The relation between coronal holes and coronal mass ejections during the rise, maximum, and declining phases of Solar Cycle 23

A. A. Mohamed, N. Gopalswamy, S. Yashiro, S. Akiyama, P. Mäkelä, H. Xie, and H. Jung

Received 20 February 2011; revised 22 October 2011; accepted 25 October 2011; published 11 January 2012.

[1] We study the interaction between coronal holes (CHs) and coronal mass ejections (CMEs) using a resultant force exerted by all the coronal holes present on the disk and is defined as the coronal hole influence parameter (CHIP). The CHIP magnitude for each CH depends on the CH area, the distance between the CH centroid and the eruption region, and the average magnetic field within the CH at the photospheric level. The CHIP direction for each CH points from the CH centroid to the eruption region. We focus on Solar Cycle 23 CMEs originating from the disk center of the Sun (central meridian distance \( \leq 15^\circ \)) and resulting in magnetic clouds (MCs) and non-MCs in the solar wind. The CHIP is found to be the smallest during the rise phase for MCs and non-MCs. The maximum phase has the largest CHIP value (2.9 G) for non-MCs. The CHIP is the largest (5.8 G) for driverless (DL) shocks, which are shocks at 1 AU with no discernible MC or non-MC. These results suggest that the behavior of non-MCs is similar to that of the DL shocks and different from that of MCs. In other words, the CHs may deflect the CMEs away from the Sun-Earth line and force them to behave like limb CMEs with DL shocks. This finding supports the idea that all CMEs may be flux ropes if viewed from an appropriate vantage point.


1. Introduction

[2] Coronal mass ejections (CMEs) are known to interact with large-scale structures such as streamers, coronal holes, and other CMEs [see, e.g., Gopalswamy et al., 2004]. These interactions lead to several observable effects such as enhanced radio emission, particle acceleration, and CME deflection. CME deflection by nearby CHs is particularly interesting because of the unexpected geospace consequences. CMEs deflected away from the Sun-Earth line may not reach Earth and hence may not cause geomagnetic storms [Gopalswamy et al., 2009b]. CMEs may also be deflected toward the Sun-Earth line resulting in unusually large geomagnetic storms [Gopalswamy et al., 2005].

[3] CMEs colliding with each other can result in large changes in the trajectory of one of the CMEs [Gopalswamy et al., 2001]. Van der Holst et al. [2002] showed using numerical simulation that a fast expanding CME collided with a northern-hemisphere helmet streamer, leading to a deflection and a wavelike deformation propagating outward along the streamer. Gopalswamy et al. [2009a] reported on the EUV wave reflection from a CH and they were able to measure the kinematics of the reflected waves and confirmed the wave nature of the EUV disturbances.

[4] The field lines from the polar CHs are suggested to guide high-latitude CMEs toward the equator [Gopalswamy et al., 2000, 2003; Gopalswamy and Thompson, 2000; Plunkett et al., 2001; Filippov et al., 2001; Cremades et al., 2006; Gopalswamy et al., 2009b]. It is also suggested that CMEs trajectories are influenced by the initial magnetic polarity of a flux rope relative to the background magnetic field [Byrne et al., 2010]. They showed that CMEs, in earlier phase of their evolution, are deflected from a high-latitude source region into a non-radial trajectories indicated by a change in their inclination angles, expanding on previous work. Other theoretical work by Chané et al. [2005], using a simulation of the CMEs superposed on different steady state solar wind models, demonstrated that the initial magnetic field polarity inside a flux rope is essential for the evolution of CMEs.

[5] Gopalswamy et al. [2009b] found that several “driverless” (DL) shocks observed in situ at L1 were...
Table 1. The Measured Parameters of the Different CHs for the 15 October 1998 Event

<table>
<thead>
<tr>
<th>CH Centroid</th>
<th>Area, $A$ (km$^2$)</th>
<th>Average Magnetic Field, $B$ (G)</th>
<th>Distance, $d$ (km)</th>
<th>FPA (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH1 N54E27</td>
<td>$9.6 \times 10^6$</td>
<td>5.4</td>
<td>$4.6 \times 10^4$</td>
<td>25 211°</td>
</tr>
<tr>
<td>CH2 N12E08</td>
<td>$1.2 \times 10^6$</td>
<td>$-1.9$</td>
<td>$1.6 \times 10^4$</td>
<td>0.9 312°</td>
</tr>
<tr>
<td>CH3 N00E10</td>
<td>$1.4 \times 10^6$</td>
<td>$-1.7$</td>
<td>$2.9 \times 10^3$</td>
<td>0.3 337°</td>
</tr>
<tr>
<td>CH4 S62E02</td>
<td>$3.4 \times 10^6$</td>
<td>$-4.4$</td>
<td>$9.3 \times 10^3$</td>
<td>0.2 358°</td>
</tr>
<tr>
<td>CH5 N94W21</td>
<td>$5.9 \times 10^6$</td>
<td>3.1</td>
<td>$3.8 \times 10^3$</td>
<td>0.1 153°</td>
</tr>
</tbody>
</table>

$^aF = 2.3$ G, FPA = 238°.

