

LOW-LATITUDE CORONAL HOLES AT THE MINIMUM OF THE 23rd SOLAR CYCLE

This article has been downloaded from IOPscience. Please scroll down to see the full text article.

2010 ApJ 712 813

(<http://iopscience.iop.org/0004-637X/712/2/813>)

[The Table of Contents](#) and [more related content](#) is available

Download details:

IP Address: 128.235.251.160

The article was downloaded on 16/03/2010 at 16:39

Please note that [terms and conditions apply](#).

LOW-LATITUDE CORONAL HOLES AT THE MINIMUM OF THE 23rd SOLAR CYCLE

VALENTYNA ABRAMENKO¹, VASYL YURCHYSHYN¹, JON LINKER², ZORAN MIKIĆ², JANET LUHMANN³, AND CHRISTINA O. LEE³

¹ Big Bear Solar Observatory, Big Bear City, CA 92314, USA

² Predictive Science, Inc., San Diego, CA 92121, USA

³ Space Sciences Laboratory, University of California, Berkeley, CA 94720, USA

Received 2009 November 12; accepted 2010 February 7; published 2010 March 8

ABSTRACT

Low- and mid-latitude coronal holes (CHs) observed on the Sun during the current solar activity minimum (from 2006 September 21, Carrington rotation (CR) 2048, to 2009 June 26, CR 2084) were analyzed using *Solar and Heliospheric Observatory*/Extreme ultraviolet Imaging Telescope and *STEREO-A* SECCHI EUVI data. From both the observations and Potential Field Source Surface modeling, we find that the area occupied by CHs inside a belt of $\pm 40^\circ$ around the solar equator is larger in the current 2007 solar minimum relative to the similar phase of the previous 1996 solar minimum. The enhanced CH area is related to a recurrent appearance of five persistent CHs, which survived during 7–27 solar rotations. Three of the CHs are of positive magnetic polarity and two are negative. The most long-lived CH was being formed during 2 days and existed for 27 rotations. This CH was associated with fast solar wind at 1 AU of approximately $620 \pm 40 \text{ km s}^{-1}$. The three-dimensional magnetohydrodynamic modeling for this time period shows an open field structure above this CH. We conclude that the global magnetic field of the Sun possessed a multi-pole structure during this time period. Calculation of the harmonic power spectrum of the solar magnetic field demonstrates a greater prevalence of multi-pole components over the dipole component in the 2007 solar minimum compared to the 1996 solar minimum. The unusual large separation between the dipole and multi-pole components is due to the very low magnitude of the dipole component, which is three times lower than that in the previous 1996 solar minimum.

Key words: solar–terrestrial relations – Sun: activity – Sun: chromosphere – Sun: corona – Sun: magnetic topology

Online-only material: color figures

1. INTRODUCTION

Coronal holes (CHs), in general, may be observed anywhere on the solar disk, however their spatial distribution, frequency of occurrence, and evolution are governed by the solar cycle. Three types of CHs may be distinguished (Storini et al. 2006). First, there are *polar* CHs, which are located at the solar poles and have a lifetime comparable to that of the solar cycle. Included in this category are CH extensions, such as the “elephant trunk” CH observed in 1996 August (Zhao et al. 1999). The second type is *isolated* CHs, which are mostly limited to the low and middle latitudes and are not connected to the polar CHs. Their lifetime is comparable to few Carrington rotations (CRs). The third type consists of *transient* CHs, which are short lived (hours or days) and their occurrence is often associated with powerful eruptions (flares) and/or filament disappearances. Polar CHs usually disappear during the maximum of a solar cycle and reappear again, already having magnetic flux of opposite polarity, thus manifesting the polar field reversal. Isolated CHs behave quite differently. They tend to be more often detected at activity maximum and disappear near activity minimum. According to Hofer & Storini (2002), during the 1986 solar minimum there were only few isolated CHs and none of them was older than five solar rotations. Similar findings were reported by Bilenko (2002) for the 1996 minimum. Potential Field Source Surface (PFSS) modeling of open field regions (Luhmann et al. 2002) also indicates a very low population of low- and mid-latitude CHs during the two previous (1986 and 1996) solar minima.

