Morphology and evolution of coronal holes at the wavelengths of 171 Å, 193 Å, and 211 Å in the Solar Cycle 24

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Abstract. Coronal holes are an area that appears dark in the corona, which is observable in EUV and X-ray wavelengths. This area has an open magnetic field structure. The magnetogram image showed that the coronal hole has one polarity (unipolar). Commonly, the shape and size of the coronal hole at the poles are related to the structural strength of the magnetic field. Because of this unipolar nature, the coronal hole becomes a source of the high-speed solar wind, which can cause a geomagnetic storm. The number, size, and position of the coronal hole vary as a function of the solar cycle, with the reversal of magnetic polarity every 11 years. The characteristics of the coronal hole will be different at the maximum and minimum phases of the solar cycle. Aims of this study are to determine the morphology of coronal hole based on the area, magnetic field strength, open magnetic flux, and the evolution of the coronal hole according to latitude during minimum solar activity (or spotless days) and maximum at the Solar Cycle 24. The method applied in this study is CHIMERA (Coronal Hole Identification via Multi-thermal Emission Recognition Algorithm). There are relations between magnetic field strength and magnetic flux with areas of coronal holes from September 2010 to May 2019 that follow the exponential and linear distributions.

1. Introduction
Corona is the outermost layer of the solar atmosphere. The magnetic field lines of the corona can be reconnected to the surface of the Sun or extended to the heliosphere, which can be called as closed and open magnetic fields. In the open magnetic field area, plasma from the corona can be ejected along the magnetic field lines, giving rise to high-speed solar winds and making plasma depletion at the footpoint of the field. Therefore, an area with an open magnetic field would look dark because of a low density and a lower temperature than the surrounding areas. Low density and temperature of the coronal hole are ~ 1.6 × 10^9 cm^-3 and ~ 0.7 × 10^6 K, respectively [1].

Coronal holes tend to be regions that behave as collisionless plasma. Because this region has an open magnetic field structure (single polarity), this region is called unipolar. Coronal holes have been long known to be a source of high-speed solar wind [2]. The coronal hole is formed in minimum local where new open fluxes rise and tend to accumulate and concentrate [3]. These particles can ionize atoms and electrons. High-speed solar wind particles can interact with Earth’s magnetosphere, which causes a geomagnetic storm. Geomagnetic storms can damage satellites and disrupt electricity networks through geomagnetically induced currents in high latitudes or polar regions, shown in [4] and [5]. The size of the coronal hole at the poles is inversely proportional to the strength of the magnetic field [6]. Figure 1 shows the relationship between the magnetic field and the area of coronal holes at the pole. This graph gives the magnetic field strengths (B) of 1.2 G and 2 G around the areas of 9 × 10^18 m^2 and 4.5 × 10^18 m^2, respectively [6].
Solar activity is characterized by sunspots, which are regions with strong magnetic field concentrations, whereas coronal holes are areas with weak magnetic fields and have one polarity. The structure of the coronal hole varies throughout the Sun's activity cycle, through the magnetic polarity reversal in every 11 years. Therefore, during the maximum phase of solar activity, the number of sunspots increases. However, the number or area of coronal holes is lower. Strong magnetic fields will prevent the presence of coronal holes.
Open flux tends to peak approximately 2 to 3 years after the maximum sunspots when the total solar dipole strength is greatest and open flux at high latitudes is seen to be much weaker during the current minimum activity than the minimum of 1976, 1986, 1996, which reflects a very weak polar field at the end of the Solar Cycle 23 [8]. The total area occupied by open flux decreases from ~20% of the surface at sunspots minimum to ~5% at sunspot maximum and the average strength of the footpoints field in the coronal hole increases from ~5 G at minimum sunspots to ~20 G at maximum sunspots [8].

The distribution area of coronal holes shows different behavior in latitude throughout the solar cycle, defining the domain of the coronal hole of the poles and low latitude. Figure 3 shows a gap between the appearance and disappearance of the polar coronal hole. Before 1999 during the Solar Cycle 23 rise phase, the distribution of coronal holes at the north pole was dominated by a positive polarity magnetic field, with the south pole dominated by the negative polarity field. While at lower latitudes, there are also two different polarities. The reversal of dominant polarity in the polar regions occurred in 2012 and 2013, respectively for the north and south poles [9].