Table 2. Disk-Center MC Events During the Three Phases of Solar Cycle 23

<table>
<thead>
<tr>
<th>Phase</th>
<th>Date</th>
<th>Start Time (UT)</th>
<th>Duration (h)</th>
<th>Time (UT)</th>
<th>Source Location</th>
<th>V (km/s)</th>
<th>MPA</th>
<th>FPA</th>
<th>$\Delta \psi$</th>
<th>$F$ (G)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rise</td>
<td>1997/01/10</td>
<td>0052</td>
<td>10/0500</td>
<td>22</td>
<td>01/06</td>
<td>1510</td>
<td>136</td>
<td>25°</td>
<td>155°</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>1997/05/15</td>
<td>0115</td>
<td>15/1200</td>
<td>14.5</td>
<td>05/12</td>
<td>0530</td>
<td>464</td>
<td>264°</td>
<td>352°</td>
<td>88°</td>
</tr>
<tr>
<td></td>
<td>1997/09/21</td>
<td>0410</td>
<td>21/0900</td>
<td>16</td>
<td>09/17</td>
<td>2028</td>
<td>377</td>
<td>263°</td>
<td>200°</td>
<td>63°</td>
</tr>
<tr>
<td></td>
<td>1998/10/18</td>
<td>1928</td>
<td>19/0400</td>
<td>26.5</td>
<td>10/15</td>
<td>1004</td>
<td>262</td>
<td>264°</td>
<td>307°</td>
<td>43°</td>
</tr>
<tr>
<td></td>
<td>1999/04/16</td>
<td>1110</td>
<td>16/2018</td>
<td>23</td>
<td>04/13</td>
<td>0330</td>
<td>291</td>
<td>194°</td>
<td>301°</td>
<td>107°</td>
</tr>
<tr>
<td></td>
<td>1999/08/08</td>
<td>1744</td>
<td>09/0500</td>
<td>23.25</td>
<td>08/03</td>
<td>0350</td>
<td>222</td>
<td>355°</td>
<td>230°</td>
<td>25°</td>
</tr>
<tr>
<td></td>
<td>2000/02/20</td>
<td>2100</td>
<td>21/2000</td>
<td>25.5</td>
<td>02/17</td>
<td>2130</td>
<td>728</td>
<td>184°</td>
<td>336°</td>
<td>152°</td>
</tr>
<tr>
<td></td>
<td>2000/07/15</td>
<td>1418</td>
<td>15/2000</td>
<td>16</td>
<td>07/14</td>
<td>1054</td>
<td>1674</td>
<td>273°</td>
<td>201°</td>
<td>72°</td>
</tr>
<tr>
<td></td>
<td>2000/07/28</td>
<td>0639</td>
<td>29/1000</td>
<td>13</td>
<td>07/25</td>
<td>0330</td>
<td>528</td>
<td>168°</td>
<td>291°</td>
<td>123°</td>
</tr>
<tr>
<td></td>
<td>2000/08/11</td>
<td>1851</td>
<td>12/0606</td>
<td>19</td>
<td>08/09</td>
<td>1630</td>
<td>702</td>
<td>12°</td>
<td>159°</td>
<td>147°</td>
</tr>
<tr>
<td></td>
<td>2000/09/17</td>
<td>1700</td>
<td>18/0154</td>
<td>21.5</td>
<td>09/16</td>
<td>0518</td>
<td>1215</td>
<td>3°</td>
<td>325°</td>
<td>40°</td>
</tr>
<tr>
<td></td>
<td>2000/10/12</td>
<td>2236</td>
<td>13/1600</td>
<td>23</td>
<td>10/09</td>
<td>2350</td>
<td>798</td>
<td>318°</td>
<td>195°</td>
<td>123°</td>
</tr>
<tr>
<td></td>
<td>2000/11/06</td>
<td>0920</td>
<td>06/1750</td>
<td>19</td>
<td>11/03</td>
<td>1826</td>
<td>291</td>
<td>57°</td>
<td>178°</td>
<td>121°</td>
</tr>
<tr>
<td></td>
<td>2001/03/19</td>
<td>1130</td>
<td>19/1830</td>
<td>43</td>
