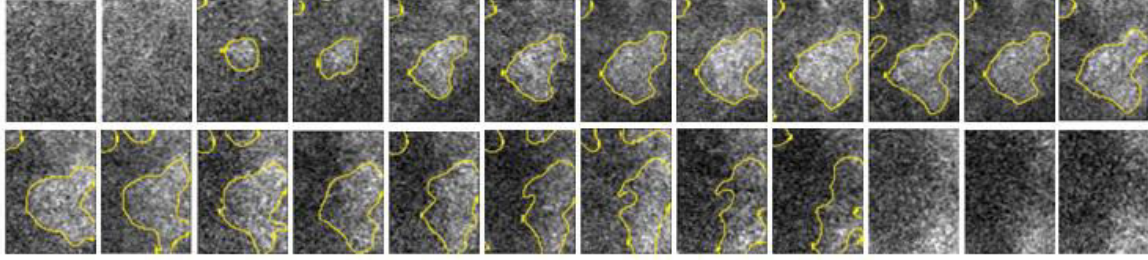
AIA 193:



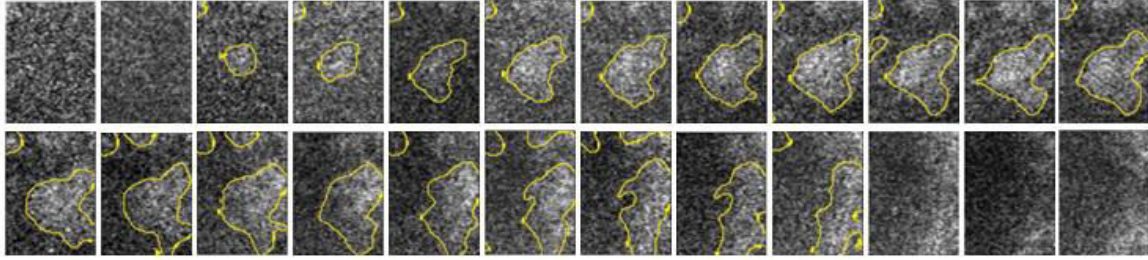
AIA 211:



AIA 335:



AIA 94:



HMI:

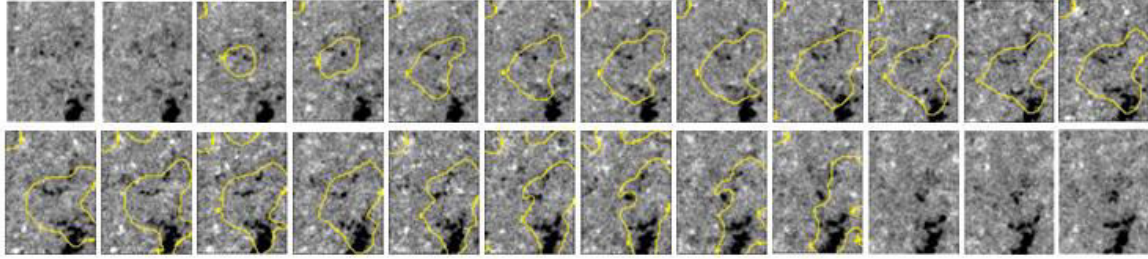
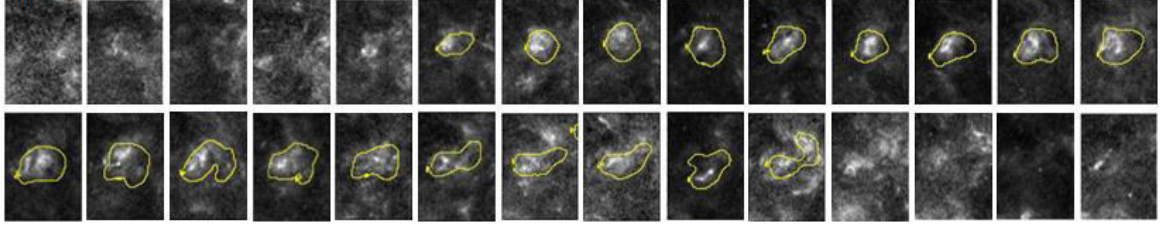


Figure 2.20: Example of an entire evolution cycle (24 frames) in each wavelength of a CBP (304 Å, 131 Å, 171 Å, 193 Å, 211 Å, 335 Å, 94 Å and HMI) is shown (from left to right). Interval: 1 frame every 10 minutes. Video of the CBP evolution is available online: <https://doi.org/10.5446/49527>

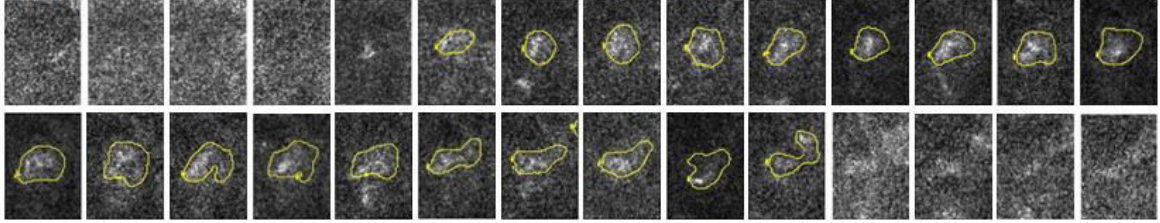
Example of CBP videos: (2015-08-14T04:00:24.10 – 2015-08-14T17:30:08.20)

In Figure 2.21, we show an example of a typical CBP evolution. At first, the bipolar magnetic-field in the HMI images of the CBP can be identified, before the CBP itself is appearing in every wavelength channel. It is fluctuating in the beginning, but then it stabilized and got a little bigger and brighter. In the meantime, its bipolar magnetic-field (negative and positive polarity) approach to each other, merge and annihilate each other. After cancellation of the bipolar magnetic-field, the CBP itself is fading away until it completely disappeared.

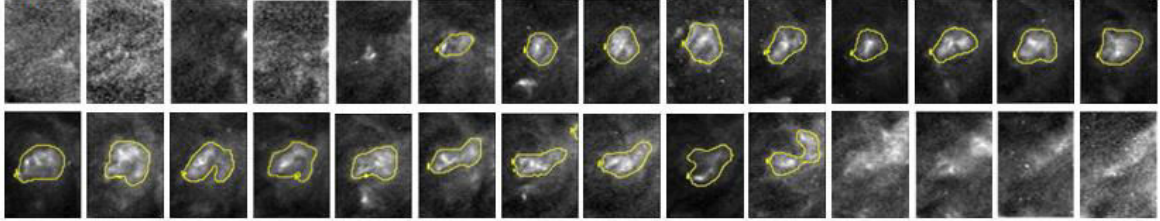
AIA 304:



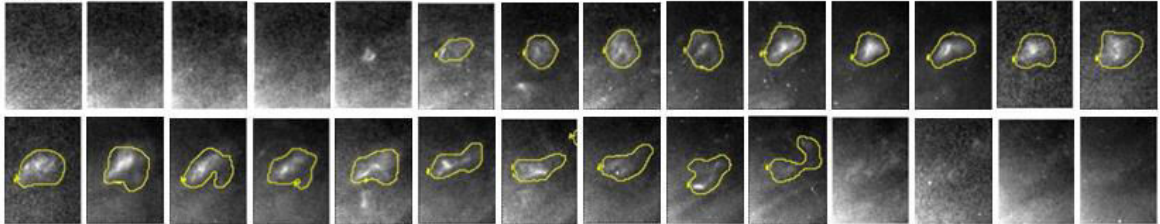
AIA 131:



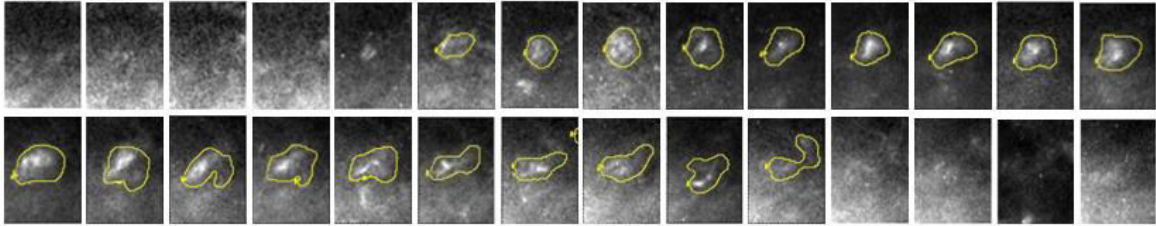
AIA 171:



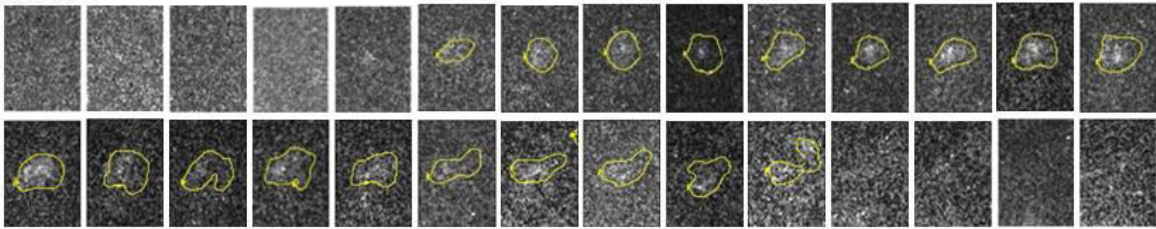
AIA 193:



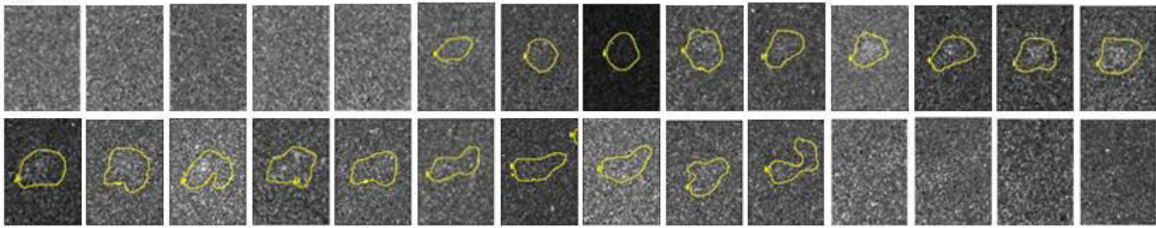
AIA 211:



AIA 335:



AIA 94:



HMI:

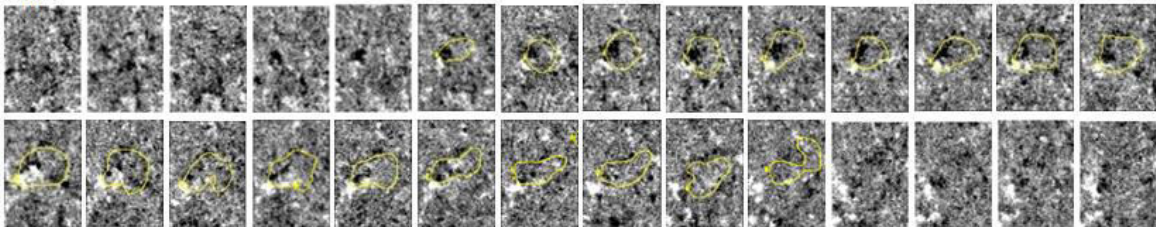


Figure 2.21: Example of an entire evolution cycle (28 frames) in each wavelength of a CBP (304 Å, 131 Å, 171 Å, 193 Å, 211 Å, 335 Å, 94 Å and HMI) is shown (from left to right). Interval: 1 frame every 30 minutes. Video of the CBP evolution is available online: <https://doi.org/10.5446/49528>

Chapter 3

Results

Examples of the selected CBPs:

CBPs are bright and have compact structures that can be loop-like. The footpoints of the loops are here well-defined, roundish, and isolated. This means the CBP forms in between two well-separated footpoints without magnetic flux cancellation, see Figure 3.1. The CBP intensity maximum (white in AIA images) is located between the bipolar footpoints (see red and blue ellipses in Figure 3.1). In contrast to this example, other CBPs may look more complex and resemble tiny ARs (see Subsection 1.3.1 shape criterion) [24,38].

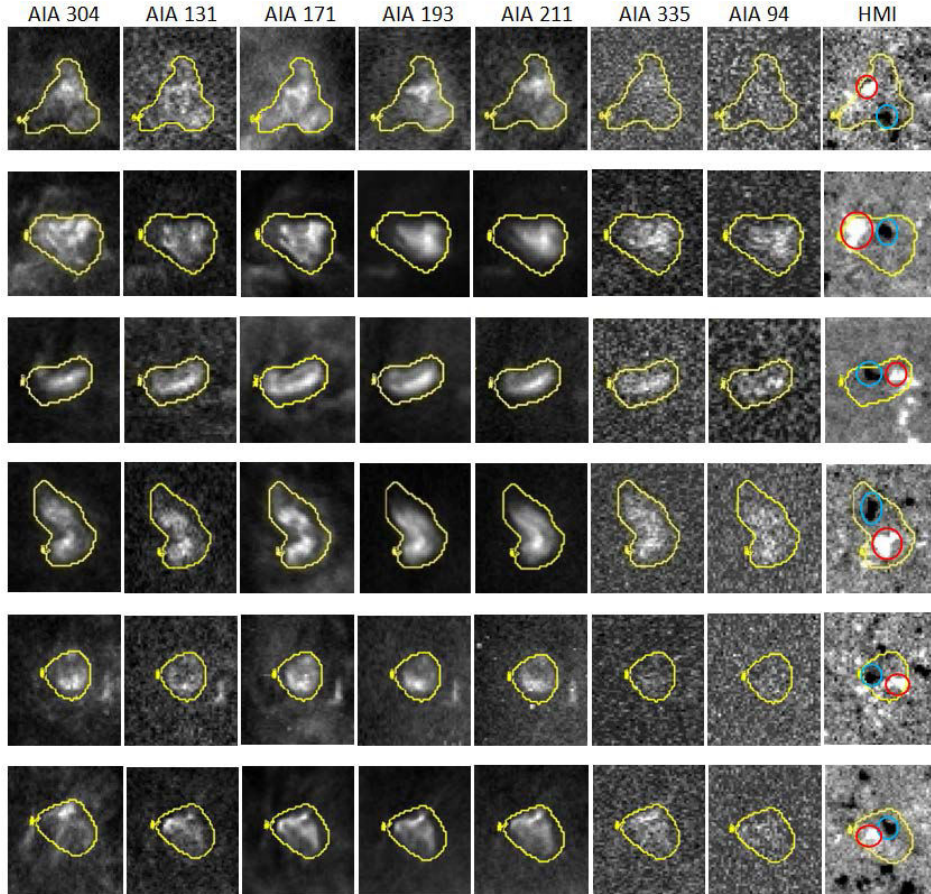


Figure 3.1: AIA images of different channels (left to right: 304 Å, 131 Å, 171 Å, 193 Å, 211 Å, 335 Å and 94 Å) together with the HMI magnetograms (rightmost column). The CBP contour is marked in yellow. We mark the opposite magnetic polarities (black and white) in the HMI magnetograms with red and blue ellipses.

In Figure 3.2 we show the total intensity trend of one CBP. We find the local intensity peaks occur at the same times in all channels. The intensity peaks are significantly higher than the average background value (see Subsection 1.3.1 intensity criterion). The same is valid for Figure 3.3, 3.4 and 3.5.

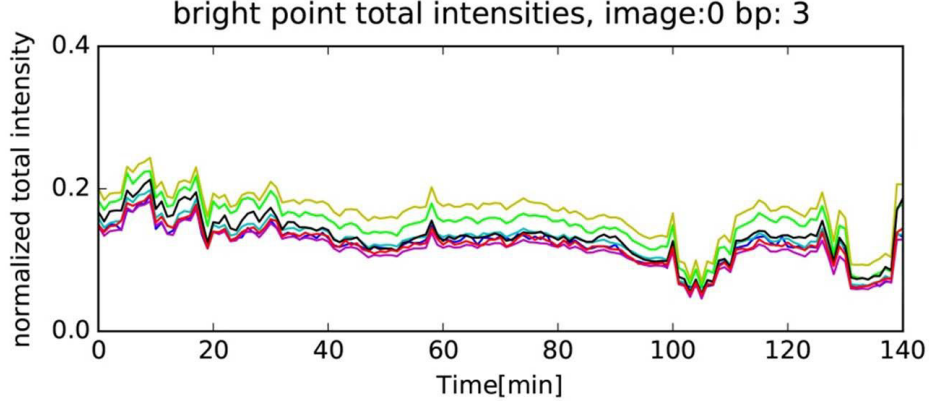


Figure 3.2: Evolution of the normalized total intensity of CBP number 3. The data from AIA channels are shown in different colors: 94 Å (blue), 131 Å (lime), 171 Å (yellow), 193 Å (cyan), 211 Å (magenta), 304 Å (black), and 335 Å (red).

In Figure 3.3, we clearly see spikes in the normalized intensity light curve that indicates the CBPs have strong brightness variations. This can be seen again on different channels at the same time. All of them show the same trend. Hence, the differential rotation is the same from the transition region to the corona. In other words, CBPs seem to be radially bound and tightly connected to the solar surface. The green line indicates the total unsigned magnetic flux in the photosphere, for comparison. The magnetic flux varies between ± 20 Gauss [9]. The same is valid for Figure 3.4 and 3.5.