Qualitatively, the above reports are consistent with the comparison of the structure of the solar corona at the 1996 solar minimum derived from three-dimensional magnetohydrodynamic (MHD) modeling (Mikić & Linker 1996; Mikić et al. 1999;

Linker et al. 1996, 1999; Linker & Mikić 1997) and actually observed during two solar eclipses in 1995 and 1997 (Figure 1). Apparently, the lack of isolated low-latitude CHs on the solar surface resulted in the formation of a well-defined closed magnetic configuration near the solar equator (streamer belt) and the well-developed *dipole* structure of the global magnetic field of the Sun.

The above scenario seems not to be applicable for the current extended 2007 solar minimum, when many global parameters of the heliospheric magnetic field differ significantly from what was measured in the past solar minima. Apart from the unusually low measured sunspot number, observations also show that: (1) interplanetary magnetic field strength is lower when compared with a similar phase of the previous 22nd solar cycle (Lee et al. 2009); (2) the meridional flows inferred by means of surface feature tracking are slower (Hathaway 2009; Schrijver & Liu 2008); (3) photospheric polar magnetic flux is smaller (Smith & Balogh 2008; Lee et al. 2009); (4) solar wind mass flux dropped by about 20% (McComas et al. 2008); (5) the tilt angle of the solar dipole throughout the current 2007 solar minimum is unusually high; and (6) co-rotating interactive regions (CIRs) are abundant and geomagnetic activity is remarkably persistent and recurrent (Mason et al. 2009).

Recently, a comprehensive analysis of a part of the declining phase of the 23rd solar cycle (from 2007 January 8 to November 4) using the PFSS and Wang–Sheeley–Arge (WSA; Arge & Pizzo 2000) models and comparison with *Solar Terrestrial Relations Observatory* (*STEREO*) and OMNI solar wind data has been carried out by Luhmann et al. (2009) and Lee et al. (2009). The model results clearly demonstrated an excess of low- and mid-latitude CHs during the time period under study (Figure 8 in Luhmann et al. 2009) and show a reduced magni-

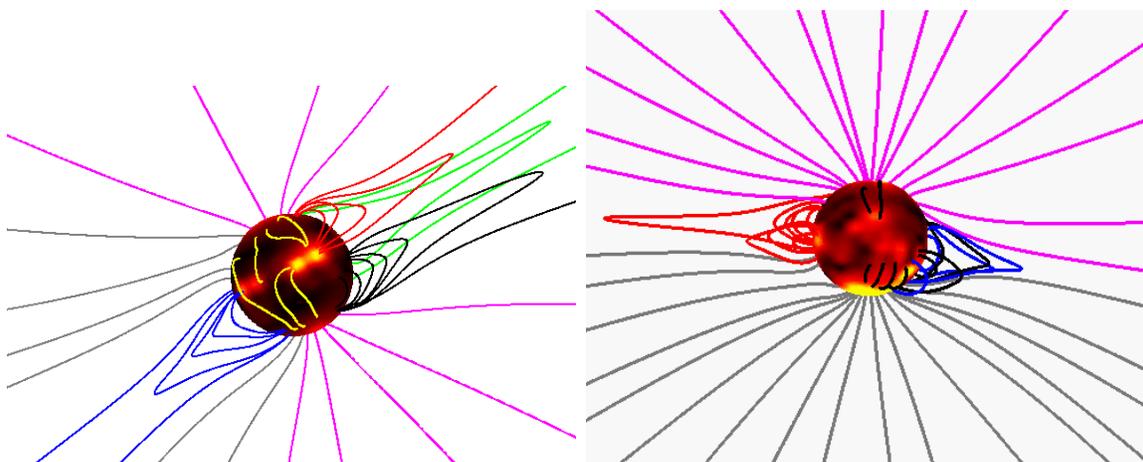


Figure 1. Typical structure of the solar corona at a solar minimum. Left panel: magnetic field lines in the corona, shown in arbitrary colors, as derived from a three-dimensional numerical simulations for CR1900 prior to the 1995 October 24 solar eclipse. The photospheric magnetic field data used in this model are Wilcox Solar Observatory synoptic maps. The image in the photosphere shows the intensity of the magnetic field: active regions with strong magnetic fields appear yellow. The view point corresponds to the approximate time of the eclipse (Carrington longitude of 39° at the central meridian). Terrestrial north is to the top. Right panel: same as the left panel, but for the 1997 March 9 solar eclipse (Carrington longitude of 257°). Note that in both models the dipole structure of the global magnetic field is very prominent and there are no significant inclusions of open flux in the equatorial zone. (A color version of this figure is available in the online journal.)