<td>03/16</td>
<td>0350</td>
<td>271</td>
<td>312°</td>
<td>348°</td>
<td>36°</td>
</tr>
<tr>
<td></td>
<td>2001/04/11</td>
<td>1619</td>
<td>11/2200</td>
<td>10</td>
<td>04/10</td>
<td>0530</td>
<td>2320</td>
<td>2411</td>
<td>166°</td>
<td>337°</td>
</tr>
<tr>
<td></td>
<td>2001/04/28</td>
<td>0502</td>
<td>28/1500</td>
<td>9</td>
<td>04/26</td>
<td>1230</td>
<td>1006</td>
<td>37°</td>
<td>62°</td>
<td>25°</td>
</tr>
<tr>
<td></td>
<td>2002/03/18</td>
<td>1313</td>
<td>20/0200</td>
<td>16.5</td>
<td>03/15</td>
<td>2306</td>
<td>957</td>
<td>309°</td>
<td>240°</td>
<td>69°</td>
</tr>
<tr>
<td></td>
<td>2002/04/17</td>
<td>1101</td>
<td>18/0100</td>
<td>25</td>
<td>04/15</td>
<td>0350</td>
<td>720</td>
<td>198°</td>
<td>335°</td>
<td>137°</td>
</tr>
<tr>
<td></td>
<td>2002/05/18</td>
<td>1951</td>
<td>19/0354</td>
<td>10</td>
<td>05/16</td>
<td>0050</td>
<td>600</td>
<td>158°</td>
<td>360°</td>
<td>158°</td>
</tr>
<tr>
<td></td>
<td>2002/08/01</td>
<td>0510</td>
<td>01/0900</td>
<td>10.5</td>
<td>07/29</td>
<td>207</td>
<td>526</td>
<td>301°</td>
<td>208°</td>
<td>98°</td>
</tr>
<tr>
<td></td>
<td>2002/08/01</td>
<td>2305</td>
<td>02/0600</td>
<td>13.5</td>
<td>07/29</td>
<td>2330</td>
<td>360</td>
<td>354°</td>
<td>223°</td>
<td>131°</td>
</tr>
<tr>
<td></td>
<td>2003/08/17</td>
<td>1340</td>
<td>18/0430</td>
<td>24</td>
<td>08/14</td>
<td>2006</td>
<td>378</td>
<td>25°</td>
<td>93°</td>
<td>68°</td>
</tr>
<tr>
<td></td>
<td>2003/10/29</td>
<td>0600</td>
<td>29/1100</td>
<td>16</td>
<td>10/28</td>
<td>1130</td>
<td>2495</td>
<td>H15°</td>
<td>160°</td>
<td>145°</td>
</tr>
<tr>
<td></td>
<td>2003/10/30</td>
<td>1620</td>
<td>31/0200</td>
<td>10</td>
<td>10/29</td>
<td>2054</td>
<td>2029</td>
<td>H190°</td>
<td>255°</td>
<td>65°</td>
</tr>
<tr>
<td></td>
<td>2004/07/24</td>
<td>0532</td>
<td>24/1530</td>
<td>20.5</td>
<td>07/22</td>
<td>0830</td>
<td>899</td>
<td>210°</td>
<td>193°</td>
<td>17°</td>
</tr>
<tr>
<td></td>
<td>2004/11/07</td>
<td>1759</td>
<td>07/2230</td>
<td>13.5</td>
<td>11/04</td>
<td>0206</td>
<td>1111</td>
<td>21°</td>
<td>94°</td>
<td>73°</td>
</tr>
<tr>
<td></td>
<td>2005/05/15</td>
<td>0219</td>
<td>15/0915</td>
<td>14.75</td>
<td>05/13</td>
<td>1712</td>
<td>1689</td>
<td>H2°</td>
<td>42°</td>
<td>40°</td>
</tr>
<tr>
<td></td>
<td>2005/05/20</td>
<td>0334</td>
<td>20/0718</td>
<td>22</td>
<td>05/17</td>
<td>0326</td>
<td>449</td>
<td>54°</td>
<td>334°</td>
<td>80°</td>
</tr>
<tr>
<td></td>
<td>2005/06/12</td>
<td>0659</td>
<td>12/1500</td>
<td>20</td>
<td>06/09</td>
<td>1436</td>
<td>125</td>
<td>52°</td>
<td>202°</td>
<td>150°</td>
</tr>
</tbody>
</table>