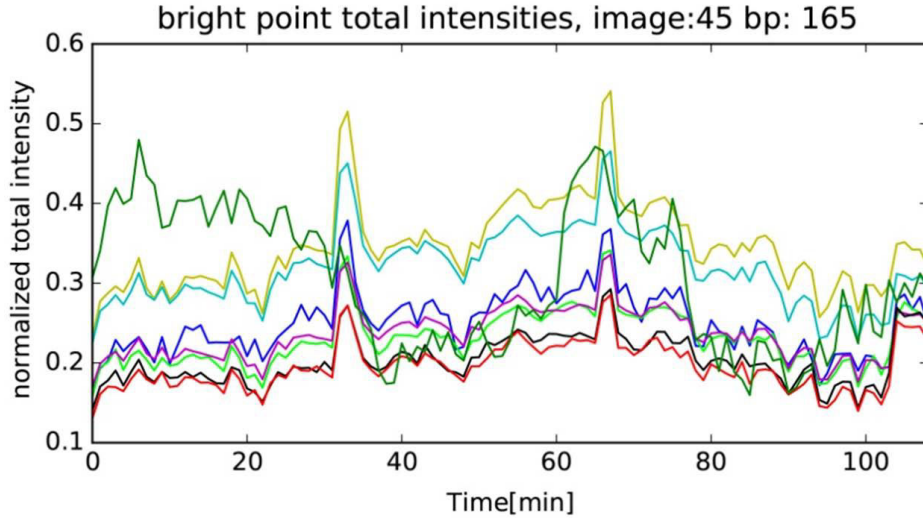


Figure 3.3: Same as Figure 3.2 but for CBP number 165. The green line indicates the total unsigned flux from HMI.

In Figure 3.4, we illustrate EUV-bright regions at different temperatures in the solar atmosphere. The intensity peaks are significantly above the mean value, which indicates this is a CBP. The same is valid for Figure 3.5.

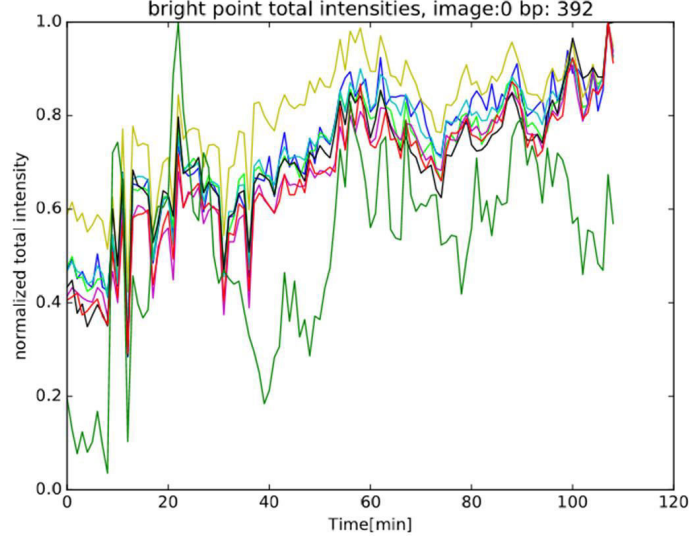


Figure 3.4: Same as Figure 3.3, but for CBP number 392.

In Figure 3.5 we show the intensity light curve for a unipolar CBP that has only one polarity. The variation in the EUV intensity seems not to correlate exactly with the total magnetic flux, but the correlation seems to be slightly better than for CBPs with bipolar footpoints. In general, the results from this study show that the EUV emission does not scale well with the total magnetic flux, instead, this is probably due to complex magnetic field reconfigurations (see Section 3.4 and Chapter 4).

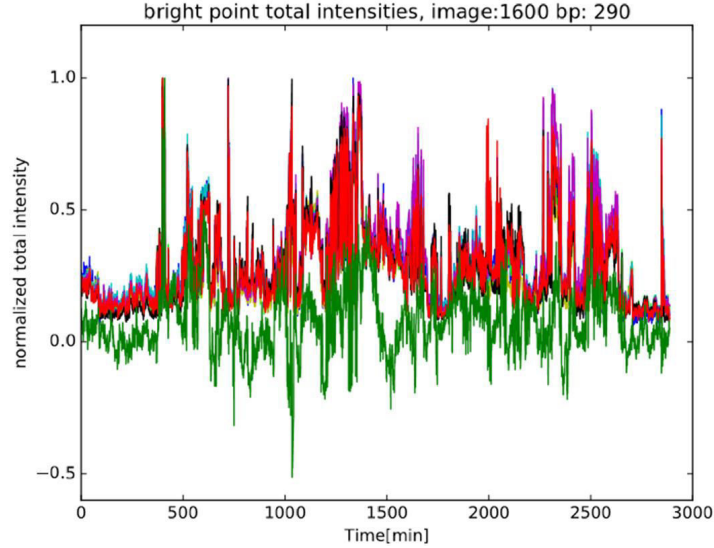


Figure 3.5: Same as Figure 3.4, but for CBP number 290. In this case, the CBP has a unipolar magnetic-field. The green line shows the total magnetic flux that we shifted vertically for better comparability.

According to Madjarska et al. (2003) [64], the cause of appearing CBPs in a specific channel is defined by the magnetic energy output and its strength of the field (see Subsection 1.3.1 reconnection process and Section 3.5). It is explained by the magnetic flux, which means the more powerful it gets, the more the emission area increase as well as the emission inside of the CBP [9].

3.1 Case studies

Now we investigate our whole database of CBPs and make statistics over the CBP lifetimes. The abbreviation “B/D/A” stands for “Before/During/After” which corresponds to the Pre-Interaction phase, the Interaction phase, and the Cancellation phase of a CBP. This means that there are sequences where the emergence or the disappearance of the CBP is missing due to algorithm problems (more details in Figure 3.7). We show, in Figure 3.6, how many CBP sequences are complete and how many are captures only partially.

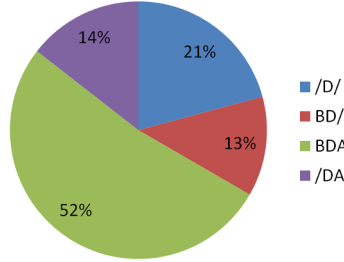


Figure 3.6: Two case studies are shown, where one selected all found sequences and the other with only 52% of them.

We have a total of 663 randomly selected CBPs of which 346 are covered with their whole evolution cycle, including their emergence and disappearance. These we call “complete sequences”. This allows us to compare “partial” and complete sequences – in order to find out if the partial sequences give significantly different results than the complete sequences. The statistical error we compute as $\frac{1}{\sqrt{n}}$. This is approximately $\pm 4\%$ for 663 sequences and $\pm 5\%$ for 346 sequences.

3.2 Algorithm gaps

A gap in the algorithm means that the tracking of a CBP was not successful for a portion of the sequence of images. Typically, gaps occur in the beginning and end of a sequence because the CBP is still faint and may drop below the intensity threshold. In Figure 3.7, we explain the fraction of tracking failures (gaps) in a CBP sequence, where 20% of all CBPs are missing 0-10% of their full-time series of images. However, the same is true for only 10% of the “complete” sequences that cover the CBP from its birth (B phase) to its death (A phase). The largest difference between all and the complete sequences we find in the category with a fraction of 0-10% of algorithm gaps. All in all, in the categories 40-50% as well as above 50%, the identification of the CBP’s sequences were a bit challenging. This involves 15% of all selected CBPs and about 20% of the complete sequences.

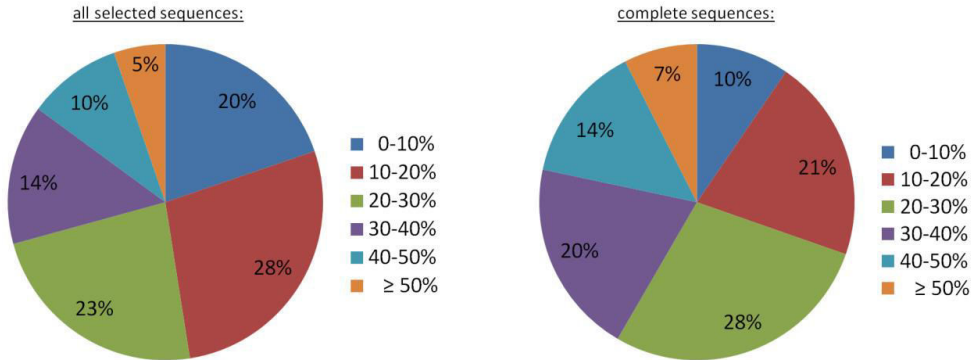


Figure 3.7: Fraction of algorithm gaps (tracking failures) in all CBP sequences (left) and the complete sequences (right). The color coding indicates how much of a time series is missing.

3.3 Lifetime

We now investigate the total lifetime of CBPs, see Figure 3.8. We find that about 20% of CBPs have a lifetime shorter than 3 hours. The interval with lifetimes of 3–6 hours contains the largest fraction of CBPs. More than half of all CBPs have a life span of less than 9 hours. The differences between all selected CBPs and complete ones become larger for lifetimes of 15 hours and more. The reason for this could be the unintended tracking failure of the algorithm at the B (before) and A (after) phases. One should note that the lifetime is only correctly measurable if the tracking worked at the B and A phase, which means only for “complete” sequences, see right panel in Figure 3.8. Only 3 CBPs reach a lifetime of 24 hours or more.

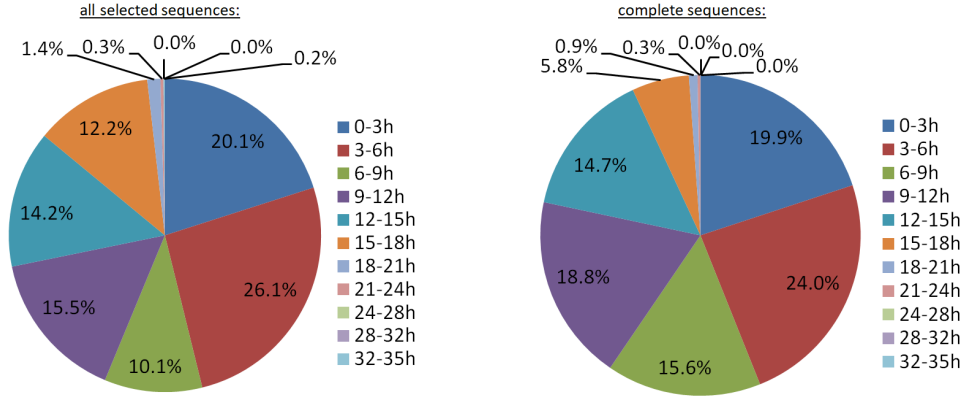


Figure 3.8: Distribution of CBP lifetimes for all (left panel) and complete (right panel) sequences. The color code indicates the fraction of CBP sequences within each lifetime interval.

3.4 Magnetic-field polarity

In Figure 3.9, we investigate if a CBP has a specific magnetic polarity at its footpoint in the photosphere (“negative” and “positive”). We find that about 90% of all CBPs have mixed magnetic activity at their footpoints. In the category “none” we group CBPs with very weak magnetic fields and without a clear polarity. The majority of CBPs show “multipolar” and “bipolar” mixed fields that may have a “balanced” flux or may be “dominated” by one polarity. E.g., a “bipolar balanced” region has mixed polarities with roughly the same amount of positive and negative flux. There is no significant difference between positive and negative dominated CBPs. In contrast, a minority of about 7% has only negative or only positive polarity (“unipolar”). We find only 3% of the CBPs have no significant polarity (“none”), which could mean they have no magnetic connectivity to the photosphere or they have a connection to a region far away from the CBP. We see no significant differences between the group of all CBPs and the sub-group of the complete sequences except the “multipolar” portion.

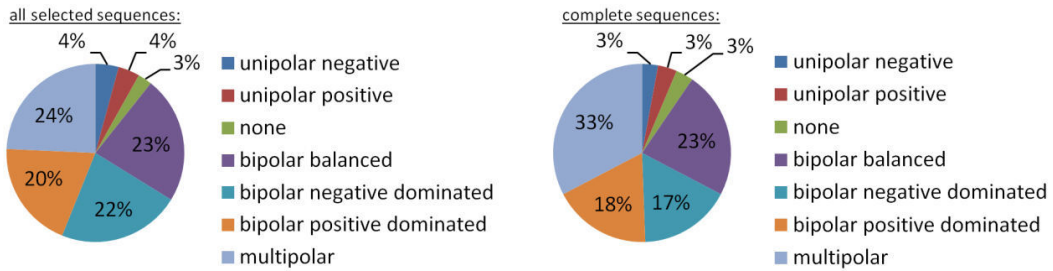


Figure 3.9: Distribution of the footpoint polarity for all CBPs (left panel) and complete sequences (right panel). The color code indicates the fraction of CBP sequences within each polarity type.

3.5 Temperature

In this section, we discuss in which AIA channel a CBP is visible. The channels roughly correspond to ranges in the coronal plasma temperature, see also Figure 2.5. We find that 53% of all selected CBPs are visible in all AIA channels, see Figure 3.10. For the complete CBP sequences, about 46% do show emission in all AIA channels. This is the only significant difference between our two groups of CBPs. In other words, CBPs that are visible in all channels are probably the hottest ones with about 6 *MK*. The second-largest category is “except AIA 94“, where the CBPs are visible in all channels, except for the 94 Å channel. These CBPs are probably slightly cooler and may be located at lower height. An interesting fact is that about 2% of the CBPs is not visible in the 304 Å channel (see category “except AIA 304“ in Figure 3.10), which could mean these CBPs have no significant contribution from the cooler and lower atmosphere and might hence be located higher in the atmosphere. About 10% of the CBPs are not visible in both channels, 304 Å and 94 Å. In general, the CBPs are always seen in the AIA 171 Å channel. We find only about 2% of the CBPs (12 sequences) that are visible only in the 171 Å channel. This type of CBPs probably has a temperature of about 0.5 – 1 *MK* and radiates only very weakly. In Table 3.1, we show the probability to observe a CBP in the AIA channels. We see that CBPs are also observable in AIA 131, AIA 193 and AIA 211 for about 90 – 95% of cases. In the AIA 304 channel, we observe about 85% of the CBPs. The least visibility with less than 70% we have in the AIA 335 and AIA 94 channels.

As discussed in Subsection 2.3.5, most of the CBPs have high temperature due to our selection criterion that requires at least one hour lifetime of the CBP.

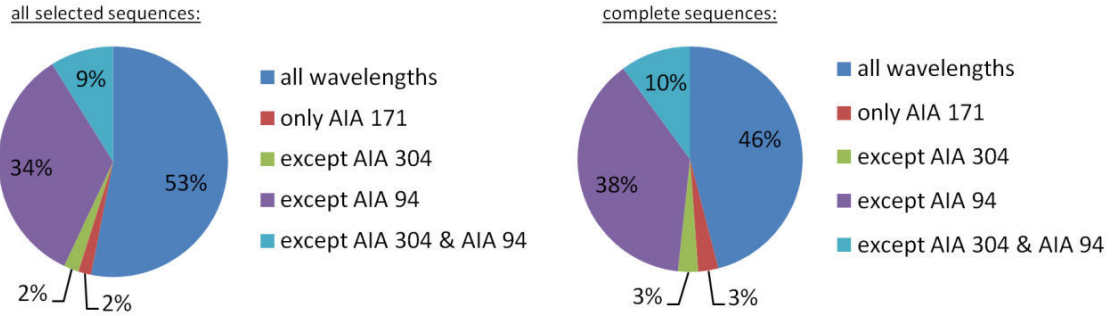


Figure 3.10: Visibility of CBPs in AIA channels for all CBPs (left panel) and complete sequences (right panel). The color code wavelength channels – visible in all channels means a hot CBPs, only visible in AIA 171 are faint CBPs. See also the CBP videos (see Section 2.5). The visibility of a CBP in a wavelength channel is connected to its temperature (see Section 2.4).

Table 3.1: Probability to observe a CBP in one of the AIA channels for all CBPs (left panel) and for complete sequences (right panel)

wavelength channel	all selected sequences	complete sequences
AIA 304	87%	84%
AIA 131	97%	95%
AIA 171	100%	100%
AIA 193	96%	94%
AIA 211	94%	91%
AIA 335	69%	63%
AIA 94	55%	49%

3.6 Fluxtube

We call a fluxtube when we find additional bright material that appears as a tail-like extension of the CBP, but is not recognized as the CBP itself because of lower intensity. We think this indicates magnetic connectivity to a nearby region on the Sun. In other words, it could be an indicator whether a CBP might be connected with another CBP. If no fluxtube is present then this CBP is probably isolated, the magnetic field is probably close to vertical, or this CBP might be connected to a far distant region on the Sun. A fluxtube has an elongated curved shape and is nearly as long as the CBP. Here we present statistics on how many CBPs show fluxtubes in which AIA wavelength channel, see Table 3.2. About 15% of the CBPs have no fluxtubes. Interestingly, only 5 CBP sequences (1%) have fluxtubes that are visible in all AIA channels at the same time. We think that these CBPs may have the highest temperatures. However, at AIA 304 only about 40% of the CBPs have a fluxtube, whereas, in AIA 131, AIA 335, and AIA 94, fluxtubes are rarely visible. For AIA 171, AIA 193, and AIA 211, the fluxtubes are often and equally visible and most of the time simultaneously observable. The higher the temperature, the better the fluxtubes are visible in these three channels.