tude of solar polar magnetic field. The presence of low- and mid-latitude CHs may have affected the enhanced ecliptic solar wind speed and explain the observed anomalous distribution of the solar wind speed with a heavy tail at $500\text{--}700\text{ km s}^{-1}$.

In this paper, we take a closer look at the low-latitude CHs during the period between 2007 and 2009 by utilizing data from the *Solar and Heliospheric Observatory (SOHO)* Extreme ultraviolet Imaging Telescope (EIT; Delaboudiniere et al. 1995) and *STEREO* Sun Earth Connection Coronal and Heliospheric Investigation (SECCHI) EUVI (Howard et al. 2008) instruments. We investigate their recurrent properties by tracking CHs in time, and we analyze the harmonic power spectrum of the solar magnetic field (Section 2). In Section 3, we analyze one of the CHs in more detail, including its magnetic field structure and solar wind signatures. Concluding remarks are in Section 4.

2. HIGH POPULATION OF LOW-LATITUDE CHs DURING THE MINIMUM OF SOLAR CYCLE 23

To study the occurrence frequency of low-latitude CHs on the solar disk, we calculated the total area of CHs (Figure 2) observed between 1996 February (CR 1905) and 2008 December (CR 2077). The CH area was determined from *SOHO*/EIT Fe xv 284 Å synoptic maps (<http://sun.stanford.edu/synop/EIT/index.html>) for all CHs located between the latitudes of -40° and $+40^\circ$. This area was calculated for each half of one CR and then normalized to the total solar surface area limited by -40° and $+40^\circ$ latitudes. (For details on the CH outlining technique, see Abramenko et al. 2009). Correspondingly, the normalized CH area was calculated from the PFSS model data (blue curve in Figure 2) in the manner as described in Lee et al. (2009). As it follows from the graph, both observed and model data show that, in contrast with the previous 1996 solar minimum, low-latitude CHs appear more frequently during the 2007 solar minimum and they occupy a larger portion of the solar surface.

Are these low-latitude CHs short-lived transient entities (as they usually are during a solar minimum), or is their appearance caused by structures that survived many solar rotations? We address this question by tracking the CHs in time.

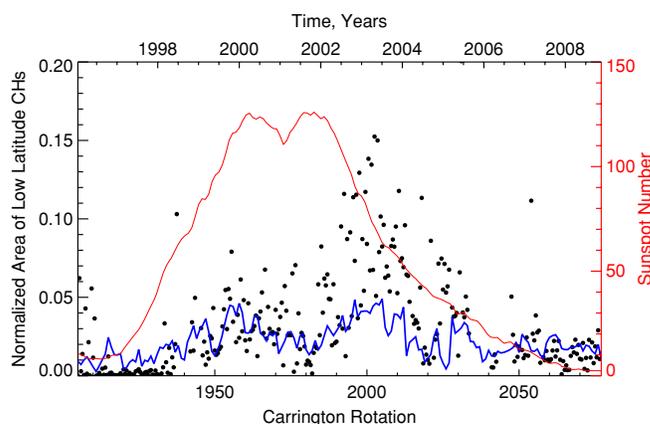


Figure 2. Dots: total area of the low-latitude (-40° to $+40^\circ$) CHs plotted vs. the CR number (bottom horizontal axis, the top horizontal axis shows years). The CH area was measured from *SOHO*/EIT Fe xv 284 Å images for each half of a CR and is plotted here normalized to the solar disk area bounded between -40° and $+40^\circ$ of solar latitude. Blue: the same area derived from the PFSS model with the source surface at 2.5 solar radii. Red: the sunspot number (right vertical axis). During the current solar minimum (2006–2009), low-latitude CHs occur more frequently and they occupy an area larger when compared to the previous solar minimum (1995–1997).