$^a$MCs were not included in the work by Gopalswamy et al. [2009b].

$^b$MCs re-analyzed due to slight revision in their solar source locations. The prefix H in column 7 denotes the halo CMEs with unidentified central position angle (CPA).
In the present paper, we extend previous studies to the rise and maximum phases of Solar Cycle 23, considering all the ICMEs that originate close to the disk center. In particular, we investigate how the CHIP for non-MCs compares with that of MCs and DL shocks.

In section 2 we present the selection criteria for the events and the method of data analysis. We also explain the method for identifying ICMEs and CHs, and present the solar source distributions of CMEs associated with MCs and DL shocks. We define the CHIP and discuss the coronal environment of CMEs resulting in MCs and non-MCs in section 3. We compare the average CHIP and average alignment angles for MCs and non-MCs during three phases of the solar cycle in section 4. In section 5 we summarize the results and present our conclusions.

2. Data Selection and Method of Analysis

The starting point of this investigation is a set of shock-driving ICMEs listed in work by Gopalswamy et al. [2010h, Table 1]. The list includes shocks driven by either MCs and non-MCs and DL shocks during May 1996 to December 2006. For each ICME, there is a corresponding CME observed by the Large Angle and Spectrometric Coronagraph (LASCO) [Brueckner et al., 1995] on board the Solar and Heliospheric Observatory (SOHO) mission. From this list we extract only those ICMEs whose solar sources are close to the disk-center, i.e., Central Meridian Distance (CMD) is within 15°.
The extracted ICMEs are listed in Tables 1 (MCs) and 2 (non-MCs). We use the list of ICMEs in the declining phase [Gopalswamy et al., 2009b, Table 3] and divide them into MCs and non-MCs. We added another 4 MC events (denoted by “a”) that were not included in their list. Two MCs (denoted by “b”) and 2 non-MCs (denoted by “c”) were reanalyzed due to slight revision in their solar source locations. We also use the set of DL shocks from Gopalswamy et al. [2009b], which correspond to ICMEs severely affected by coronal hole deflection.

2.1. ICME Identification for Selected Events

Gopalswamy et al. [2009b] identified the MCs and ejecta behind interplanetary (IP) shocks from the following data: Advanced Composition Explorer (ACE) [Stone et al., 1998] data in GSE coordinates for the magnetic field magnitude ($B$) and its $Y$ and $Z$ components ($B_Y$, $B_Z$), solar wind bulk flow speed ($V$), proton temperature ($T_p$), proton density ($N_p$), the alpha to proton density ratio ($N_{a}/N_p$), flow pressure ($p_{flow}$), plasma beta, and oxygen and iron charge states. The expected solar wind proton temperature ($0.5 \times T_{exp}$) based on relations by Lopez and Freeman [1986] and Neugebauer et al. [2003] was used as a primary criterion. $N_{a}/N_p > 0.08$ was used as a secondary criterion and it should be met during the $T_p$ depression for at least part of the interval.

In the present work, we followed the same procedure to identify the end of the ejecta so that we can define
the ICME interval. Figures 1 and 2 show two examples of shock-driving ICMEs: an MC on 2005 May 15 at 02:19 UT and a non-MC on 1999 September 22 at 12:00 UT. The MC event occurred during the declining phase and the non-MC occurred during the maximum phase. It is clear that the $T_p$ is enhanced in the sheath region between the shock and the start of ejecta (this region is common to all shocks irrespective of whether the ICME signatures exist or not). The sheath lasts for $\sim 7$ h in the 2005 May 15 event and $\sim 9$ h in the 1999 September 22 event. The enhancement in the magnetic field ($B$) and the depression of $T_p$ below 0.5 $T_{\text{exp}}$ mark the onset of the ICME (09:15 UT and 21:00 for 2005 May 15 and 1999 September 22, respectively). $N_a/N_p$ was definitely enhanced above 0.08 with respect to the pre-shock values in the case of the non-MC event, while for the MC event the enhancement was below 0.08 for the entire interval. The enhancement in $N_a/N_p$ was below 0.08 but is shown above 0.08 for what may be considered a second event following the first one. Note also the continuation of the $T_p$ depression and most of the other signatures beyond the described MC interval which may correspond to a single or several non-MCs following up the first MC. The duration of the MC event is 14.75 h and $\sim 9$ h for the non-MC event. The end times of the MC and non-MC are determined to be at 00:00 UT and 02:00 UT on 16 May 2005 and 24 September 1999, respectively. For the 15 May 2005 MC event, the onset time is $\sim 3$ hours later than the time reported by Richardson and Cane [2010] and also in the MC list based on the observations of the Magnetic Field Investigation (MFI) [Lepping et al., 1995] on-board Wind: (http://wind.gsfc.nasa.gov/mfi/mag_cloud_pub1.html). We are using the $T_p$ depression as the primary criterion in defining the ICME boundaries. Our end time is only 2 hours later than their reports. Interestingly, most of the signatures persist until about 2:00 UT on 22 May 2005 suggesting another non-MC or ejecta following this MC event. In general there are slight discrepancies in the identification of ICME boundaries among various authors but the differences are only about a few hours.

In the 22 September 1999 non-MC event, the ICME interval seems to be divided into two regions both satisfying the ICME signatures at $\sim 9$ UT on 23 September 1999 marked by the vertical dash-dotted line shown in Figure 2. This suggests that there is more than one non-MC following each others resulting from the eruption of successive CMEs.