Table 3.2: Probability of visibility of fluxtube-connected CBPs in different AIA channels for all CBPs (left panel) and for complete sequences (right panel)

wavelength channel	all selected sequences	complete sequences
AIA 304	40%	36%
AIA 131	8%	5%
AIA 171	73%	75%
AIA 193	79%	77%
AIA 211	76%	73%
AIA 335	1%	1%
AIA 94	1%	1%

3.7 Merging bright points

When CBPs come close together, our method detects a merge, but for this section, we consider only CBPs that separate again after a short time. This is the case for about 37% of all CBPs, but the majority of about 63% of the CBPs stays isolated, see Figure 3.11. The same is true if we consider only the subset of complete sequences that span the whole lifecycle of a CBP.

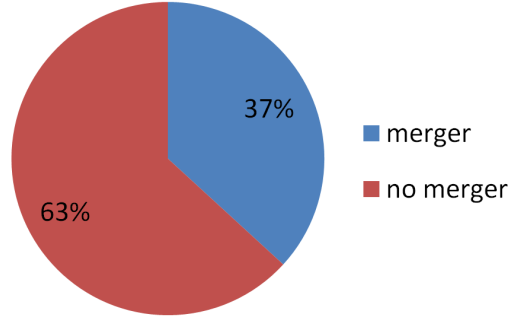


Figure 3.11: Distribution of the merging of bright points during their lifetime for all CBPs and complete sequences.

3.8 Shape

We turn to an investigation of the spatial shape of CBPs. We find that a large fraction of the CBPs have a loop-like structure and only a minority of about 17% is mostly roundish and of simple geometry, see Figure 3.12. Complex shapes also provide a significant share of the CBPs and do not fall in the aforementioned two categories (loop-like or roundish). We see some differences for the loop-like and complex CBPs when we look at our two groups of all CBPs and the complete sequences.



Figure 3.12: Distribution of the shape for all CBPs (left panel) and complete sequences (right panel). The color code indicates the fraction of CBP sequences within each shape type.

3.9 Lifecycle

3.9.1 Pre-Interaction Phase

We describe the appearances of magnetic regions before a potential CBP is visible in any of the wavelength channels.

It was very challenging for the algorithm to find sequences. 13% of the identified CBPs have sufficiently long sequences that allow checking the magnetic activity before the CBP becomes bright in any of the AIA channels. From these cases, we learn that some magnetic activity needs to exist and to grow, before a CPB may appear.

In Figure 3.13, we show the time needed for CBPs to become visible after the first sign of magnetic activity. For that, we analyze about 73% of the complete CBP sequences. If the time for the appearance of a CBP is below 5 minutes, we call this “fast” emergence. A time of 5 – 10 minutes is “normal” and times above 10 minutes are “slow” emergence.

We show that the fast, as well as the slow appearance of a CBP, is well balanced in the group of randomly selected CBPs and the sub-group of complete sequence CBPs. Only a minority appears within the 5 – 10 minutes category. In other words, the appearance of a CBP is usually either fast or slow for most of the cases.

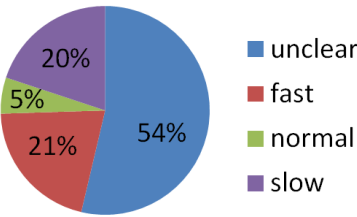
In Table 3.3, we present the behavior at the beginning of a CBP’s appearance. For that, we use only the complete sequences, so that we know about the situation before a CBP is identifiable. About 60% of these CBPs show a “flickering” behavior where the CBP brightness varies and needs some time to develop to the full intensity. Another large portion of 40% of the CBPs shows the behavior to “get bigger”.

In nearly 20% of the cases, the separation from another CBP takes place and creates a new isolated CBP. In another 14%, smaller CBPs merge and form a new larger isolated CBP (see Subsection 1.3.1 distance criterion).

All other categories in Table 3.3 have together only a share of 5.5% and are exceptional. This includes the ability of shape-changing from one type to another within their time of appearance (see Figure 2.20).

Other exceptions are CBPs that initially “get smaller”, as well a new CBP that emerges from a previous one (“appear after another CBP”). This means when the previous CBP disappears, the new CBP is immediately formed after that without any pause in between (see Chapter 4).

all selected sequences:



complete sequences:

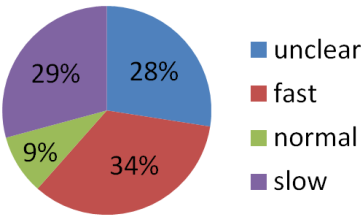


Figure 3.13: Time a CBP needs until it first becomes visible in one of the AIA channels. Less than 5 minutes (“fast“), 5-10 minutes (“normal“), and more than 10 minutes (“slow“).

Table 3.3: Overview of the situations before a CBP emerges. Multiple properties are possible.

appear after another CBP	→ 1.4%
separating from another CBP	→ 20.5%
merging with another CBP	→ 13.6%
flickering	→ 59.5%
get smaller	→ 0.3%
get bigger	→ 39.6%
shape initially appears roundish	→ 2.3%
shape initially appears loop-like	→ 0.9%
shape initially appears complex	→ 0.3%
unclear	→ 0.3%

fast appearance vs slow appearance of CBPs:

In Figure 3.14, we present the comparison between fast and slow appearance. In the upper row, it seems that the faster the CBPs appear, the hotter they are. For slow appearing CBPs, we see a trend that they become cooler and fainter.

In the middle row, there is only a marginal indication that slow appearing CBPs seem to live shorter. This could be because the lifetime is counted only after the CBP has appeared and the entire lifetime including the appearance might be constant.

The lower row illustrates the fast appearance against the shape. It turns out that fast appearing CBPs have a slight tendency to be more loop-like than the global average. Furthermore, for slow appearing CBPs, we find a significantly higher number of loop-like structures and significantly less complex structures.

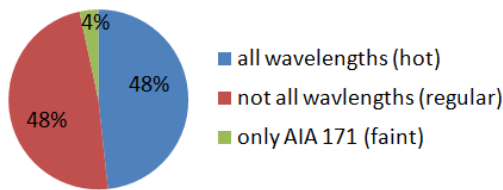
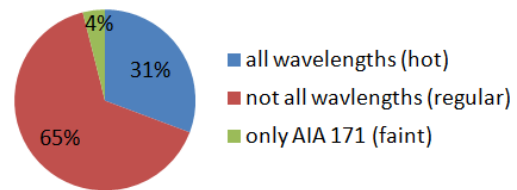
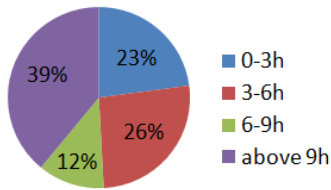
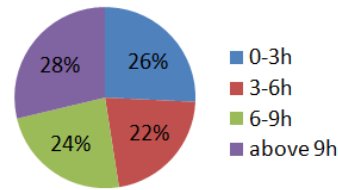
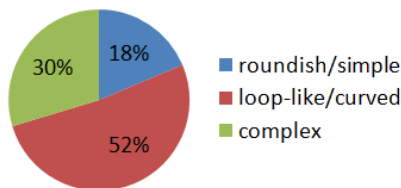
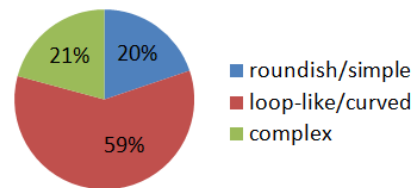
fast appearance of CBPs vs temperature:**slow appearance of CBPs vs temperature:****fast appearance of CBPs vs lifetime:****slow appearance of CBPs vs lifetime:****fast appearance of CBPs vs shape:****slow appearance of CBPs vs shape:**

Figure 3.14: Differences between fast and slow appearance of CBPs versus the temperature (upper row), the lifetime (middle row), and the shape (lower row).

3.9.2 Interaction Phase

In Figure 3.15, it turns out that most of all magnetic polarities are merging with each other during a CBP's lifetime (see more in Chapter 4 lifecycle).

In a more comprehensive explanation, the most prominent part is called “new small magnetic regions appear, merge with each other and annihilate“. This part has a percentage of about 70% and is split into three subparts: 1) “new small mixed magnetic region“ with a bit more than 40%, 2) the “new small negative magnetic region“ with about 15%, and 3) the “new small positive magnetic region“ one with about 15%.

The second-largest group with more than 60% is “merging of polarities“, i.e. there are just two polarity regions or a few more of them, but big enough to count them. This group we split into three subparts: “merging of mixed polarities“ with about 12%, “merging of negative“ with about 23%, and “merging of positive“ with about 25%.

About 60% of the CBPs with merging polarities are later cancelling each other. We split this group into two parts: a large majority of “new small magnetic regions appear, merge with each other and annihilate“, as well as a small remaining part of “cancellation of polarities“ that have countable concentrations of magnetic polarities (see Chapter 4 lifecycle).

Besides that, there is a group with about 20% share, where CBPs seem to undergo little or no development, neither in the magnetic regions nor at the CBP itself. We find this behavior in all wavelength channels and in the HMI magnetogram as well.

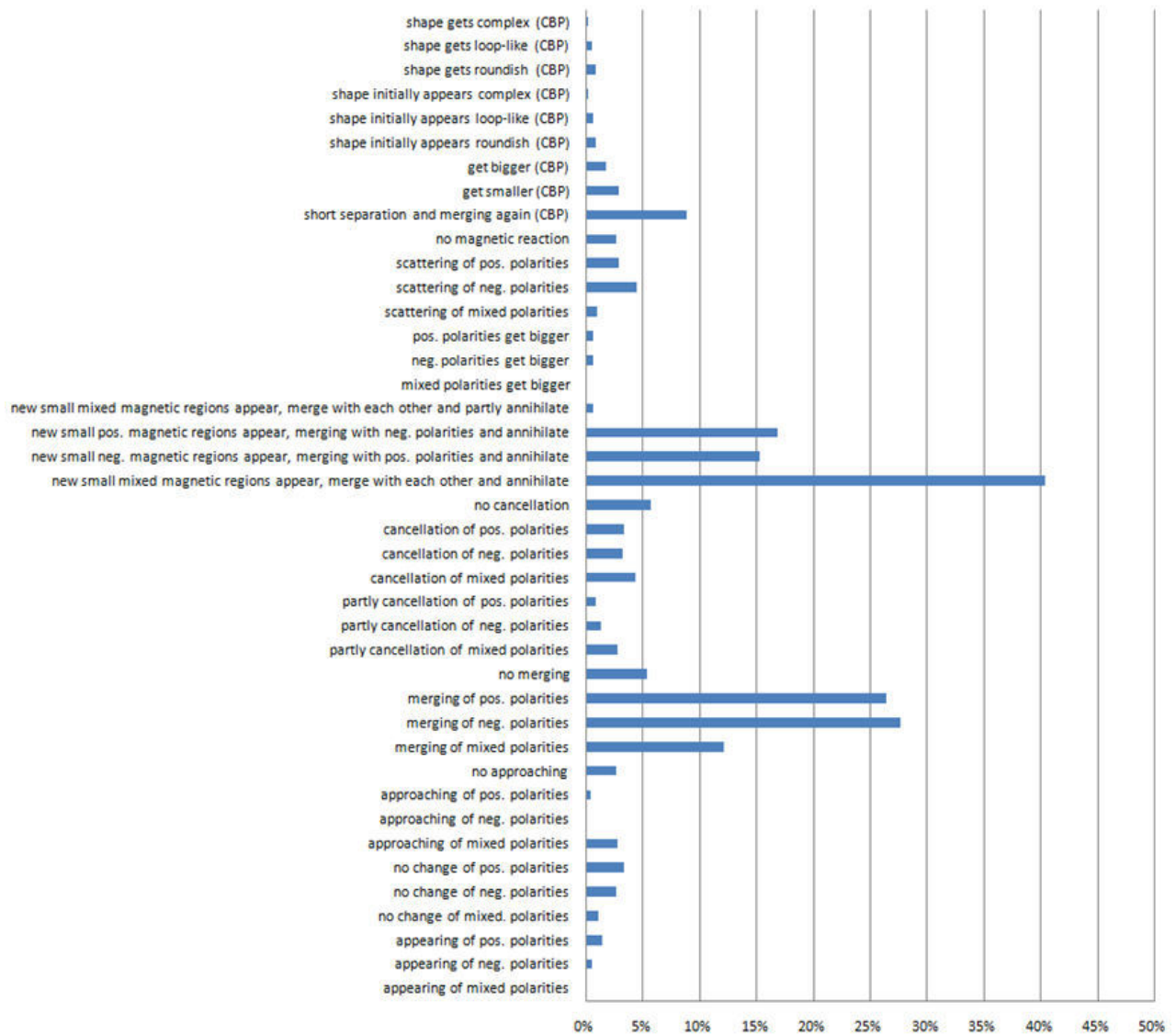
In about 5-7% of the cases, no change of polarities is recorded, namely for “mixed polarities“, for “negative polarities“, and for “positive polarities“. 2.6% of the cases are affected by “no approaching of polarities“ and about 5% by “no merging of polarities“. About 4-6% of the cases have “no cancellation of polarities“ and about 3% have “no magnetic region reaction at all“. The “no magnetic reaction at all“ part is similar to the “none“ category in Figure 3.9 that have no visible polarity. It turns out that the probability of “no magnetic region reaction at all“ is higher for cooler CBPs. As a consequence, if a CBP is cool, it might be that it is formed only within the corona and not connected to strong magnetic polarities in the photosphere (see Chapter 4 polarity).

Furthermore, Figure 3.15 shows a total of about 20% (all CBPs) 35% (complete sequences) of the remaining categories that describe other events during the evolution of a CBP in the so-called interaction phase.

The remaining categories include the “approaching“, “partly cancellation“, the “polarities getting bigger“, as well as “size and shape-changing“ CBPs, which summarizes to about 10% (all CBPs) or 18% (complete sequences). About 5% (all CBPs) or 9% (complete sequences) are of the category “short separation and merging again“, which means the CBP splits into two parts for a few minutes and then merges again. A similar fraction of 5-8% is “scattering of polarities“, which means that magnetic polarities are moving away from each other instead of merging.

Summing up, there are no remarkable effects in the wavelength channel visibility during the main phase of the life of a CBP regarding its size or shape. However, we observe fundamental changes in the magnetic field.

all selected sequences:



complete sequences:

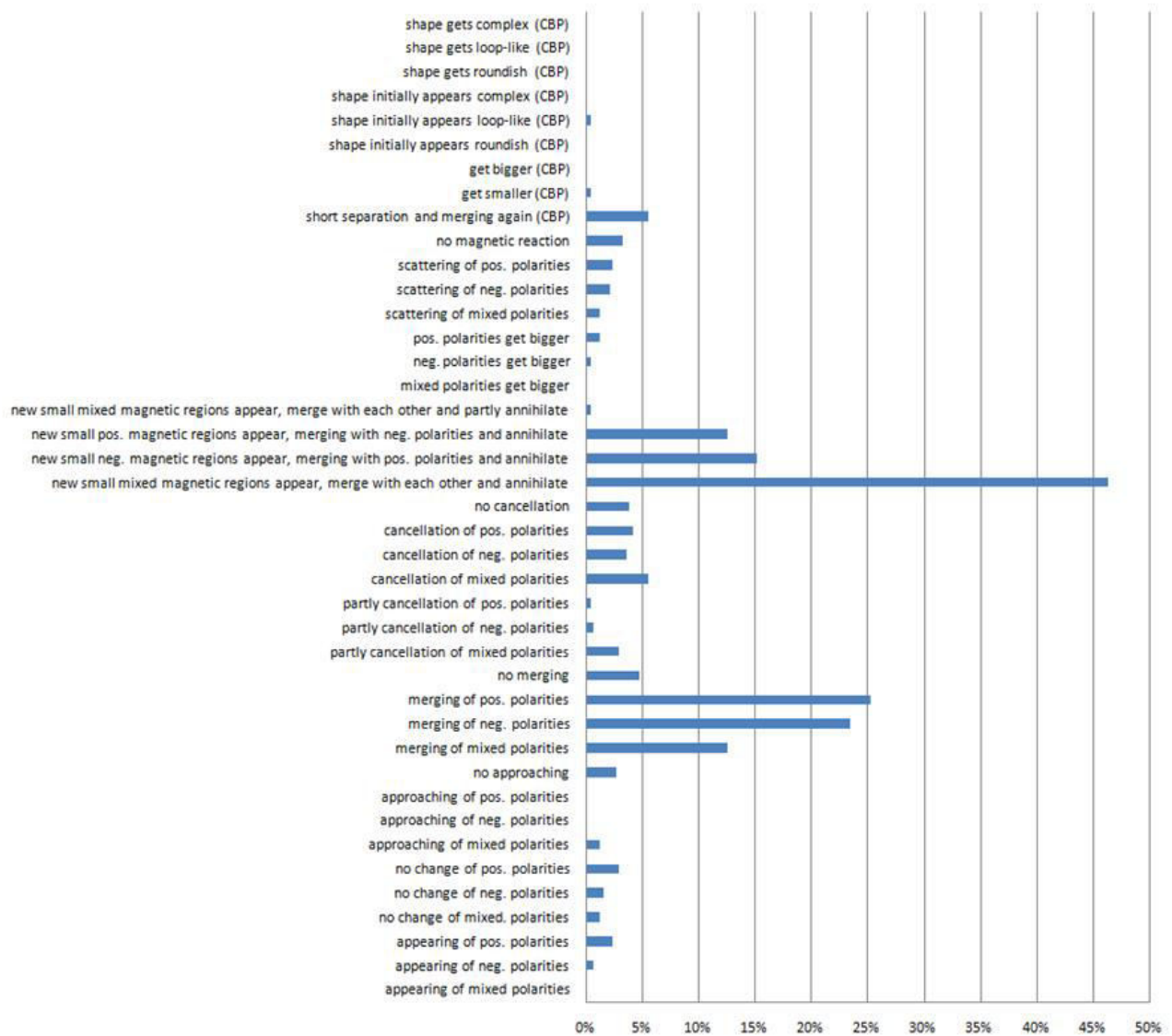


Figure 3.15: Overview of the situations during a CBP's lifecycle. Multiple properties are possible.