Figure 3. Time graphs for latitude from [a] Sunspots numbers; [b] distribution; [c] magnetic field; [d] open magnetic flux of coronal holes from 31 March 1996 to 19 August 2014 [9].
From figure 3, during the solar minimum in 1996–1998, the coronal hole was concentrated in the solar poles; with positive polarity at the north pole and negative polarity at the south pole and as well as the open magnetic flux. From 1999 to 2003, the coronal holes expand to lower latitudes, and during maximum solar activity, there was a polarity switch from 2001 to 2003. The positive and negative polarity tended to be in northern and southern latitudes. A fraction of the open magnetic flux also tends to be at various latitudes. From 2006 to 2012, the distribution of coronal holes returned to the Sun poles, with positive polarity at the south pole and negative polarity at the north pole. Finally, from 2012 to 2014, the distribution of the coronal hole extends to low latitudes and the polarity exchange begins. There are positive and negative polarities at various latitudes. This study aims to study the morphology and evolution of coronal hole in Solar Cycle 24 based on its area, magnetic field, and open magnetic flux.

2. Data and Method
Data used are EUV wavelength and HMI magnetogram data from the AIA instrument onboard the SDO (Solar Dynamics Observatory) satellite. The AIA EUV data used are at the wavelengths of 171 Å, 193 Å, and 211 Å. While the HMI Magnetogram data is used to resolve the magnetic field in the coronal holes. The method used is Coronal Hole Identification via Multi-thermal Emission Recognition Algorithm (CHIMERA) [10], which can be obtained from solarmonitor.org. We used data from September 2010 to May 2019 of the Solar Cycle 24 from CHIMERA.

CHIMERA works based on the segmentation of multi-thermal intensities that pass through three EUV wavelengths (171 Å, 193 Å, and 211 Å) from the AIA image. CHIMERA analyzes the intensity of the three wavelengths to estimate the temperature and density of each pixel and later divide the pixels with the same properties or characteristics as the coronal hole [10]. Furthermore, the HMI Magnetogram image is used to analyze the magnetic properties of coronal holes, particularly by removing non-unipolar regions that do not have unipolar properties such as coronal holes. CHIMERA analyzes one image every day and can be obtained from www.solarmonitor.org. The results of the CHIMERA segmentation include the area in the percentage of the solar disc unit (%), centroid in degrees, the magnetic field in Gauss (G) and the open magnetic flux in Maxwell (Mx).
Figure 5. Segmentation of coronal holes on 1 February 2018 (CHIMERA, solarmonitor.org).

3. Result and Discussion
There are about 8691 data from September 2010 to May 2019 with $|B| < 100$ G, while there are ~97.25% data with $|B| \leq 10$ G, thus there are only about 3% coronal holes that have $|B| > 10$ G. There are around 90.55% and 82.6% data with $|B| \leq 5$ G and $|B| \leq 3$ G, respectively. From this data distribution, it can be concluded that coronal holes have weak magnetic fields.

Figure 6. The relation between the areas and magnetic fields of the coronal hole, with $|B| \leq 10$ G.

The relation between the magnetic field and the area of coronal holes follows an exponential distribution. When the area of the corona hole is smaller, the range of magnetic field value will be greater. However, when the area of the coronal holes is larger, the range of magnetic field values are smaller. This result is similar to previous studies [6]. These values will be as summarized in Table 1.
Table 1. Range of coronal holes area and the magnetic fields.

| Area (A)         | Magnetic field (B) [G] |
|------------------|------------------------|
| A ≥ 20%          | -1.4 ≤ B ≤ 1.7         |
| 20% > A > 10%    | -3.0 ≤ B ≤ 2.5         |
| 10% ≥ A > 5%     | -4.5 ≥ B ≤ 7.8         |
| 5% ≥ A > 0 %     | -89.9 ≤ B ≤ 60.2       |

Figure 7. The relation between area and the open magnetic flux of coronal holes (Data from September 2010 to May 2019).

The following relation is between open magnetic flux and area of coronal holes. Figure 7 shows the relation between area and the open magnetic flux of coronal holes from September 2010 until May 2019. Some data seem approaching zero because of the different order of magnitude of open magnetic flux. As approaching the minimum cycle (from June 2018 to May 2019) the open magnetic flux of coronal hole tends to be lower around $10^{19}$–$10^{22}$ Mx. However, during September 2010–June 2018 open magnetic flux was exceeding $10^{23}$ Mx.