[15] Figure 1 shows that the 2005 May 15 MC event is unipolar, i.e. the $B_z$ component is fully north (FN) and the direction of the Y-component rotates smoothly from east to west. So the internal magnetic cloud structure can be classified as ENW (see Bothmer and Schwenn [1994], Mulligan et al. [1998], and Gopalswamy [2008] for details on the different MC types). The examples in Figures 1 and 2 show how a typical sequence proceeds at 1 AU: the shock followed by the sheath ($T_p > 0.5T_{\text{exp}}$), and ejecta ($T_p < 0.5T_{\text{exp}}$). Similar identification of the boundaries was done for the 72 ICMEs studied in this paper.

2.2. Solar Source Locations of the ICMEs

[16] The association between ICMEs and the corresponding CMEs observed by SOHO/LASCO was made by examining all CMEs that occurred over a window of 0.5 to 5 days prior to the shock arrival time at 1 AU [Gopalswamy et al., 2009b]. The solar source locations of the CMEs are defined as the heliographic coordinates of the associated eruption such as H-alpha flare and soft X-ray flare (Solar Geophysical Data) or the location of the associated disk activity, e.g., post eruption arcades or EUV dimming (see Gopalswamy et al. [2007, 2009b] for details on CME source identification). Here we take the source identification provided by Gopalswamy et al. [2010b].

[17] Figure 3 shows the solar source locations of CMEs associated with MCs (circles), non-MCs (triangles) and the DL shocks (stars). The sources are at the highest latitudes in the rise phase, at intermediate latitudes in the maximum phase and at the lowest latitudes in the declining phase because the emergence of active regions follow the well-known butterfly diagram. The number of MCs and non-MCs among the disk-center events is the largest during solar maximum and the least during the rise phase. This is directly related to the increased solar activity during solar maximum. The solar source locations of the five disk-center CMEs associated with DL shocks have been discussed in detail by Gopalswamy et al. [2009b].
2.3. Coronal Hole Identification

We use 284 Å images from the Extreme ultraviolet Images Telescope (EIT) [Delaboudinière et al., 1995] on-board SOHO, to identify the coronal holes. The areas that are dim in EUV are the CHs, where the magnetic field is predominantly unipolar. EIT 284 Å images are preferred compared to X-ray images because, X-ray images are not available for all the events. EIT 284 Å images are preferred over EIT 195 Å images because the coronal holes are clearer in these images compared to those at 195 Å. However, 195 Å images occasionally used whenever there was lack of data at 284 Å. The CHs are defined as areas outlined by a single contour at the 50% level of the median EUV intensity of the solar disk (see Figure 4). In order to obtain photospheric magnetic fields within the CHs, we use the line of sight magnetograms obtained by the Michelson Doppler Imager (MDI) [Scherrer et al., 1995] onboard SOHO. We have also used He 10830 Å images from the

---

**Figure 4.** Coronal holes and eruption centers of CMEs on 6 January 1997, 12 May 1997, 17 September 1997, and 15 October 1998. The heliographic grid spacing is 15°. For the first event, the CH contour outlines 75% of the median brightness of the solar disk when in the He 10830 Å image, while for the other events in the 284 Å image the contours are at 50% of the median EUV intensity of the solar disk. The dashed red lines connect the eruption region to the centroid of each coronal hole. The red arrow points from the solar source of the CME to the direction of the CHIP. The blue arrow indicates the measurement position angle (MPA) along which the CME height time history has been measured. The alignment angle which is the difference (Δψ) between FPA and MPA, is noted on each image.
Mauna Loa Solar Observatory for some events such as the 6 January 1997 MC due to data gaps in other wavelengths as shown in Figure 4. The coronal holes appear as bright regions in He 10830 Å images so that the contour outlining the coronal hole encloses an area (~75%) in which the brightness exceeds the median brightness of the solar disk at this wavelength.

[19] In the magnetograms obtained by SOHO/MDI, the areas within the CHs that have a minor opposite magnetic polarity are eliminated. We also eliminated the areas of nearby filaments that appear dark in the EIT images as well.

[20] The average magnetic field in the coronal hole is determined from the SOHO/MDI magnetograms obtained in the synoptic mode (one magnetogram every 96 min). The CH contour from the EIT 284 Å images is superposed on the magnetogram after rotating the magnetogram to the time of sight.

[21] Figure 5 shows the distribution of magnetic field strengths in the CH of 12 May 1997 event at the CME eruption time (5:30 UT). The magnetic field distribution is near-Gaussian and slightly asymmetric.