3.9.3 Cancellation Phase

Figure 3.16 describes how long a CBP needed for its complete disappearance. For that, we analyze about 52% of the complete CBP sequences. As in Subsection 3.9.1, if the time for disappearance of a CBP is below 5 minutes, we call this “fast” disappearance. A time of 5 – 10 minutes is “normal” and times above 10 minutes are “slow” disappearance.

We see that the “fast” disappearance is more probable than the “slow” disappearance. The “normal” appearance is an exceptional case because the disappearance of a CBP is more often fast than slow. Table 3.4 illustrates the behavior at the end of the CBP’s disappearance. Here, we use only the complete sequences, so that we know about the situation after a CBP vanished completely. About 69% of theses CBPs show a “fading” behavior where the CBP constantly loses intensity and appears weaker and weaker.

The “flickering” CBPs form a significantly large fraction of 60%, where the CBPs vary between stronger and weaker intensity.

The “get smaller” and the “the merging with another CBP” categories both have with a share of 30%. Another exception is that in about 6% of the CBPs, a new CBP immediately emerges after a CBP disappeared with only a short pause in between (see Chapter 4). All other categories are quite rare and more exceptional. This includes the ability of shape-changing from one type to another during the disappearance of a CBP.



Figure 3.16: Time a CBP needs until it disappears in all AIA channels. Less than 5 minutes (“fast”), 5-10 minutes (“normal”), and more than 10 minutes (“slow”).

Table 3.4: Overview of the situations after a CBP disappears. Multiple properties are possible.

next CBP appears	→ 6.1%
merging with another CBP	→ 28.0%
fading	→ 68.8%
flickering	→ 60.4%
get smaller	→ 29.8%
shape gets roundish	→ 2.0%
shape gets loop-like	→ 3.2%
shape gets complex	→ 0.3%
unclear	→ 0.3%

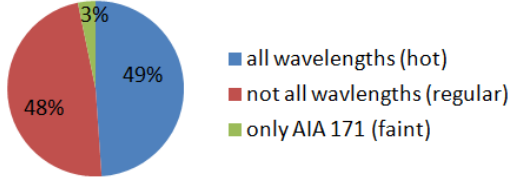
fast disappearance vs. slow disappearance of CBPs:

In the upper row of Figure 3.17, we have the same trend as the appearance diagram (see Figure 3.14). The hotter a CBP, the faster it disappears. There is indication for a trend that cooler and fainter CBPs disappear slower.

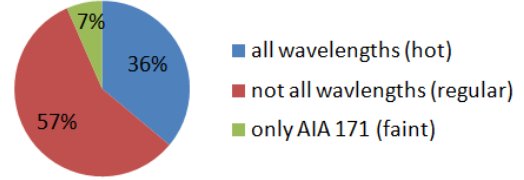
In the lower row, we see that long-living CBPs seem to disappear faster. This agrees with the trend we found for the appearance of CBPs versus their lifetime (see middle row in Figure 3.14), where the fraction of long-living CBPs is significantly enhanced for fast appearance and disappearance. Likewise, this fraction is significantly smaller for slow appearance and disappearance of CBPs.

Our statistics show that the majority of both, fast and slow disappearing CBPs, are probably more loop-like shaped.

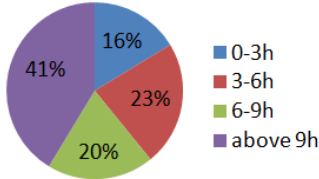
fast disappearance of CBPs vs temperature:



slow disappearance of CBPs vs temperature:



fast disappearance of CBPs vs lifetime:



slow disappearance of CBPs vs lifetime:

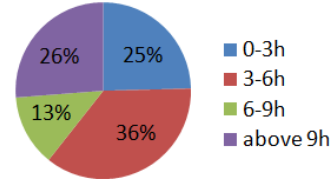


Figure 3.17: Differences between fast and slow disappearance of CBPs.

3.10 Comparison

3.10.1 Hot vs faint CBPs

In Figure 3.18, we find that the magnetic polarity of CBPs which are visible in all wavelengths (hot CBPs) has differences to the polarity of all CBPs if we compare to Figure 3.9. In Figure 3.18, we find the group of “bipolar balanced” CBPs is about 10% larger than in Figure 3.9 and the “multipolar” group is about half as large as for all CBPs. For CBPs without a clear polarity (“none”) we find almost no hot CBPs, see Figure 3.18 (upper left panel). In contrast to this, the “none” category is much larger for faint CBPs (upper right panel). For faint CBPs the most dominant category is “multipolar”, whereas the categories of “unipolar negative” and “unipolar positive”, as well as the “bipolar balanced” and “bipolar positive dominated” are empty. There is no physical reason why there should exist “bipolar negative dominated” CBPs but there are no “bipolar positive dominated”. Therefore, we think this is due to the low number of faint CBPs.

CBPs that are hot and visible in all channels show an equal merging probability to the global average; see Figure 3.11. In contrast to that, about 92% of the faint CBPs do not merge with others.

From our analysis, we find a tendency that there are more hot CBPs with a complex shape and less with loop-like structure than compared to the global average, whereas there are significantly more (58% instead of the usual 45%) loop-like structures for fainter CBPs. Also, we see the number of CBPs with a complex magnetic structure is only about half for faint CBPs than compared to the global average, see Figure 3.12.

We find that only about one-third of the hot CBPs (visible in all channels) have a lifetime of less than 6 hours, while this is the case for 45% for the global average. In contrast, more than 90% of the faint CBPs (only visible in 171 Å) live less than 6 hours. This indicates a trend that the lifetime of CBPs is significantly longer if they are visible in all channels.

In general, for this section, we find no differences between all randomly selected CBPs and the sub-group of complete sequences.

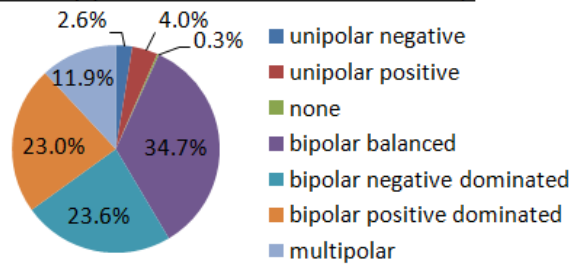
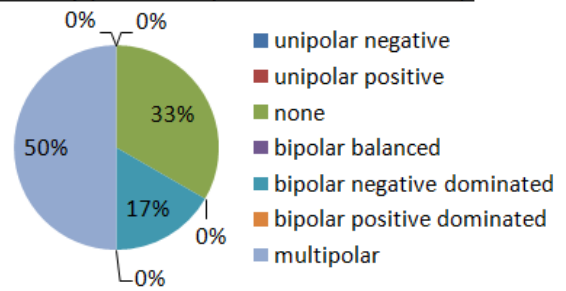
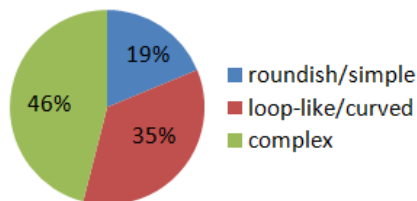
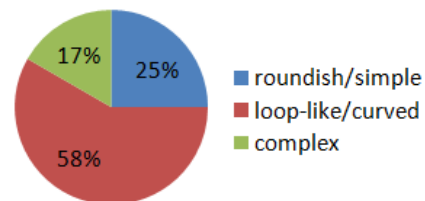
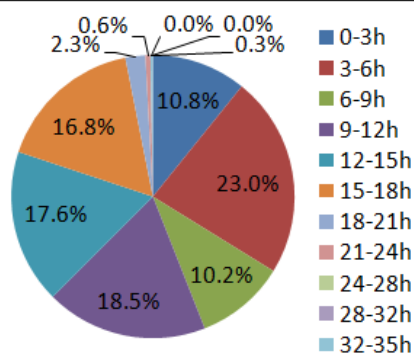
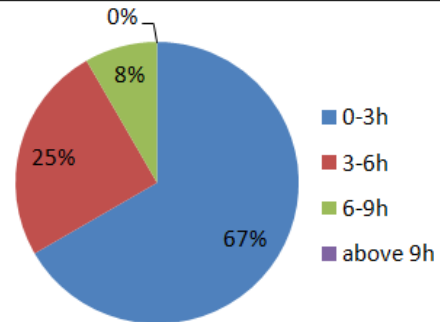
Polarity (visible in all channels – hot CBPs):Polarity (visible only in 171 Å – faint CBPs):Shape (visible in all channels – hot CBPs):Shape (visible only in 171 Å – faint CBPs):Lifetime (visible in all channels – hot CBPs):Lifetime (visible only in 171 Å – faint CBPs):

Figure 3.18: Statistics of all CBP sequences which are visible in all channels with respect to the polarity, the shape and the lifetime of CBPs.

3.10.2 Growing vs not growing bright points

In Figure 3.19, we find that only about one-quarter of the growing CBPs have a lifetime of less than 6 hours. In contrast, already more than half of the non-growing CBPs live less than 6 hours. If CBPs grow in size during their lifetime, they seem to have a longer lifetime.

There is a correlation between higher temperature and the possibility of a CBP to grow. While the temperature is higher for growing CBPs, the temperature for non-growing CBPs seems to be the same as compared to the average in Figure 3.10 for all randomly selected CBPs. For the complete sequences, there is a stronger tendency to cooler temperatures.

Furthermore, we find only negligible differences between growing and non-growing CBPs regarding their polarity, merging behavior, or shape, c.f. Figure 3.9, 3.11 and 3.12. The only exception is growing CBPs with no clear polarity, where we find this group is smaller than the global average.

We find no other differences between all randomly selected CBPs and the sub-group of complete sequences.

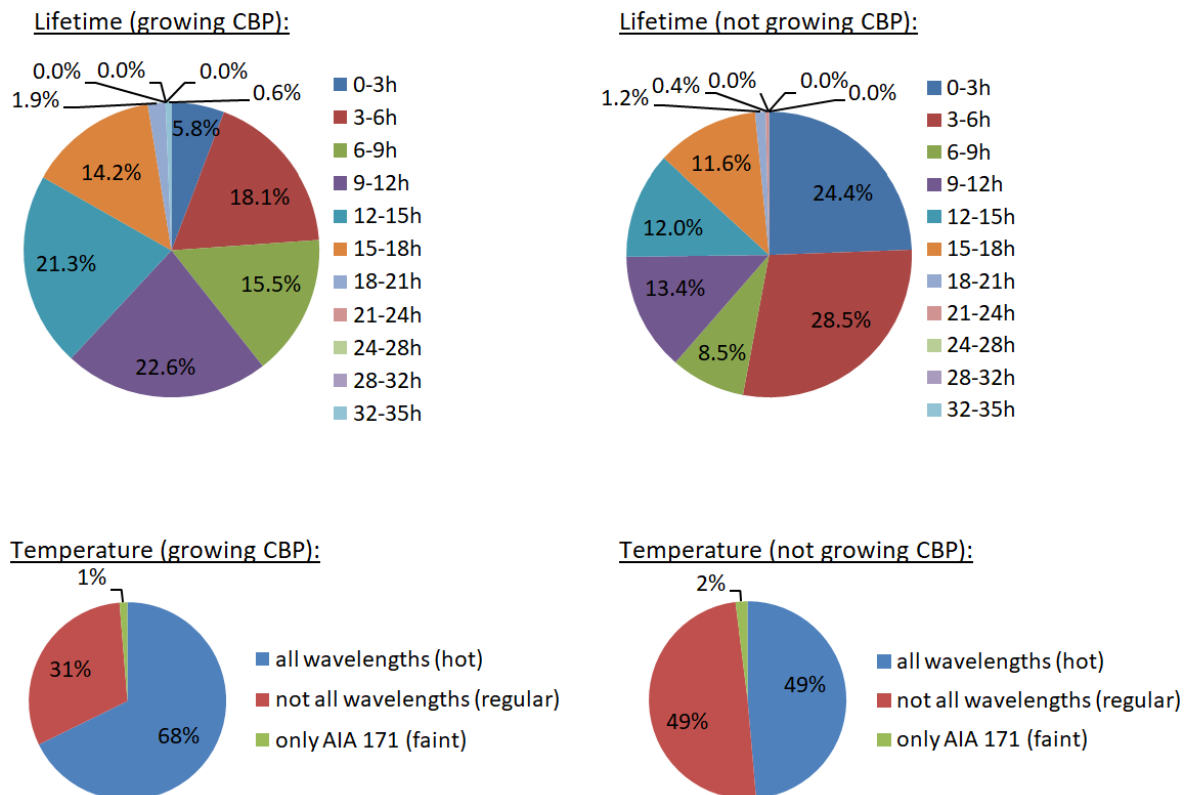


Figure 3.19: Statistics of all CBP sequences with a growing CBP in its lifetime with respect to the lifetime and the temperature of CBPs.

3.10.3 Lifetime vs Shape

In Figure 3.12, we show the probability of shape as the mean value over all lifetimes. In Figure 3.20, the sequences of different lifetimes are displayed in 3 hours time steps, and there are slight differences between the group of all randomly selected CBPs and those CBPs with a complete sequence. We see that there is a trend depending on the shape of the CBPs. For CBPs with a lifetime of 12 hours and above, we find these are much more likely to develop a complex shape. In contrast to that, CBPs with a lifetime shorter than 12 hours are more likely to be roundish (simple) or loop-like (curved). The trend is visible over all lifetimes and is relatively smooth and well to recognize for both, all selected CBPs and the complete sequences, when we compare the upper and lower panel in Figure 3.20. In general, for CBP sequences with a lifetime above 21 hours, there are too few samples for good representative statistics.

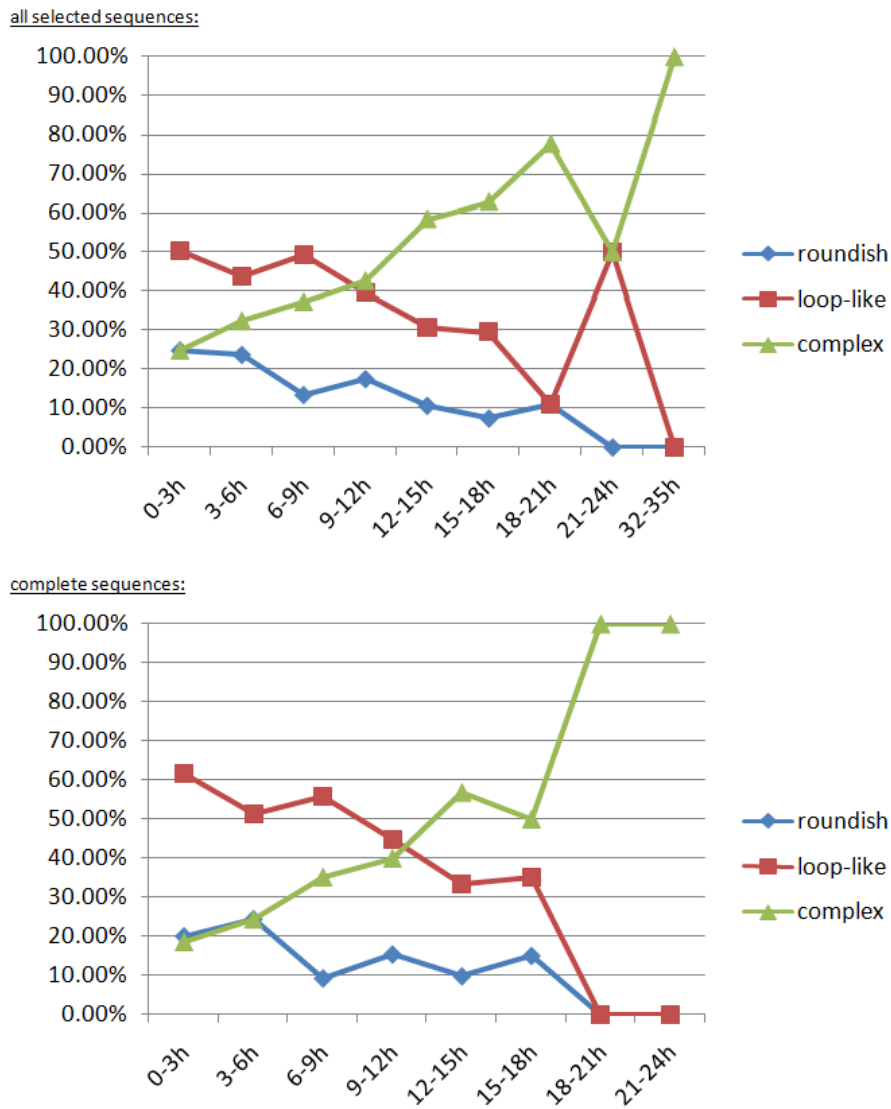


Figure 3.20: Statistics of CBPs that shows the probability of CBP shape with respect to the lifetime of the CBPs.