Figure 8. The relation between magnetic fields and coronal hole magnetic flux (Data from September 2010 to May 2019).

The r-squared value or the coefficient of determination of the linear equation in figure 7 is $\sim 0.37$. However, the r-squared value from September 2010–June 2018 data is $\sim 0.5$, which indicates the compatibility of the data with the model is about 50%. The maximum and minimum flux from the data
(September 2010–May 2019) are $2.4 \times 10^{34}$ Mx (around 2014–2015) and $1 \times 10^{19}$ Mx (April 2019). While the relation between magnetic field strength and open magnetic flux in figure 8 also follows an exponential distribution, the greater the open magnetic flux the smaller the magnetic field strength range.

**Figure 9.** Distribution of centroid coronal hole in longitude and area (Data from September 2010–May 2019).

Figure 9 shows the distribution of the coronal hole area in the centroid of longitude. The pattern shows that the area of the coronal hole is relatively small toward the eastern and western solar limb due to the projection effect. Consequently, toward the central meridian, between the longitude of -40° to 40° has a larger area.

**Figure 10.** Distribution of coronal hole magnetic fields across latitudes with $|B| \leq 10$.

The distribution of the coronal hole magnetic polarity is shown in figure 10 as red (positive polarity) and blue (negative polarity) squares. Due to data limitations in 2010–2011 and 2013, only a small sample of data exist before the maximum solar cycle. Figure 10 has a boundary of $|B| < 0.5$ G because it can be related to the graph previously shown [9]. From available data, it is shown that before the solar cycle approaches maximum (2010–2012) positive polarity is dominating the southern latitude and south pole. After that, the coronal hole's polarity moves or migrates during the maximum phase. Both polarities are found in all latitudes from 2013–2016. After 2016, the negative polarity becomes dominant in the southern latitudes. Before 2012, there were weak magnetic field distributions
of coronal holes in the low latitudes. However, weak magnetic field distributions were found in the north pole in 2012–2016. Then, weak magnetic field distributions were found throughout the latitudes after 2016. This result is similar to a previous study [9].

Figure 1. The distribution of the magnetic flux of coronal holes across latitudes.

The positive and negative polarity also seen from the distribution of open magnetic flux across all latitudes. From figure 11, the maximum open magnetic flux is at the northern and southern latitudes until 2018. Since 2018, the magnetic flux has been relatively low.

Figure 12. The distribution area of coronal holes across latitudes (A > 10%).

Figure 12 shows the distribution of coronal holes area throughout all latitudes with A > 10%. Coronal holes with A > 15% occurred in September 2015 at the north pole, around 16 months after the maximum phase of the Solar Cycle 24 in April 2014. While the area of coronal holes with A > 20% occurred at the north pole in October 2015, around 17 months from the maximum peak. The initial appearance of a large coronal hole at the poles, with A > 15% and A > 20%, occurs at the north pole. However, at the south pole, the coronal hole with A > 15% was seen in October 2016, and A > 20% occurred in December 2016. The delays appearance of the large coronal hole between the north pole and south pole is around 13–15 months. A large coronal hole area that extends to the equator would have more influence on the geomagnetic storm.
4. Conclusion

The relation between coronal holes area and magnetic field follows the exponential distribution, the greater the area the smaller the magnetic field's range. For coronal hole with $A > 20\%$, the magnetic field range value is $|B| \leq 2$ G. However, for an area between 10–20%, the strength of the magnetic field increases to $|B| < 3$ G. The relationship between the coronal hole area and the magnetic flux follows a linear equation with a determined coefficient of $\sim 0.5$ in September 2010–June 2018. The weak open magnetic flux of coronal holes occurred in 2018–2019, around $10^{19}$–$10^{22}$ Mx. The polarity of the coronal hole changes throughout the solar cycle. After the solar cycle maximum, the negative polarity is more dominant at the south pole. Before around solar minimum, the low magnetic field strength of the coronal hole is dominant at the solar poles but it expands across all latitudes during the minimum cycle. The lag between a large coronal hole that occurs at the south pole and north pole is about 13–15 months.

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