3. The Coronal Hole Influence Parameter (CHIP)

[22] The CHIP has a magnitude \( F \) that depends on the CH area, the distance between the CH and the eruption region, and the magnetic field within the CH at the photospheric level. The direction of \( F \) acts along a position angle (FPA), which is the direction along which the resultant of all the coronal holes acts. Thus, for each CH, we have

\[
f = \left( \langle B \rangle A \right) / d^2 \
\]

where \( f \) is a vector and \( \mathbf{e}_x \) is the unit vector, which acts in the direction from the CH centroid to the eruption region. The dimension of (1) is in gauss (G). Then, we calculate the vector sum of the influence parameters over all coronal holes present on the disk to obtain the CHIP magnitude, \( F \), and the direction of \( F \) (position angle FPA).

\[
F = \sum_{i=1}^{N} f_i, \quad i = 1, \ldots, N,
\]

where \( N \) is the total number of coronal holes present on the disk. The magnetic field lines inside the CH are assumed to be radial and therefore a correction to the projection effects for the field strength and the CH area is applied using the known angle of the CH centroid with respect to the line of sight:

\[
A = \hat{A} \cos \phi \\
B = \hat{B} \cos \phi,
\]

where \( A \) and \( B \) are the corrected area and magnetic field inside the CH, respectively. \( \hat{A} \) and \( \hat{B} \) are the observed CH area and magnetic field inside the CH, respectively, and \( \phi \) is the angle between the CH centroid and the line of sight.

3.1. CHIP for MCs and Non-MCs

[23] Figure 4 illustrates the coronal environment of the four CMEs during the rise phase (6 January 1997, 12 May 1997, 17 September 1997, and 15 October 1998) that resulted in MCs observed on 10 January 1997 at 00:52 UT, 15 May 1997 at 01:15 UT, 21 September 1997 at 16:51 UT, and 18 October 1998 at 19:28 UT, respectively. For the first event, we use the He 10830 Å image from the Mauna Loa Solar Observatory and for others we use the EIT 284 Å images. There were no magnetograms obtained by SOHO/MDI for the 15 October 1998 event so, we used the MDI data of 21 October 1998 and rotated the image to the CME time on 15 October 1998.

[24] For the 15 October 1998 event, the largest CH is located in the northeast (NE) and has its centroid at N54E27. The CH centroid is at a distance \( d \) of \( -4.6 \times 10^8 \) km from the eruption site (N22W01). The CH area \( \langle A \rangle \) corrected for the projection effects is \( \approx 9.6 \times 10^{10} \) km\(^2\). The average magnetic field \( \langle B \rangle \) obtained from the MDI magnetogram is \( \approx 5.4 \) G. Applying the formula in equation (1), we obtain \( f_1 = 2.5 \) G and the position angle in which \( f_1 \) is directed is \( 211^\circ \). The second CH is also located in the northeast quadrant and has its centroid at N12E08. Using \( A_2 = 1.2 \times 10^{10} \) km\(^2\) and \( d_2 = 1.6 \times 10^5 \) km, and \( \langle B_2 \rangle = -1.9 \) G, we obtain \( f_2 = 0.9 \) G directed along a position angle of \( 312^\circ \). The third CH is located close to the disk center with its centroid at N00E10. For this CH, \( A_3 = 1.4 \times 10^{10} \) km\(^2\), \( d_3 = 2.9 \times 10^5 \) km, and \( \langle B_3 \rangle = -1.7 \) G, so \( f_3 \approx 0.3 \) G directed along a position angle of \( \approx 337^\circ \). The fourth CH is located in the south with its centroid is at S62E02. From \( A_4 = 3.4 \times 10^{10} \) km\(^2\), \( d_4 = 9.3 \times 10^5 \) km, and \( \langle B_4 \rangle = -4.4 \) G, we get \( f_4 \approx -0.2 \) G with a position angle \( \approx 358^\circ \). The last CH is located in the northwest (NW) quadrant at N49W21 with \( d_5 = 3.8 \times 10^5 \) km, \( A_5 = 5.9 \times 10^9 \) km\(^2\), \( \langle B_5 \rangle \approx 3.1 \) G, so \( f_5 \approx 0.1 \) G with a position angle \( \approx 153^\circ \). The net influence of the five CHs is \( F = 2.3 \) G pointed along the PA of \( 238^\circ \). We denote this
position angle as FPA. Note that this FPA is close to the FPA of the first CH because it has the maximum CHIP (2.5). The red arrow in Figure 4 represents the direction of the first CH because it has the maximum CHIP (2.5). Height-time measurements of CMEs are made along a position angle at which the CME appears to be moving the fastest, and is referred to as the measurement position angle (MPA) (eighth column); the measurement position angle (MPA in degrees) of the CME (ninth column); the PA (tenth column); the ICME start time in dd/hhmm format (third column); the ICME duration in hours (fourth column); the corresponding white-light CME (date and time of the first appearance of the CME in mm/dd hhmm format in the fifth and sixth columns); the heliographic coordinates of the eruption region (seventh column); the average sky-plane speed of the CME obtained from LASCO observations (eighth column); the measurement position angle (MPA in degrees) of the CME (ninth column); the PA (tenth column); and the alignment angle ($\Delta \psi$) in degrees and (F) in gauss (eleventh and twelfth columns, respectively).