3.10.4 Shape vs Merging bright points

In Figure 3.11, we illustrate the likeliness of short-time merging with another CBP as the mean value over all shapes. In Figure 3.21, we show how the probability of merging depends on the different CBP shapes. For roundish and loop-like shapes, we find a clear trend of significantly lower probability for merging with another CBP within its lifetime. The situation is entirely different for complex shapes, where we find a higher probability for merging CBP. We get the same result if we analyze only the complete CBP sequences that span over the whole lifetime of a CBP.

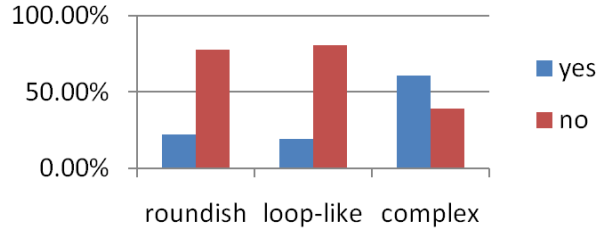


Figure 3.21: Statistics of CBPs that shows the probability of CBP mergers with respect to the shape of the CBPs.

3.10.5 Polarity vs Merging bright points

In Figure 3.11, we show the probability of short-time merging with another CBP as the mean value over all polarities. In Figure 3.22, there are small differences between all the randomly selected CBPs and the complete sequences, but following the same trend. In the case of “unipolar negative” polarity, a merge occurs in more than 50% of the cases. We find that the probability for a merger is higher for unipolar regions (“negative” and “positive”) and for one dominating polarity (“bipolar negative dominated” and “bipolar positive dominated”), as compared to the global average in Figure 3.11. In contrast to that, we find the merging probability is significantly lower if there is no clear polarity (“none”). If the flux of a bipolar region is “balanced”, we find a probability for a merger of a bit more than one-third, which is the same as for the global average, see Figure 3.11. However, for “multipolar” regions that are usually also almost balanced in flux, we report a significantly higher probability for no mergers.

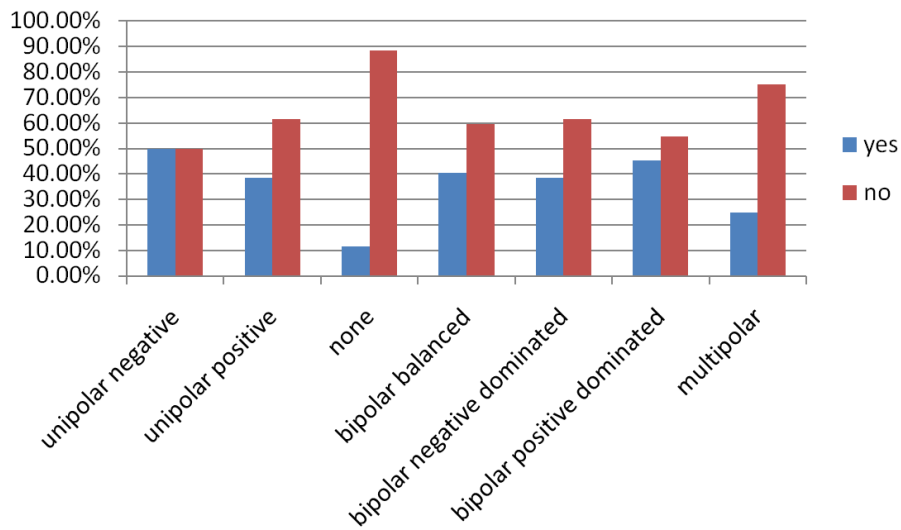


Figure 3.22: Statistics of CBPs that shows the probability of CBP mergers with respect to the polarity of the CBPs.

3.10.6 Lifetime vs Merging bright points

In Figure 3.8, we present the likelihood of lifetime as the mean value over all short-time merging to another CBP within a lifetime. In Figure 3.23, we display the sequences of different lifetimes in 3-hours time intervals. There are hardly any differences between all randomly selected CBPs and the complete sequence. Short-time merging CBPs seem to be a bit more likely in the lifetime interval of 12-15 hours. However, sequences which do not merge during their lifetime are more likely for lifetimes shorter than 12 hours.

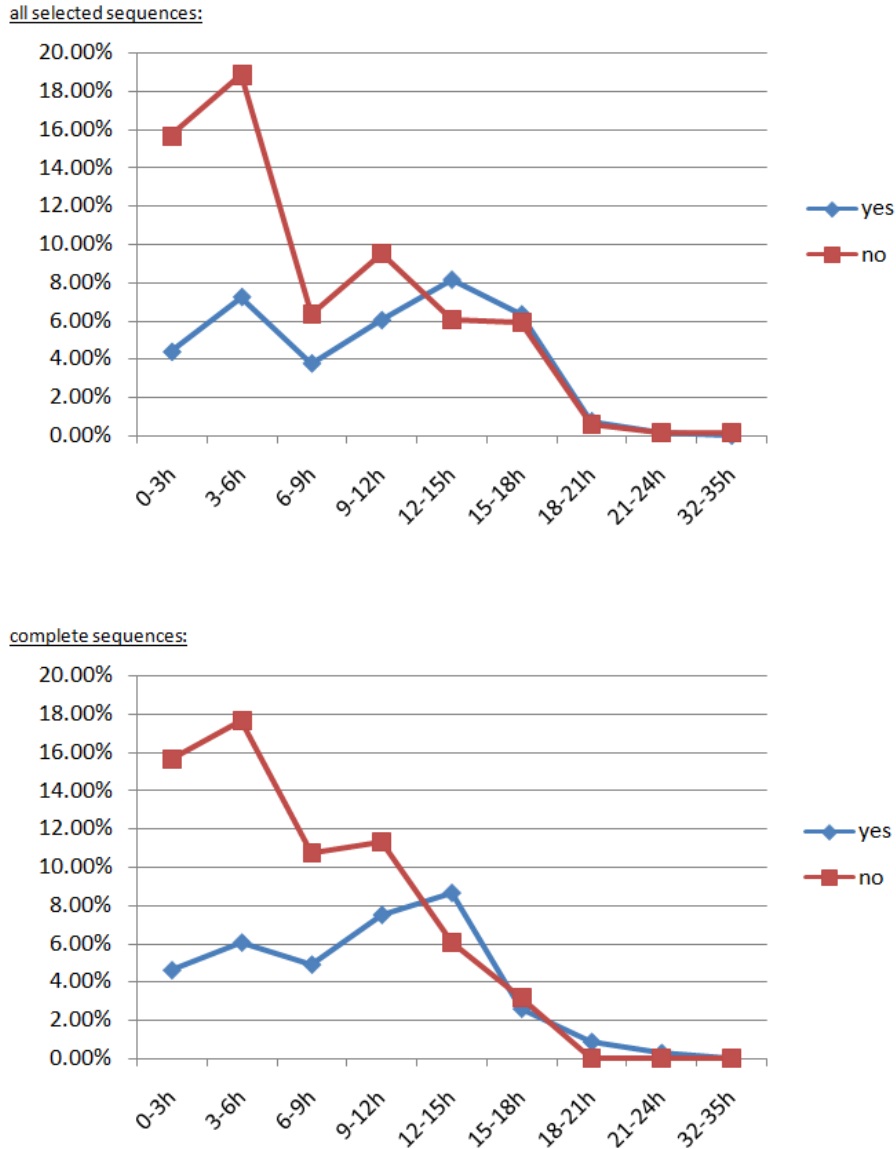


Figure 3.23: Statistics of CBPs that shows the probability of CBP mergers with respect to the lifetime of the CBPs.

3.10.7 Polarity vs Shape

In Figure 3.12, we illustrate the probability of observing a given CBP shape, irrespective of the magnetic polarity below the CBP. In Figure 3.24, we now separate CBP ensembles according to their magnetic polarity. We find few differences between the ensembles of all randomly selected CBPs versus the sub-group of complete sequences that has a similar trend.

For the category of “unipolar negative” field in Figure 3.24, we see more “complex”-shaped CBPs and less “loop-like” structures as compared to Figure 3.12. The “unipolar positive” magnetic fields have nearly the same fraction of “complex” shapes as compared to Figure 3.12. In contrast to that, we find about double the amount of “roundish” CBPs and about 15% less “loop-like” ones.

In Figure 3.24, for CBPs without a clear polarity (“none”), the shape is typically “loop-like” (55%) and therefore enhanced by about 10% to the global average from Figure 3.12. For the “roundish” shape, we see a difference of about 10% between the ensembles of all randomly selected CBPs and the complete sequences. The “roundish” shape is significantly enhanced by up to 28% in comparison to the global average over all polarity categories; see Figure 3.12. We also find that the fraction of “complex” shapes almost vanishes if we have no clear polarity. This already gives a hint that the shape of a CBP is probably dominated by the topology of the magnetic field.

For bipolar magnetic-fields with “balanced” flux, we find a similar shape distribution as the global average shown in Figure 3.12, while “multipolar” regions are significantly more loop-like. The fraction of shapes for the “bipolar negative dominated” and “bipolar positive dominated” groups deviate by about 10% to the global average shown in Figure 3.12.

We expect a similar behavior of negative and positive dominated bipolar magnetic-fields in the context of a quiet Sun magnetic network, which we also confirm with our Figure 3.24.

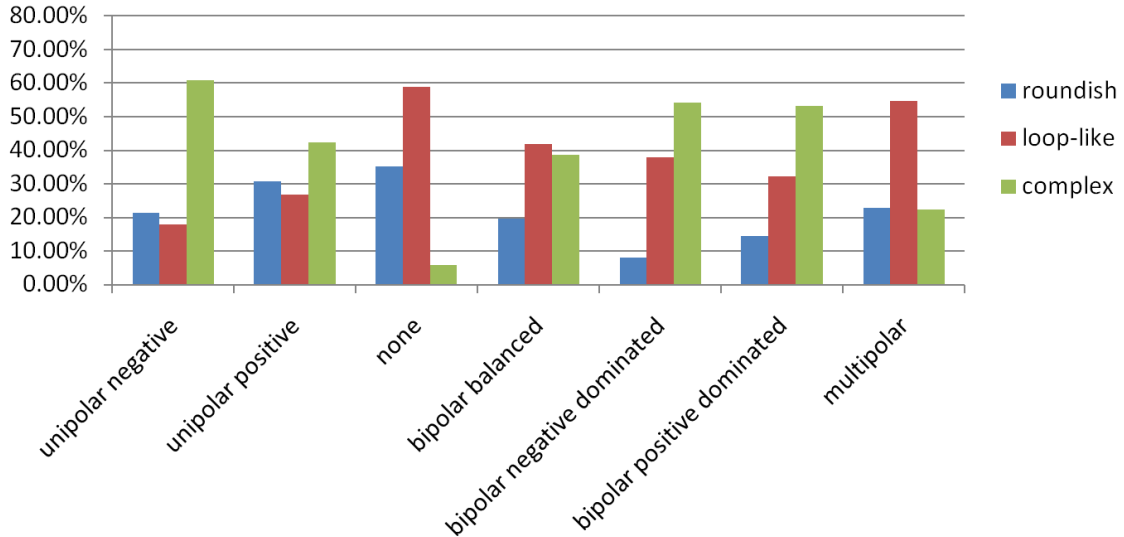


Figure 3.24: Statistics of CBPs that shows the probability of CBP polarity with respect to the shape of the CBPs.

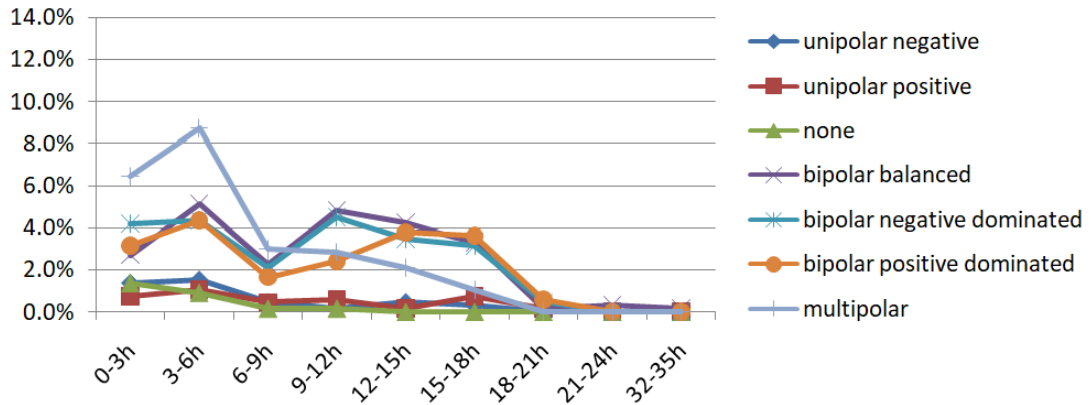
3.10.8 Lifetime vs Polarity

In Figure 3.9, we show the portion of the different polarity categories, irrespective of the lifetime of the CBPs. Now, in Figure 3.25, we display how these portions change if we divide our observations into lifetime intervals. The relative fractions within each category are well representative below a lifetime of 18 hours. For longer lifetimes above 18 hours, we have poor statistics due to the low number of observed CBPs. We find there are only few differences if we compare the two groups of all randomly selected CBPs (upper panel) versus the complete sequences (lower panel).

Within the intervals of 0-18 hours, we see the “unipolar negative” and “unipolar positive” polarities represent only a minority of CBPs that even decreases further for longer lifetimes. We find a significant fraction of CBPs without a clear polarity (“none”) only for lifetimes below 6 hours, while most of them are in the interval of 0-3 hours. This means a CBP is expected to live only for a short time if no polarity is observed below the CBP.

The portion of CBP with “bipolar balanced” magnetic-fields is larger for lifetimes of up to 15 hours and decreases significantly for longer lifetimes. The “bipolar negative / positive dominated” portions show a similar behavior. However, the portion of “multipolar” magnetic fields has a higher percentage for a shorter lifetime up to 6 hours and significantly decreases for longer lifetimes. If we restrict our analysis to the sub-group of only complete CBP sequences, we find that the general trends are very similar. The relative fractions of “bipolar balanced” and “multipolar” regions are not significantly higher because the statistical error is about similar to the differences.

all selected sequences:



complete sequences:

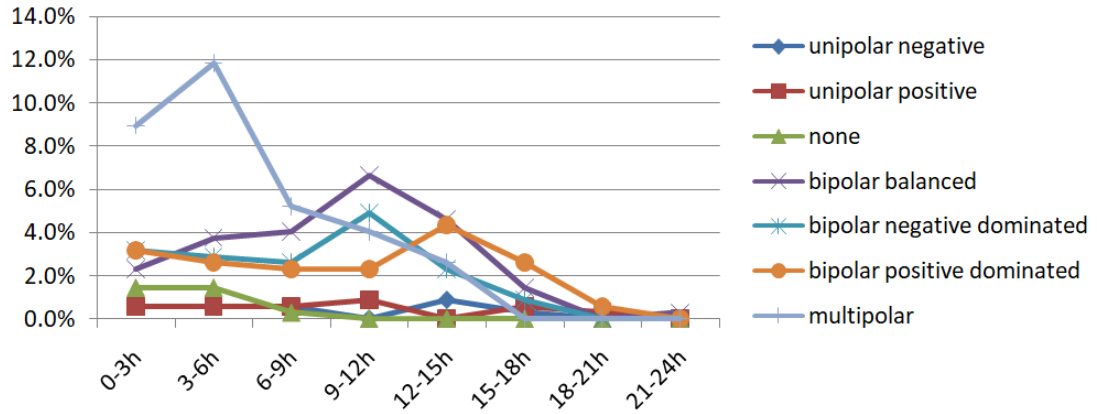


Figure 3.25: Statistics of CBPs that shows the probability of CBP polarity with respect to the lifetime of the CBPs.

Chapter 4

Discussion

General methods and results in the literature:

In 2001 a model from Longcope et al. [35] showed that CBPs could be formed from reconnection of a prior unpaired bipolar connection. Such a reconnection or flaring caused by a single CBP may provide just a small contribution to the total energy. However, by combining all the CBPs together, this energy release may play a crucial role in heating up the corona. In addition to that, there are at least 300-400 CBPs on solar disk on each image which are uniformly distributed [24]. As described in the literature, there are magnetic fields with negative and positive poles connected with the respective CBPs [15,32], where these fields appear with an approximate value of 10^{18} - 10^{19} M_x [33,47]. The estimation of all, just once released CBP energy together is about 2×10^{29} *erg*, whereby CBPs usually can flare more often in their lifetime [24,38,51]. A typical CBP usually has a life span that ranges from minutes to days and is smaller than 60 arcsec [66,73]. It can be seen in regions of QS and CH that within 24 hours, 1500 CBPs can appear [13,14].

There is a recent statistical CBP study of SDO observed in EUV wavelengths to find more information about the CBP's properties such as their spatial, temporal and magnetic behavior [2]. In this study from Alipour & Safari in 2015 [2], the period of their observation took place from June 2010 to December 2014, which makes 4.4 years. They selected 700 CBPs and found different shapes, i.e. point-like, loop-like and multiple-loop ones. The "separate events" (see Subsection 1.3.1 distance criterion) reach between 427 to 790 CBPs, which makes a mean number of 572 CBPs. Compared to older studies from Priest et al. (1994) and Sattarov et al. (2010) [47,53], this is about 1.5 times higher. The density reaches between 1.39×10^{-4} to 2.56×10^{-4} Mm^{-2} and makes on average 1.9×10^{-4} Mm^{-2} [2]. Beyond the $\pm 60^\circ$ latitude as well as longitude, which is seen from the center of the solar disk, the area is excluded due to the lack of accuracy at the solar limb. The reason is too high area ratio. So, the observing analysis takes place within the $\pm 60^\circ$, whereby on average, nine CBPs newly emerging every 45 seconds. By including the not considered area outside the $\pm 60^\circ$, there will be an appearance of approximately 27 ± 3 new CBPs on the solar disk every 45 seconds. 2.6% of the solar disk consists of bright points, whereas half of this percentage or 1.3% of the solar disk consists of their bright point's cores (see Section 2.5) [2].

In another study, AIA shows all the fine structures of the CBPs, including its single but often multiple existing poles too, including their connectivity, which resemble small active regions. In the channel AIA 193 as well as in channel AIA 211 the morphological structure of CBPs can be clearly identified, and their changes can be observed over their entire lifetime (see Section 2.4 and 2.5). The area is defined by 50×50 arcsec to capture the CBP as a whole to simplify the tracking path of its lifetime in each channel [9]. In addition to that, the regions of magnetic fields are examined and well observable in active regions [24].

Compared to the literature, we show results with about 900 to slightly more than 1,000 CBPs at any given time during the research period of 12 days (between the 13th of August and 24th of August 2015). We exclude the solar limb in this thesis as well (see Subsection 2.3.3). The shape of the CBPs is best seen in AIA 171 and AIA 193 and by adding the channel AIA 211 to the existing database, the fluxtube of CBPs can be better identified (see Table 3.2). Moreover, the structure is observable.

Problems with identification of CBPs:

The CBPs might have a trend to anti-correlation to the 11-year solar cycle using observations. However, in the literature, it is emphasized that this is not the case and even show independence of the solar cycle [19, 39, 52]. In other words, suggestions indicate that there is an anti-correlation between the CBPs and the 11-year solar cycle, but it becomes apparent through the bias of observations that the quantity of CBPs is not dependent on the solar cycle [27]. Some publications conclude contradictory insights into this topic. The solar maximum, as well as the solar minimum, seem to show a different amount of CBPs. They show up more at a maximum, while at a minimum there are less of them including a more uniform distribution [34]. Otherwise, another study in 2010 showed that a slight decline in the density number of CBPs was observed during the solar maximum. Consequently, this question is not definitely cleared [27]. It has to be taken into account geometrical and observational effects too.

In the literature, the data set of CBPs in the regions QS and CH is studied through visual judgment by eye, although sometimes there are difficulties in the identification of magnetic footpoints. Adding additional channels such as AIA 171, AIA 193 and AIA 211 show clearly the existence of a CBP and if they can be seen in HMI magnetograms too, a correct selection of a CBP has been made [2].

The CBPs have a slightly different appearance in every single channel because of different temperatures and heights [2]. The identification of the respective CBP's appearance and disappearance is quite tricky since some of them do not match with a typical CBP due to the cancellation of magnetic poles in the conventional sense. Sometimes the formation and evolution of a CBP within two polarities can lead to disconnection of magnetic flux instead of building it up. Otherwise, some are formed within two polarities, and one of them may show flux cancellation while the other does not. The reconnection of CBPs can be caused by surrounding magnetic poles or their different separation. They could be induced or even prevented by large-scale magnetic field's orientation [24].

Compared to the literature, we are faced with exactly this kind of CBPs identification problem by eye-tracking too. The difference in different channels was clearly visible due to their respective temperature and height. Moreover, the majority of the found CBP sequences have not caused any problems, and the active regions, as well as the solar limb, are excluded in advance too (see Subsection 2.3.3).

Moreover, as can be seen in Figure 3.6 in this thesis, there are two different tracking scenarios, which are implemented and already explained in Chapter 3. In general, the randomly selected CBP sequences and the complete sequence CBPs are summarized in this Chapter and their values are explained as an average.

Gap Problems:

In the literature, gap problems occur [2]. So, there are also gaps in the data [25]. The missing images could be solved by adding the missing image from one channel to the other one. Therefore, the CBPs have to be identified at least by one of the two channels, 171 Å or 211 Å. This is tagged as a single event. Apart from that, the beginning of a new subsequent CBP is initiated [2].

Compared to the literature, our results show no gap problems by missing images. The only gaps are triggered by the algorithm, which is responsible for the mapping of CBPs. The contours of the CBPs are sometimes difficult to track by the algorithm due to intensity fluctuation, especially at the beginning and at the end of a CBP's lifetime. Therefore, our results show that about 15-20% of the sequences indicate that gaps occupy more than 40% of the sequence itself. In turn, the other 80-85% shows sequences with much less than 40% of gaps within a CBP sequence (see Figure 3.7). As mentioned before, the occurrence of gaps is most likely at the beginning and end of a CBP's lifetime.

Lifetime:

In the literature, the lifetime of CBPs is less than 20 minutes for 52% of all CBPs, which makes 12 minutes on average and called “transient events”. On the contrast, the average of the other 48% is about 6 hours and called “persistent events”. According to Wang et al. (1999) [67], the majority of microflares can be found in transient events. More precisely, over 95% of CBPs have a lifespan below 20 hours [2]. Another study indicated that the CBP could last for more than 30 hours too [9], but a lifetime above 48 hours is rare [2]. As an exception, Alipour & Safari in 2015 found nine long-lived CBPs with more than 72 hours [2]. Pursuant to the study, the shorter the lifetime, the higher the size distribution, which means small as well as large CBPs are detected no matter of lifetime influence. However, the size trend shows a weak increase with time (see in the Comparison part below) [2]. The size of a CBP seems to have only a minor influence on a CBP’s lifetime, which does not automatically mean the longer the lifetime, the bigger the CBP.

Our results fit well compared to the literature. It is nearly the same portion of about 46% of CBPs with a life span of 6 hours. Moreover, the portion below 18 hours is about 98% and also agrees with the value of the literature. This means the remaining 2% of CBPs or 12 sequences have a lifetime above 18 hours. There is only one CBP sequence, which lasts longer than 35 hours (see Figure 3.8). On the basis of our much shorter research period of only 12 days, the algorithm’s possibility of finding a longer-lived CBP sequence was quite low.

Magnetic-Field Polarity:

In the literature, the main formation reason for a CBP is the reconnection of opposite poles which causes a noticeable increase in intensity [42]. CBPs are most probably corresponding to the magnetic field in the photosphere. There they appear either as more often magnetic bipolar or as quite unlikely isolated unipolar structures that have positive or negative flux (see Section 2.4) [24, 38].

Compared to the literature, our results perfectly agree with this statement. Moreover, the results show that about 90% demonstrate non-unipolar magnetic-fields, whereby about 23% of them have bipolar balanced polarities and more than 25% are multipolar. The other about 20% of them has bipolar magnetic-fields with negative dominated distribution, whereas the remaining 20% of them has bipolar magnetic-fields with positive dominated distribution. The remaining 10% can be divided into a bit more than 3% of unipolar negative polarity and another about 3% of the unipolar positive polarity, and a bit less than 3% of CBPs with no polarity (see Figure 3.9).

According to literature, some CBPs could have been formed in the corona and not in the photosphere. Therefore, a CBP could be visible without being generated in the photosphere, and no magnetic flux would be observable too (more in cool and hot components of CBPs below) [41].

Shape (complexity):

In the literature, only the shape of a CBP’s area is examined, but the shape of its kernel and the CBP itself, respectively, have not taken into account due to complexity [13]. Small-scale bipolar magnetic loops are frequently common characteristics of a CBP, and in case of more complexity, the shape of a CBP’s appearance is more complex as well (see Section 2.4 and 2.5). The emerging, as well as the cancellation of opposite polarities of a CBP, is clearly seen in HMI magnetograms [2, 29]. It seems to be that the CBP’s temporal evolution shows dependency with the appearance of magnetic polarities as well as their disappearance. So, new connectivity arises and can also vary in different pairs of polarities as their evolution continues. The CBPs are formed point or loop-like after some time, but can change these structures during their lifetime as well (more details in the lifecycle below) [9].

Compared to the literature, our results represent CBP sequences with loop-like structure of about 45%, roundish ones with a bit more than 15% and complex ones with a bit less than 40% (see Figure 3.12). The more complex the polarity, the more complexity the CBP in each channel is showing, which agrees with the literature (see more in the Comparison part below). The same is valid for the CBP’s evolution, if the magnetic-field polarity changes, i.e. appear or disappear, the CBP shows corresponding changes too (see Section 2.5). CBPs can also change their shape during their lifetime, which is also clearly visible but it happens quite rarely in the thesis (see Figure 3.15).

Temperature:

The mean temperature of CBPs goes from 1.1 *MK* to 3.4 *MK* due to their temperature variations caused by their changing X-ray outputs. Moreover, it seems to be, the shorter the timescale, the higher the variability of the heating rate of CBPs. Nanoflares possibly cause the occurrence of temperature peaks of 7 *MK*. This indicates the assumption of an existing reconnection source. The intensity and the temperature of a CBP are increasing immediately at the same time during the reconnection process, as long as the energy deposit is high enough [27].

Cool and hot components of CBPs:

Through the determination of CBP's temperature of utilizing two filters in X-ray, CBPs can be encountered for lower and higher temperature in the upper layer of the Sun's atmosphere. This means at different heights or different temperatures they have cool and hot components ranging from the transition region to the corona. Consequently, for the filter with He II, the CBPs are classified as cool components of the CBPs in the transition region and for the filter, with soft X-ray, they are classified as hot components of the CBPs in the corona (see Subsection 1.3.1 and Table 2.1) [27].

All these previous studies observed the CBPs in the atmosphere in different heights and therefore, are generated at different temperatures. The variability in temperature and morphology, i.e. the change in the structure of CBPs, and how this is connected with the plasma, is not entirely captured. The knowledge of whether co-existence of low and hot temperature CBPs in the corona itself exists would be an interesting aspect. Kariyappa et al. 2011 [27] found out that in the corona CBPs can be formed at the same heights at different temperatures. This means that the temperature of CBPs does not absolutely depend on the height of the atmosphere [27].

However, the correlation between the temperature and the intensity is valid for all CBPs. It is suggested that a CBP's formation is formed through the fluctuations in temperature, which show a connection to the reconnection of the magnetic field in the photosphere. Results of observed CBPs show that there are CBPs without large variations, but in the end after a given time, all CBPs reveal a continuous decline in brightness and temperature [27]. The path and movement of the magnetic field, as well as the cancelling or fragmenting process in a CBP's lifetime, is difficult to observe on the photosphere. Some CBPs can be generated in the corona and not on the solar surface by movements of magnetic fields. Regarding this, the highest brightness is observable in the corona, whereas in the lower layers such as the chromosphere, the brightness is decreasing. Thus, there is a correlation between the temperature and the brightness (see Section 3.5) [41].

Compared to the literature, our results also show a different CBP's appearance in different channels due to their different temperatures in each channel (see Section 2.4 and 2.5). By adding the channel AIA 335 to the existing database, the temperature range is extended and thus, CBPs can be better identified between AIA 211 and AIA 94. Each found CBP is recognizable in AIA 171 without any exceptions due to the fact of its best emission response (see Section 2.1 temperature response). In the other channels like AIA 131, AIA 193 and AIA 211 there are about 90% of all CBPs visible, whereas AIA 304 in about 80% of cases, AIA 335 in at least about 60% and AIA 94 at about 50% of cases. Another reason for the weak response in AIA 335 as well as in AIA 94 could be the temperature of CBPs, which have to be quite hot to reach these two channels.

In contrast, the channel AIA 304 is quite cool, and therefore the missing approximately 3% (except AIA 304) can come from the formation process which takes place in the corona and not in the photosphere. This is visible in about 3% of the "except AIA 304" part of the pie chart, i.e. a certain CBP is not observable due to its generation occurs in the corona (see Section 2.4 and 2.5). The "except AIA 94" part is also considered with a portion of about 35%, which means that these CBPs are not that hot. The "except AIA 304 and AIA 94" part with about 10% reveals a possible formation of a CBP in the corona, which is not hot enough for channel AIA 94. The biggest portion is represented with about 50%, where all wavelengths are visible in each channel, i.e. CBPs are created in the photosphere and have hot components. As mentioned before, every CBP sequence is visible in AIA 171, but there are also the faint and cool CBPs, which are only visible in the AIA 171 channel. It is the smallest portion with only about 2% (see Figure 3.10). The specific temperature of each separate channel is listed in Table 2.1.

Lifecycle:

One-third of the CBPs are generated at ephemeral magnetic regions (erupting magnetic flux), and two-thirds are created at the upper top of the cancellation processes of bipolar magnetic-fields (encounters of opposite magnetic polarity by chance) [2, 9, 20, 68]. The required energy of CBPs during their lifetime is provided by repeating of emerging and elimination of reconnections.

This happens until the flux completely disappears in a particular region [9]. According to literature, there are two possible causes of forming a CBP. The one caused by the emergence of magnetic flux, and the other caused by the cancellation of magnetic flux of opposite polarities due to their approaching, merging and finally their disappearing again. During these processes, the flux's value is more than $10^{17} M_x$ or $20 G$. In more detail, the regions within $-20 G$ to $20 G$ are considered for a CBP. The results suggest that cancellation seems to be more common with 75%, while the other 25% is caused by emergence [68] (see Subsection 1.3.1 reconnection process and Figure 3.15) [2]. When the process of reconnection is finished, the plasma gets cooler. The duration of the cooling time takes about 5 to 20 minutes, although the reconnection is not over at that time, there is no intense reconnection anymore. Otherwise, there are results which are indicating some CBPs reconnection showing intense energy release, where the hot plasma with high temperature suggests an association between them [27]. In another study in 2013 from Zhang [75], they assume that the CBPs are influenced by the evaporation of the chromosphere that is generated through heat transportation by the previous CBP (see Figure 3.13 and Figure 3.16). It reveals that it is not usual to have such a counterpart in the chromospheres (comparison to Subsection 1.3.3) [24].

Compared to the literature, our results show that they fit well into the literature ones, concerning the cooling time or time for disappearing. There is a preference for fast disappearance within 5 minutes than for slow disappearance with more than 10 minutes. However, the appearance is either fast or slow. Moreover, it turns out that the hotter CBPs, the faster they appear. In contrary, cooler or fainter CBPs show slower appearance in the channels, and therefore they need more time for formation. The exact same is valid for the disappearance of CBPs (see Figure 3.14 and Figure 3.17). There is just a tiny indication that the faster they appear, the longer the lifetime and a loop-like or roundish shape is more likely. However, there is an even stronger indication of short-living CBPs for slow appearance and a loop-like shape. That also seems to be analogue for the disappearance of CBPs. It even does not matter if CBPs disappear fast or slow, the main tendency is the loop-like shape. In all found cases of CBP's sequences, their respective magnetic regions initially appear in the HMI channel before the CBP itself gets visible in the wavelength channels. Some of these magnetic polarities, whether positive or negative, are getting bigger too. As mentioned in the CBP's lifetime above, there is also shown a weak increase in size with time in this thesis (see more in the Comparison part below).

We find that about 40% of the CBPs show a growing behavior in the beginning phase of a CBP's lifetime. The flickering part is even more significant with about 60% of cases. We demonstrate the separation from another CBP to create a new one with about 20%, and the merging with another CBP to form a new CBP is demonstrated with about 14%. The CBPs, which initially appear in a certain shape in the beginning phase and change afterwards, is only true for about 3-5% (see Figure 3.13). This value does not change much during and after the lifecycle. In other words, only 3-5% of CBPs show a shape-changing behavior at the beginning, during or at the end of their lifetime. Most of the CBPs evolve and slightly change their shapes with time but not that dramatic to categorize them in another shape type. Another exception is the appearance immediately after another CBP with only 1.4%.

Within the CBP's lifecycle, our results show that most of all CBPs have polarities that merge with other polarities at some point. About 60% of these merging polarities finally annihilate with opposite polarities. Although the value from literature is a bit higher, the trend clearly shows that cancellation plays an essential role. Other portions are the 20% where are hardly any changes neither in magnetic regions nor in the AIA channels of CBPs themselves.

In other words, a percentage of about 20% of all CBPs show barely any activities. This includes the “no change of polarities” category. Just a few CBPs show only a subset of the activities like “approaching”, “merging”, “annihilate with each other”, and “any magnetic reaction at all”. Moreover, the 20-35% where other activities are shown, e.g. the polarities are scattering, or the CBPs have a short separation and merge again after a few minutes. The size of CBPs is neither getting significantly bigger nor smaller during their lifecycle (see Figure 3.15).