During the three phases of the solar cycle, Tables 1 and 2 show that the CHIP (F) values range from 0.2 to its largest value of 8.2 G for MCs while a moderate values are varied from extremely lower 0.1 G to another extremely higher value of 37 G in the case of 20 September, 1999 (see Table 3). Few other large values $F \sim 10 G$ existed in the maximum phase.
3.2. The Peculiar Case of 20 September 1999 Non-MC Event That Occurred at the Maximum Phase

The 20 September 1999 event has a CHIP value = 37 G, which is very high compared to those of the other events in this study. This is due to the very large area \( A = 9.03 \times 10^{10} \text{ km}^2 \) of the CH (centroid at S27W12), which is close \( d = 1.15 \times 10^5 \text{ km} \) to the eruption region (S20W05) and has also a relatively strong magnetic field \( \langle B \rangle = 5.6 \text{ G} \) as shown in Figure 6. The very high CHIP value and FPA angle = 48° make it possible that the CME was deflected toward the Sun-Earth line as an example of the opposite case of the driverless shocks, where the CMEs of the DL shocks were deflected away from the Sun-Earth line so that they did not hit Earth as discussed by Gopalswamy et al. [2009b]. It is worth noting that the resultant FPA = 48° and the alignment angle of 34° is consistent with the significant deflection. Without such deflection, this CME would not have reached Earth. This event indicates also that the distance between the CH centroid and the source location is the most effective parameter in determining the CHIP than the CH area and CH average magnetic field.

4. The Average Coronal Hole Influence Parameter

The average CHIP values \( (F_{r}^{av}, \Delta \psi^{(av)}) \) are presented in Table 4. Both values are determined for the rise, maximum and declining phases denoted by subscripts r, m, and d, respectively. \( F_{r}^{av} = 1.7 \text{ G} \) for MCs is higher (almost three times) than that of the non-MCs \( (F_{r}^{av} = 0.6 \text{ G}) \). In the maximum phase, \( F_{m}^{av} = 2.4 \text{ G} \) for MCs is comparable to non-MCs \( (F_{m}^{av} = 2.9 \text{ G}) \). For the combined set of MCs and non-MCs, \( F_{m}^{av} = 2.7 \text{ G} \). In these calculations, we have excluded the 20 September 1999 non-MC, which has very high \( F \). If we include this event \( (F = 37 \text{ G}) \), we obtain \( F_{m}^{av} = 4.6 \text{ G} \) for non-MCs. In the declining phase, we obtain \( F_{d}^{av} = 2.1 \text{ G} \) for non-MCs. For the combined MCs and non-MCs, we obtain \( F_{d}^{av} = 2.3 \text{ G} \). This value for the combined set of MCs and non-MCs in the declining phase is consistent with that reported by Gopalswamy et al. [2009b] to be \( F_{d}^{av} = 2.55 \text{ G} \).

Table 4 shows that the average alignment angle for non-MCs is less than that for MCs during the three phases. The average alignment angles for non-MCs is intermediate between the DL shocks (lowest) and MCs (highest). Since a smaller alignment angle implies a greater coronal hole influence, we can see that the non-MCs are affected more by

![Figure 6. EIT image of the 20 September 1999 non-MC event. The eruption is from S27 but the CME propagates northward. This is certainly due to the influence of the CH to the south and west of the eruption region. The alignment angle is also very small, confirming the influence of the CH.](image)

![Figure 7. The individual CHIP (f) versus the CH parameters: area (A), average magnetic field (⟨B⟩), and inverse square distance (d⁻²) for 308 CHs on the solar disk in the 72 events during the three phases of the solar cycle 23. The correlation coefficient is the highest for f vs d⁻².](image)
the coronal holes, consistent with the discussion based on $F$ values. Also, the lowest value is obtained for the non-MCs in the rise phase, $\Delta\psi_{av}^\prime = 44^\circ$, which is very close to that for DL shocks ($\Delta\psi_{av}^\prime = 40^\circ$) given by Gopalswamy et al. [2009b].

[30] Recalling that the highest average CHIP value is obtained for non-MCs at maximum phase $F_m^\prime = 2.9$ (about half of that for DL shocks), we may say that the non-MCs resemble the DL shocks in that both have large $F$ value and small alignment angle. This finding suggests that non-MCs may have a flux rope structure similar to the MCs but the CME deflection by CHs make them appear as non-flux ropes.

[31] Figure 7 shows the dependence of $f$ on the CH area ($A$), average magnetic field strength $\langle B \rangle$, and the distance between the CH centroid and eruption region $d^\prime$. The highest correlation coefficient refers to $\langle d^\prime \rangle$ ($CC = 0.57$), while it is smaller for $A$ ($CC = 0.29$) and $\langle B \rangle$ ($CC = 0.27$).