We find in about 30% of cases that the CBPs get smaller at the end of a CBP’s lifecycle. Moreover, the flickering part with about 60% and the fading away part with about 70% are even more significantly visible. After the lifecycle, about 28% of the CBPs are merging with another CBP, and a new lifecycle begins. Further, in about 6% of cases, an entirely new CBP appears and the lifecycle starts again. Hence, the cancellation of the previous CBP is a significant part of the next CBP’s emergence (see Figure 3.13 and Figure 3.16).

In this thesis, we investigate in further aspects like fluxtube and merging CBPs behavior.

Merging bright points:

We find that a bit more than a third of all CBP sequences have a short-time merging with another CBP within their lifetime. In turn, two-third never merges with another CBP (see Figure 3.11).

Fluxtube:

We show that about 15% of CBPs have no fluxtube in their entire lifetime while most of CBPs show fluxtube. There are nearly equal portions of about 75% each for AIA 171, AIA 193 and AIA 211 and most of the time they are even simultaneously visible. About 40% show fluxtube in AIA 304, whereas AIA 335 and AIA 94 show hardly any fluxtube activities with a value of about 1% each and AIA 131 with a bit more than 5%. For AIA 335 and AIA 94, the reason could be the required high temperature, which is not reachable for all CBPs because they are too cool for these channels. An interesting aspect is that there is only about 1% where the fluxtubes are observable in all wavelengths, i.e. they only can be seen in the hottest CBP sequences (see more in Table 3.2).

Comparisons:

In general, the longer the lifetime of CBPs, the hotter is the temperature, the higher is the probability of a complex shape, and the higher is the probability of short merging of CBPs. The shorter the lifetime, the fainter is a CBP, the more likely is a roundish or loop-like shape, and the lower is the probability of short merging of CBPs.

The probability of a short merging during their lifetime is a bit higher for long-lived CBPs. The tendency shows that the more complex the shape, the more likely is a short-time merger of CBPs, whereas the loop-like CBPs and roundish ones stay more isolated during their lifetime.

There is a tendency of longer lifetime and higher temperatures if CBPs grow in size during their lifecycle. If a CBP grows or not does not change the shape distribution or the short merging behavior. The polarity is almost not influenced by the growing behavior of CBPs. Except for growing CBPs we find less CBPs with no clear polarity.

The polarity of CBPs is influenced by the lifetime. The unipolar polarities, the none polarity, as well as the multipolar ones, are more likely at shorter lifetime, while the bipolar polarities seem to have only a marginal tendency to longer lifetime.

The polarity has few influences whether CBPs have a roundish, loop-like or complex shape. However, for unipolar negative and bipolar negative and positive dominated magnetic regions, the complex shape seems to have the highest probability. In contrary, the unipolar positive polarities, the roundish shape is more dominant than for unipolar negative ones. For the bipolar balanced magnetic regions, there is hardly any influence, whereas the multipolar ones are more dominated by loop-like shapes. For non-existing polarity, the loop-like portion makes up the majority and also the roundish ones play an essential role, but there are hardly found any complex-shaped CBPs.

In general, for the unipolar negative and positive magnetic regions as well as for the bipolar balanced, bipolar negative and positive dominated ones, the merging is a bit more probable, while for none and multipolar magnetic regions the merging is significantly less. In other words, the more the polarity is shifted to one specific negative or positive side, the higher the probability of merging.

The hot temperature has hardly any influence on the polarity, except that there are more bipolar balanced CBPs and less multipolar magnetic regions. For faint CBPs with a lower temperature, the multipolar and none polarity portions are significantly higher and the bipolar negative dominated portion is a bit lower. The other polarity types cannot be found at low temperature.

Summary:

The main findings imply that the majority shows a good correlation between the samples of 663 CBP sequences and the sub-group of 346 complete CBP sequences. There are just a few differences if we analyze either of these two CBP ensembles, which is an indication our statistics are robust even if we apply it on the larger ensemble of incomplete CBP sequences.

Why SDO was the best option for the thesis?

The reason we choose the satellite SDO is the higher accuracy. In comparison to earlier studies from SOHO with EIT onboard, the SDO with AIA onboard has an 8% higher found average number of CBPs on solar disk in 193 Å. Hence, spatial resolution, time cadence, as well as the space between the observed CBP and their surrounding CBPs, is crucial for the tracking algorithm. This makes a big difference in identifying such small events [2]. The precision of tracking CBPs have huge effects on their lifetime. According to Zhang et al. in 2001 [73] a mean life span is specified of 20 hours for a typical CBP using SOHO with EIT onboard, whereas the mean life span using AIA lies at about 6 hours and less [2]. As expected, the same mean value is also found in our results. This agrees with the assumption that the higher the lifetime, the fewer CBPs can be found [34]. The difference between EIT's and AIA's cadences is responsible for different lifetime measurements of CBPs. While the cadence of SDO with AIA onboard has a time step every 60 s, SOHO with EIT onboard only has a time step every 26 min. This was leading to this misjudgment (see Figure 2.3) [2].

Chapter 5

Conclusion and Outlook

McIntosh et al. (2014) [37] found out that the formation region of CBPs is mainly located around the edges of huge convective cells also called supergranules [61]. The average value of the CBP's height according to Kwon et al. (2010) [30] is at about 5 to 7 Mm above the photosphere [2]. Normally, CBPs occur from the photosphere into the chromosphere further to the corona (Sun's atmosphere) [34].

CBPs and their most probably contribution for corona heating was subject of several studies over the last decades. According to Golub & Pasachoff in 1997 [16], there is suggested the assumption of CBPs generating new magnetic flux all over the solar surface more than the active regions do. So, there is a certain chance that the magnetic field is interacting with the CBP's generating process. Furthermore, the number of CBPs indicates the extent of the source energy of magnetic activity [25]. Assuming, that they have a significant effect on coronal heating, studies show that each single CBP is heated up to several MK and their density is $\sim 10^9 \text{ cm}^{-3}$ [34]. In the literature, the majority of the CBPs are generated by the magnetic bipole's cancellation, while only a small proportion is generated by the emergence of magnetic flux with 10^{18} - $10^{19} M_x$ [43, 47, 68, 74]. The fact remains that magnetic reconnections occur especially from CBPs with opposite polarities, so they might be at least locally the main essential factor of heating up the plasma in the corona [2, 34].

Other studies show the well visible irregular movements of bright structures from the center of the CBP to the edge of these structures utilizing all 9 AIA wavelengths onboard of SDO. Their mean velocity is approximately 300 km s^{-1} , and they have a mean period of 90 s. The result of moving to each other is possible evidence of confirming magnetic reconnection model. These bi-directional structures could be the direct seen consequences after the reconnection [34]. In other words, the strong release of energy may indicate the reason for these oscillations through CBP reconnections [27]. CBPs are indicators for coronal rotation, whereby they function as tracers. Another aspect is the X-ray irradiance variability where the CBPs are contributors [25].

The intention of this master thesis is to analyze and compare similarities and differences of CBPs at different wavelengths in the solar atmosphere. This study comprises a succession of processes to get results of CBP's properties [2]. For this analysis, we use the SolarSoft libraries in IDL, as well as Python. On the solar disc, every day, 1500 CBPs appear [13] which makes 800 CBPs at each instant of time, according to Zhang et al. in 2001 [73]. In the literature, a 4.4 years study analyzed 1400 CBPs due to obtaining representative results which included all sizes, shapes, brightness and lifetime of CBPs [2]. So, statistically speaking, their results agree with our results of this thesis with about 900 to slightly more than 1000 CBPs, which are present at any given time.

Starting with an identification algorithm as well as later on a tracking algorithm, those are utilized for a combination of 171 Å and 193 Å AIA images and 6173 Å HMI magnetograms from SDO with a resolution of 0.6 arcsec per pixel and a sufficient cadence of 60 seconds. However, AIA and HMI have not the exact same cadence, rather an original exposure time of 12 seconds for AIA and 45 seconds for HMI [2].

As in the literature, the data is leveled up from 1.0 to 1.5, and correction of the solar differential rotation is done as well as the removal of the active regions [2]. After data reduction, the database is built up for a 12 days period where the sequences can be found.

Within the scope of this thesis, many sequences with clearly recognizable CBPs are found for 12 days, from 13th of August to 24th August in 2015. For this analysis, we found 663 randomly selected sequences, whereby 346 CBPs of them fulfill the criteria of an entire evolution cycle. This also contains the emergence and disappearance of CBPs. The sequences are found and analyzed by the algorithm, whereby the final concluding check is accomplished visually by eye. The intensity of coronal and magnetic field is defined. Hence, heliographic coordinates are computed by coordinates of images of solar disk center including radius and orientation [2, 24]. In this work we follow the same scheme.

We only consider CBPs with a smaller size than 50×50 pixels (2500 pixels). Another limitation is the size change from one image to another, which is at a maximum of 30%. We exclude the active regions and the solar limb due to the possible influence on CBPs. Therefore, a threshold of 300 pixels away from the center of an active region is necessary. Another algorithm criterion is that CBPs should at least have a lifetime of one hour to get at least 60 images for analyzing. Otherwise, if CBPs would have a shorter lifetime, this could lead to insufficient knowledge about a CBP's evolution process.

According to the literature, the areas, the magnetic fluxes, the intensities on its maximum and on average, as well as the lifetime and their variations of the CBPs, are analyzed [24]. In this master thesis, we treat even further properties. So, the primary investigations are the value of the CBP's algorithm gaps, the lifetime, the temperature, the fluxtube, the short merging during the lifetime, the magnetic polarity, the behavior of the lifecycle and the shape.

In summary, in this thesis, we reveal the primary key points as mentioned in the following. Most of the CBPs have algorithm gaps between 10-30% within the entire sequence. Furthermore, a typical CBP's lifetime is about 3-6 hours. We find that most of the CBPs show high temperature due to they are visible in each wavelength channel. In addition, the clear majority of CBPs have fluxtubes, which is an indication of interaction with other CBPs. In other words, the higher the temperature, the higher the chance to see the fluxtubes. Otherwise, there is just a marginal percentage of CBPs where the fluxtubes can be seen in all wavelengths. The best chance to see the fluxtubes are in AIA 171, AIA 193 and AIA 211 since they have the best available temperature responses. A typical CBP has bipolar magnetic-fields, whereas unipolar and non-existing polarity is quite rare in relative terms. About a third of CBPs has a short merging to another CBP within their lifetime. The most preferred shape of CBPs is a loop-like one, followed by a complex one, whereby roundish seems to be the rarest type.

We analyzed the behavior of merging between CBPs and their growth in size. We find that there is no difference for the growing behavior due to mergers of CBPs. However, we see that growing CBPs tend to be hot. Furthermore, if we look at faint and cooler CBPs, we see they typically have no or only weak magnetic field below them. For these three reasons, we conclude that the mechanism that creates and heats the CBPs is not due to energy transported with plasma packets being added to an existing CBP. Other mechanisms that come into question are, e.g. the dissipation of magnetic energy.

Faint and cooler CBPs have a far less complex shape and are significantly more loop-like than the average of all CBPs. This indicates that cooler CBPs are probably low-laying magnetic loops that just reach to the base of the corona, where the plasma can be heated to coronal temperatures by magnetic energy dissipation. We also find that cooler CBPs have a significantly shorter lifetime. We think this is because weak magnetic fields have less energy to heat the CBP and undergo a quicker reconfiguration due to advection processes in the photosphere.

In order to compare all these results with the literature, it should be considered that the CBPs sequences analysis is based on automated algorithm tracking. This includes a few gaps where the shape is not recognized by the algorithm, and the application of inspection and analysis is done by eye. A further explanation of the possible discrepancies is based on the fact that some of the found sequences do not fulfill the criteria of an entire lifecycle.

As mentioned in the literature, it is difficult to find the connection of CBP and their respective magnetic footpoints. There are situations, a CBP is bright and part of a larger loop, where the footpoints are definitely visible. Otherwise, CBPs are emerging between magnetic regions that are far away from each other and even not part of the cancellation process [24].

In conclusion, the found results in this master thesis mostly agree or at least show a trend qualitatively in agreement with other studies. Although our research period is much shorter compared to the literature, and therefore the sample is quite smaller, the results are representative. They even show nearly the same values.

Outlook:

In summary, it can be said that this CBP analysis is mostly consistent with the literature, but there are two possible improvements related to an even better analysis. The possibility exists that the number of sequences we used for this master thesis analysis is too small. So, enlarging the sample would allow making more accurate statements about the evolution of CBPs and consequently enabling more significant comparisons with other studies.

It seems reasonable to suppose that the mapping algorithm needs improvement due to the possible uncertainty of a few not well identified CBPs or other misguided contours of them cannot be ruled out. In particular, for analyzing the quick changing components of periodicity, it makes sense to use the wavelet analysis [41].

The example of SOHO shows that by measuring images of total flux from the SOHO's EIT instrument, the temperature peak of the loops, as well as their maximum value and the emission measure, can be calculated. The spacecraft response of plasma is using a density of $n_e=10^9 \text{ cm}^{-3}$.

By using a loop model with constant pressure and the aid of the EIT responses, the response curves can be created. The data numbers per unit (DNs) are plotted against the maximum value of temperature (T_{max}), whereby the temperature is not a dependent variable.

In the case of EIT's loop response, it shows at a higher maximum value of temperature an extended tail. The reason for that might be hot loops of cool footpoints. The flux ratio represents the temperature:

$$T_{max} = 10^{6.3} \left(\frac{F_{195}}{F_{171}} \right), 0.9 \text{ MK} < T_{max} < 1.6 \text{ MK} \quad (5.1)$$

The respective temperature is described for the appropriate loop. On the other hand, the unresolved loops have been estimating by using a linear combination. Then a flat response can be obtained over a particular range of temperature, which looks as follows:

$$EM = 1.4 \times 10^{43} \text{ cm}^{-3} (F_{171} - 0.4 F_{195}) \pm 19\% \quad (5.2)$$

In the case of the unresolved loops, the total power heating is illustrated. With the aid of the loop scaling laws from Serio et al. 1981 [57], the needed power for the reconnection can be calculated [35]:

$$P = 1.3 \times 10^{-19} EM T_{max}^{-1/2} \quad (5.3)$$

Through differential emission measure (DEM) functions, the variability of emission measure (EM) is considered with height [49].

For emission measure, $EM \propto n^2 e$ is used and indicate that the emission measure is proportional to electron density. For creating spectra, differential emission measure (DEM) curves are required. Therefore, the temperature range from the cool chromosphere, where the emission is optical thick with a temperature of $2 \times 10^4 \text{ K}$, to the hot corona, where the emission is highly ionized with a temperature of $5 \times 10^7 \text{ K}$, is useful. By integration over the defined range of wavelengths, a single temperature with its counts per second per pixel is given. In other words, the sensitivity of the instrument at a single temperature is measured in $\text{DN s}^{-1} \text{ pix}^{-1}$. By using CHIANTI, an atomic database for spectroscopic diagnostics, this procedure gives resulting DEM curves for four classes of solar features such as quiet Sun (QS), coronal holes (CH), flares (FL) and active regions (AR) [49].

The term dh is the emitting plasma and is used for CHIANTI routines, which can be demonstrated by:

$$EM = \int n_e^2 dh \quad (5.4)$$

$$DEM = n_e^2 dh/dt \quad (5.5)$$

So, we obtain:

$$EM = \int_{\Delta T} DEM dt \quad (5.6)$$

The DEM curve is given for a temperature range of $\log_{10} \Delta T = 0.1$ and can be extracted for EM.

In Figure 5.1, the trend of the curves of all four solar features is quite similar in a comparison between DEM to EM. The curves among themselves show a similar trend too, at least at the beginning. At about more than 1 MK, there is no or just a little bit of plasma left in the coronal hole, and its curve is decreasing significantly. The peak of AR is at about 1.6 MK, while QS has its peak at about 2 MK. The peak of the FL lies at about 10 MK. The density of plasma determines the amount of atomic transition that takes places in the upper levels. In turn, this transition determines the intensity of an emission line.

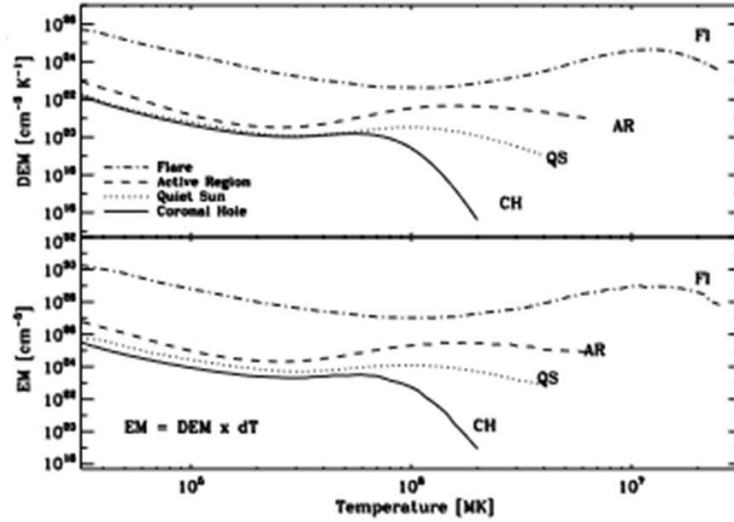


Figure 5.1: Solar features such as flares, active regions, the quiet Sun and coronal holes are shown by the function of temperature versus DEM (Differential emission measure) and EM (emission measure) [49]. The following density values are used for these different solar features: Coronal holes with 10^7 cm^{-3} (Wilhelm 2006) [69], Quiet Sun with $6 \times 10^8 \text{ cm}^{-3}$ (Young 2005) [71], Active regions with $5 \times 10^9 \text{ cm}^{-3}$ (Gallagher et al. 2001) [12] and Flares with 10^{11} cm^{-3} (Raftery et al. 2009) [48]. (Image taken from [49].)