We computed the confidence level for our correlation coefficients using a simple code based on the Fisher transformation ($z = 1/2\ln[(1 + CC)/(1 - CC)]$) Fisher [1921]. The resulted confidence level for correlation coefficients of $\langle d^\prime \rangle$, $A$, and $\langle B \rangle$ is: 100%, 100%, and 99.9%, respectively. This indicates that the distance is the most important quantity in equation 1. One reason for the high percentage of the confidence level is due to the large sample size ($n = 308$) used.

5. Discussion and Conclusions

[32] The main result of this study is that the influence of CHs on CMEs that erupt close to the disk center is found to be the strongest for DL shocks, intermediate for non-MCs and the smallest for MCs during the three phases of Solar Cycle 23. This result gives further support to the suggestion by Gopalswamy et al. [2009b] that the trajectories of the CMEs are highly affected when the eruptions occur from source regions close to CHs, which act as if they were magnetic barriers guiding the CME propagation. This result indicates that the difference in observed structure between MCs and non-MCs may be due to the difference in the relative position of the ICME magnetic flux rope structure to the observer at 1 AU. The results support the hypothesis that non-MCs are due to CMEs that are ejected at intermediate angles relative to the Sun-Earth line. The higher CHIP and lower alignment angles in the case of CMEs associated with non-MCs are consistent with this hypothesis. The statistics presented in this paper can be improved by investigating the CHs influence on the CMEs that erupt from an intermediate distance from the solar disk center (i.e., central meridian distance $\leq 30^\circ$).

[33] Our results confirm that the propagation of CMEs can be severely affected by the presence of coronal holes nearby. We also see a clear ordering of the interplanetary events by the CHIP. Driverless shocks are affected the most, non-MCs intermediate and MCs the least. When there is no influence from the coronal holes, all CMEs from the disk center are likely to appear as MCs at Earth. Of course, one has to consider additional factors such as inherent non-radial eruptions that might mimic deflection. Observations of the flux rope structure near the Sun is difficult for Earth-directed CMEs due to the occulting disk that blocks their central part; flux rope structure is readily observed in a subset of the limb CMEs [see, e.g., Chen et al., 1997]. The observations from the post-eruption eruptions in EUV, H-alpha ribbons, and soft X-rays do not show any difference between the eruptions that end up as MCs and non-MCs. One of the important evidences that supports the flux rope scenario is the relation between the azimuthal fluxes of MCs measured in the solar wind and the reconnected magnetic flux measured in the flare ribbons on the solar surface [Qiu et al., 2007]. By examining the flare geometry for MCs and non-MCs, it may be possible to infer how CME propagation may affect the final appearance of CMEs at 1 AU as MCs or non-MCs.

[34] Future theoretical models and observations rely on the STEREO mission to provide additional information to address the geometrical aspects of CMEs and ICMEs. We would like to point out that the physical mechanism of CME deflection at the boundaries between open and close regions of the solar atmosphere and in the Heliosphere is yet to be worked out.

[35] The main results of this study may be summarized as follows:

[36] 1. The average value of the CHIP is the lowest for the non-MCs and MCs in the rise phase, $F_m^\prime = 1.7$ G and 0.6 G, respectively.

[37] 2. For MCs, the average CHIP has the smallest value in the rising phase $F_m^\prime = 1.7$ G, where as the CHIP values are comparable for maximum and declining phases ($F = 2.4$).

[38] 3. The CHIP increases from the rise through the maximum to the declining phase.

[39] 4. The CHIP ($F_m^\prime = 2.9$ G) for non-MCs during the maximum phase is fairly large when compared to the rise and declining phases. One usually expects to have MCs associated with disk-center CMEs, the large number of non-MCs from the disk center may indicate that deflection by coronal holes makes MCs appear as non-MCs at Earth.

[40] 5. The highest CHIP ($F = 5.8$ G) is obtained for the DL shocks. The average CHIP ($F$) for MCs and non-MCs is two times lower than that for the DL shocks obtained by Gopalswamy et al. [2009b].

[41] Acknowledgments. We thank the SOHO, Wind and ACE science teams for making the shock data available online. A.A.M. acknowledges the scholarship from the Ministry of Higher Education in Egypt and NASA grant NNX09AT38A.

Philippa Browning thanks the reviewers for their assistance in evaluating the paper.

References


Fisher, R. A. (1921), On the “probable error” of a coefficient of correlation deduced from a small sample, Metron, 1, 3–32.


S. Akiyama, H. Jung, P. Mäkelä, H. Xie, and S. Yashiro, Department of Physics, Catholic University of America, Washington, DC 20064, USA.

N. Gopalswamy, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA.

A. A. Mohamed, School of Physics, University of Sydney, Sydney, NSW 2006, Australia. (amaal.shahin@nasa.gov)