Concerning SDO's AIA instrument, a CBP analysis would be possible by using CHIANTI. The new approach can be used to get new insights and would allow making more precise statements regarding the definition and evolution of the CBPs. In other words, it is possible to make reliable and better statements about the behavior of CBPs during their lifecycle.

Appendix A

Appendix

In the course of this work several computer codes have been developed and redesigned. These codes are used for data pre-processing, segmentation, data compression, creation of a database, filtering, and CBP tracking. The two tables below (A.1 and A.2) list the file names and their purpose for Python and IDL codes. The DVD attached to the printed thesis contains these codes and some selected videos of CBPs, as well as the database of CBP properties.

A.1 Python Codes

Name	Purpose
bpt_filesearch_and_informationandmaps	finds all downloaded CBP fits files without missing files in between (overview of all original fits files)
bpt_file_search_and_informationlvl15andmaps	finds all prepared CBP fits files without missing files in between (overview of all level 1.5 fits files)
bp_merge_fits2bin	reads in all fits files, merges the data together into a single table and writes the table into a single binary file
bp_find_sequence	reads in the binary file and finds CBP sequences in the file
bp_plot_sequence	reads in the binary file and plots CBP sequences
bp_sequence_fits_files	finds CBP sequences and creates fits files
bp_sequence_filter	filters the CBP sequences with criteria factors: maximum size in pixels, its maximum allowed percentage change of size from one time step to next time step, minimum allowed distance to the active regions, minimum lifetime of 60 minutes

A.2 IDL Codes

Name	Purpose
download	This routine will download the data of the input instrument between start_time and end_time.
bpt_file_search_and_info	This routine searches and checks the data from all wavelengths (AIA 94, AIA 131, AIA 171, AIA 193, AIA 211, AIA 304, AIA 335 and HMI) at a certain date. 1440 fits per day have to be available. It finds all downloaded CBP files without missing files in between (overview of all level 1 fits files) and ensures that no file got lost.
bpt_aia_prep	This routine will apply aia_prep.pro to AIA or HMI lev1 images from a directory dir_AIA lev1 or HMI lev1 and create AIA or HMI lev15 images in a directory dir_AIAlev15. AIA images for all wavelengths or HMI magnetogram images are transferred from level 1 to level 1.5. Level 1.5 images are centered and the limb position is established. Additionally, all level 1.5 images have the same coordinate systems. (Same pixel position is same position on the Sun.)
bpt_compress_fits	This routine compresses all fits files to save disk space and deletes uncompressed files.
bpt_start_segmentation	This routine starts the CBP segmentation algorithm to produce CBP segmentation maps.
bpt_overarch	This routine downloads the data from start_time to end_time at 1 minute interval and process the data: 1) calibrate AIA data 2) start CBP segmentation
bpt_file_search_and_infolev15	This routine searches and checks the data from all wavelengths (AIA94_lv15, AIA131_lv15, AIA171_lv15, AIA193_lv15, AIA211_lv15, AIA304_lv15, AIA335_lv15 and HMI_lv15) at a certain date. 1440 fits per day have to be available. It finds all prepared CBP files without missing files in between (overview of all level 1.5 fits files) and the ensures that no file got lost.
bpt_create_database	This routine scans all map images and finds the daily CBP database. It reads out CBP information from image data and saves it to a database. The image data covers 24 hours of observation with a cadence of 1 minute. For each date, a separate database is created.
bpt_combine_databases	The routine reads single database files and combine them to one database file. This way many databases can easily be read by other programs by using just one input file.
bpt_load_database	This routine sets the database in the global variables, to make the routine much faster.
bpt_db_videocontour	The routine draws contour lines on the CBP videos. The whole CBP evolution is visualized.
bpt_movie	The routine selects randomly 663 CBPs for video creation.
make_movies	The routine creates a video file from the image series.

A.3 List of abbreviations

AIA	A tmospheric I maging A ssembly
bpt	b right p oint t racking
CBP	C oronal B right P oint
CCD	C harge- C oupled D evice
CME	C oronal M ass E jection
db	d atabase
DEM	D ifferential E mission M easure
EIT	E xtrême U ltraviolet I maging T elescope
ESTEC	E uropean S pace R esearch and T echnology C entre
EUV	e xtrême U ltra V iolet
EUVI A	E xtrême U ltra V iolet I mager A
EUVI B	E xtrême U ltra V iolet I mager B
EVE	E xtrême U ltraviolet V ariability E xperiment
FITS	F lexible I mage T ransport S ystem
HMI	H elioseismic and M agnetic I mager
IDL	I nteractive D ata L anguage
JSOC	J oint S cience O perations C enter
MBP	M agnetic B right P oint
MDI	M ichelson D oppler I mager
PROBA2	P ROject for O n B oard A utonomy satellites 2
SDO	S olar D ynamics O bservatory
SECCHI	S un E arth C onnection C oronal and H eliospheric I nvestigation
SOHO	S OLar and H eliospheric O bservatory
STEREO	S olar T ERrestrial R ELations O bservatory
SWAP	S un W atcher using A PS detectors and image P rocessing
TIMED	T hermosphere I onosphere M esosphere E nergetics and D ynamics
TRACE	T ransition R egion A nd C oronal E xplorer
UTC	U niversal T ime C oordinated
XBP	X -ray B right P oint
X-ray	X -radiation
XRT	X - R ay T elescope
XUV	soft X -ray

A.4 Conclusion (German version)

McIntosh et al. (2014) [37] fanden heraus, dass der Entstehungsbereich von CBPs hauptsächlich an den Rändern riesiger konvektiver Zellen liegt, die auch Supergranula genannt werden [61]. Der Durchschnittswert der CBP-Höhe nach Kwon et al. (2010) [30] befindet sich etwa 5 bis 7 Mm über der Photosphäre [2]. Normalerweise treten CBPs von der Photosphäre in die Chromosphäre weiter bis zur Korona (Sonnenatmosphäre), auf [34].

CBPs und ihr wahrscheinlichster Beitrag zur Koronaerwärmung waren in den letzten Jahrzehnten Gegenstand mehrerer Studien. Laut der Annahme von Golub & Pasachoff im Jahr 1997 [16] erzeugen CBPs neuen magnetischen Fluss auf der gesamten Sonnenoberfläche, stärker als in den aktiven Regionen. Es besteht also eine gewisse Wahrscheinlichkeit, dass das Magnetfeld mit dem Erzeugungsprozess des CBP interagiert. Darüber hinaus gibt die Anzahl der CBPs das Ausmaß der Energiequelle der magnetischen Aktivität an [25]. Unter der Annahme, dass sie einen signifikanten Effekt auf die koronale Erwärmung haben, zeigen Studien, dass jedes einzelne CBP auf mehrere MK erhitzt wird und ihre Dichte $\sim 10^9 \text{ cm}^{-3}$ beträgt [34]. In der Literatur werden die meisten CBPs durch die Aufhebung des magnetischen Bipols erzeugt, während nur ein geringer Anteil durch das Auftreten eines magnetischen Flusses mit 10^{18} - $10^{19} M_x$ erzeugt wird [43, 47, 68, 74]. Es bleibt die Tatsache, dass magnetische Wiederverbindungen insbesondere bei CBPs mit entgegengesetzten Polaritäten auftreten, so dass sie zumindest lokal der wichtigste Faktor für die Erwärmung des Plasmas in der Korona sein könnten [2, 34].

Andere Studien zeigen die gut sichtbaren unregelmäßigen Bewegungen heller Strukturen vom Zentrum des CBP zum Rand dieser Strukturen unter Verwendung aller 9 AIA-Wellenlängen an Bord von SDO. Ihre mittlere Geschwindigkeit beträgt ungefähr 300 km s^{-1} und sie haben eine mittlere Periode von 90 s. Das Ergebnis der Bewegung zueinander ist ein möglicher Beweis für die Bestätigung des magnetischen Wiederverbindungsmodells. Diese bidirektionalen Strukturen könnten die direkten Konsequenzen nach der Wiederverbindung sein [34]. Mit anderen Worten, die starke Freisetzung von Energie kann den Grund für diese Oszillationen durch CBP-Wiederverbindungen anzeigen [27]. CBPs sind Indikatoren für die koronale Rotation, wobei sie als „Tracer“ fungieren. Ein weiterer Aspekt ist die Variabilität der Röntgenstrahlungsintensität, bei der CBPs dazu beitragen [25].

Das Ziel dieser Masterarbeit ist es, Ähnlichkeiten und Unterschiede von CBPs bei verschiedenen Wellenlängen in der Sonnenatmosphäre zu analysieren und zu vergleichen. Diese Studie umfasst eine Reihe von Prozessen, um Ergebnisse der CBP-Eigenschaften zu erhalten [2]. Für diese Analyse verwenden wir die SolarSoft-Bibliotheken in IDL sowie Python. Auf der Sonnenscheibe erscheinen jeden Tag 1500 CBPs [13], das zu jedem Zeitpunkt 800 CBPs ausmacht gemäß Zhang et al. im Jahr 2001 [73]. In der Literatur wurden in einer 4,4-jährigen Studie 1400 CBPs analysiert, um repräsentative Ergebnisse zu erhalten, die alle Größen, Formen, Helligkeiten und Lebensdauern von CBPs umfassten [2]. Statistisch gesehen stimmen ihre Ergebnisse also mit unseren Ergebnissen, mit etwa 900 bis etwas mehr als 1000 helle Punkten, die zu einem bestimmten Zeitpunkt vorhanden sind, überein.

Beginnend mit einem Identifikationsalgorithmus sowie später mit einem Tracking-Algorithmus werden diese für eine Kombination von 171 Å und 193 Å AIA-Bildern und 6173 Å HMI- Magnetogrammen von SDO mit einer Auflösung von 0,6 Bogensekunden pro Pixel und einer ausreichenden Kadenz von 60 Sekunden verwendet. AIA und HMI haben jedoch nicht die gleiche Kadenz, sondern eine ursprüngliche Belichtungszeit von 12 Sekunden für AIA und 45 Sekunden für HMI [2].

Wie in der Literatur werden die Daten von Level 1.0 auf 1.5 erhöht, und die Korrektur der solaren Differenzialrotation sowie die Entfernung der aktiven Regionen werden durchgeführt [2]. Nach der Datenreduktion wird die Datenbank für einen Zeitraum von 12 Tagen aufgebaut, in der die Sequenzen gefunden werden können.

Im Rahmen dieser Arbeit werden vom 13. August bis zum 24. August 2015 für 12 Tage viele Sequenzen mit klar erkennbaren CBPs gefunden. Für diese Analyse haben wir 663 zufällig ausgewählte Sequenzen gefunden, von denen 346 CBPs die Kriterien eines gesamten Evolutionszyklus erfüllen. Dies beinhaltet auch die Entstehung und das Verschwinden von CBPs. Die Sequenzen werden vom Algorithmus gefunden und analysiert, wobei die abschließende Prüfung visuell per Auge durchgeführt wird.

Die Intensität des koronalen und magnetischen Feldes wird definiert. Daher werden heliographische Koordinaten durch Koordinaten von Bildern des Sonnenscheibenzentrums einschließlich Radius und Orientierung berechnet [2, 24]. In dieser Masterarbeit wird dasselbe gemacht wie in der Literatur.

Wir berücksichtigen nur helle Punkte mit einer Größe von weniger als 50×50 Pixel (2500 Pixel). Eine weitere Einschränkung ist die Größenänderung von einem Bild zum anderen, die maximal 30% beträgt. Wir schließen die aktiven Regionen und den Sonnenrand aufgrund des möglichen Einflusses auf CBPs aus. Daher ist ein Schwellenwert von 300 Pixeln von der Mitte eines aktiven Bereichs entfernt, erforderlich. Ein weiteres Algorithmerkriterium ist, dass CBPs eine Lebensdauer von mindestens einer Stunde haben sollten, um mindestens 60 Bilder für die Analyse zu erhalten. Andernfalls könnten CBPs mit einer kürzeren Lebensdauer zu unzureichendem Wissen über den Entwicklungsprozess eines CBP führen.

Laut Literatur werden die Flächen, magnetische Flüsse, maximale und durchschnittliche Intensitäten sowie die Lebensdauer und ihre Variationen analysiert [24]. In dieser Masterarbeit behandeln wir noch weitere Eigenschaften. Die primären Untersuchungen sind also der Wert der Lücken des CBP-Algorithmus, die Lebensdauer, die Temperatur, das Flussrohr, die kurze Verschmelzung während der Lebensdauer, die magnetische Polarität, das Verhalten des Lebenszyklus und die Form.

Zusammenfassend zeigen wir in dieser Arbeit die wichtigsten Punkte, die im Folgenden erwähnt werden. Die meisten CBPs weisen innerhalb der gesamten Sequenz Algorithmuslücken zwischen 10 und 30% auf. Darüber hinaus beträgt die Lebensdauer eines typischen CBP etwa 3-6 Stunden. Wir stellen fest, dass die meisten CBPs eine hohe Temperatur aufweisen, da sie in jedem Wellenlängenkanal sichtbar sind. Zudem weist die klare Mehrheit der CBPs Flussröhren auf, was ein Hinweis auf die Interaktion mit anderen CBPs ist. Mit anderen Worten, je höher die Temperatur, desto höher ist die Chance, die Flussröhren zu sehen. Ansonsten gibt es nur einen sehr geringen Prozentsatz von CBPs, bei denen die Flussröhren in allen Wellenlängen sichtbar sind. Die beste Chance die Flussröhren zu sehen, bieten AIA 171, AIA 193 und AIA 211, da sie die besten verfügbaren Temperaturreaktionen haben. Ein typischer CBP hat bipolare Magnetfelder, während unipolare und nicht vorhandene Polarität jedoch relativ gesehen recht selten ist. Etwa ein Drittel der CBPs hat innerhalb ihres Lebens eine kurze Verschmelzung mit einem anderen CBP. Die am meisten bevorzugte Form von CBPs ist eine schleifenartige, gefolgt von einer komplexen Form, wobei eine runde Form die seltenste Form zu sein scheint.

Wir haben das Verhalten der Verschmelzung von CBPs und ihrem Größenwachstum analysiert. Wir stellen fest, dass es keinen Unterschied für das Wachstumsverhalten aufgrund von CBP-Verschmelzungen gibt. Wir sehen jedoch, dass wachsende CBPs dazu neigen, heiß zu sein. Wenn wir schwache und kühlere CBPs betrachten, sehen wir außerdem, dass sie typischerweise kein oder nur ein schwaches Magnetfeld unter sich haben. Aus diesen drei Gründen schließen wir, dass der Mechanismus, der die CBPs erzeugt und erwärmt, nicht auf Energie zurückzuführen ist, die mit Plasmapaketen transportiert wird, die zu einem vorhandenen CBP hinzugefügt werden. Andere Mechanismen, die in Frage kommen, sind z.B. die Ableitung von magnetischer Energie.

Schwache und kühlere CBPs haben eine weitaus weniger komplexe Form und sind deutlich schleifenartiger als der CBP-Durchschnitt. Dies weist darauf hin, dass kühlere CBPs wahrscheinlich niedrig liegende Magnetschleifen sind, die gerade bis zur Basis der Korona reichen, wo das Plasma durch magnetische Energiedissipation auf koronale Temperaturen erhitzt werden kann.

Wir stellen auch fest, dass kühlere CBPs eine deutlich kürzere Lebensdauer haben. Wir glauben, dass schwache Magnetfelder weniger Energie haben, um den CBP zu erwärmen, und aufgrund von Advektionsprozessen in der Photosphäre eine schnellere Rekonfiguration erfahren.

Um all diese Ergebnisse mit der Literatur zu vergleichen, sollte berücksichtigt werden, dass die CBP-Sequenzanalyse auf einer automatisierten Algorithmusverfolgung basiert. Dies schließt einige Lücken ein, in denen die Form vom Algorithmus nicht erkannt wird und die Anwendung der Inspektion und Analyse mit dem Auge erfolgt. Eine weitere Erklärung der möglichen Diskrepanzen basiert auf der Tatsache, dass einige der gefundenen Sequenzen die Kriterien eines gesamten Lebenszyklus nicht erfüllen.

Wie in der Literatur erwähnt, ist es schwierig, die Verbindung von CBP und ihren jeweiligen magnetischen Fußpunkten zu finden. Es gibt Situationen, in denen ein CBP hell und Teil einer größeren Schleife ist, in der die Fußpunkte definitiv sichtbar sind. Andernfalls entstehen CBPs zwischen magnetischen Regionen, die weit voneinander entfernt sind und nicht einmal Teil des Auslöschungsprozesses sind [24].

Zusammenfassend lässt sich sagen, dass die in dieser Masterarbeit gefundenen Ergebnisse größtenteils übereinstimmen oder zumindest qualitativ einen Trend zeigen, der mit anderen Studien übereinstimmt. Obwohl unser Forschungszeitraum im Vergleich zur Literatur viel kürzer ist und die Stichprobe daher recht klein ist, sind die Ergebnisse repräsentativ. Sie zeigen sogar fast die gleichen Werte.

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