(A color version of this figure is available in the online journal.)

In Figure 3, we show a *STEREO-A* SECCHI EUVI 195 Å synoptic map (background) where we outline the boundaries of five isolated low-latitude CHs. Two of them were associated with negative polarity magnetic field (N1, N2) and three were of positive polarity (P1, P2, and P3). Color lines in Figure 4 trace the CHs positions between consecutive CRs (note that the color coding in Figures 3 and 4 is the same). The positive polarity CHs were long-lived. P1 (double green line) and P2 (blue line) appeared during CRs 2049 and 2048, respectively, and both lasted for about 13 solar rotations. Meanwhile, P3 (thick green line), which appeared during CR 2058, lasted for 21 solar rotations.

The negative polarity CH N1 (double red line) appeared during CR2053 and was observed for at least 7 rotations (see

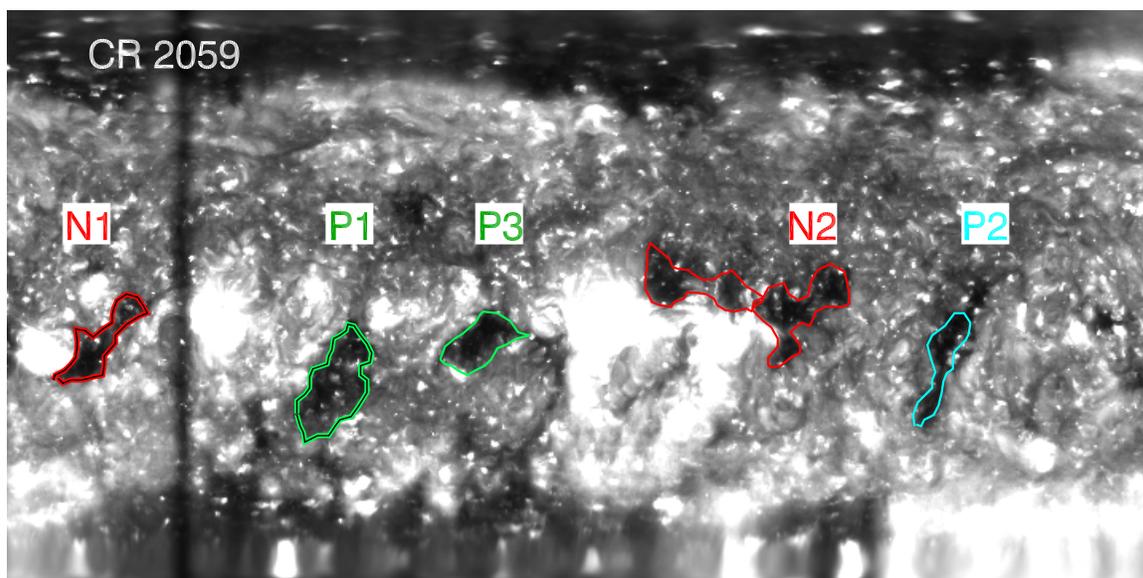


Figure 3. *STEREO-A* SECCHI EUVI 195 Å synoptic map for CR 2059 (from 2007 July 18 to August 14) showing five low-latitude CHs. The red lines outline two negative polarity CHs (N1 and N2), while the green and blue lines encircle three positive polarity CHs (P1, P2, and P3).

(A color version of this figure is available in the online journal.)

also Luhmann et al. 2009), while N2 (thick red line) was first detected during CR2058 (2007 June 28) and survived until 2009 May for almost 27 solar rotations. CHs P3 and N2 observed during CR 2063 have been modeled by Luhmann et al. (2009).

It appears that the observed excess of low-latitude CHs during the current 2007 solar minimum is, to a large extent, caused by the repeated and persistent appearance of these five CHs on the visible solar hemisphere. Quite possibly, their existence may be a manifestation of strong multi-pole moments in the harmonic spectrum of the magnetic field of the Sun, which can be written as $S_n = \sum_{m=0}^n [(g_n^m)^2 + (h_n^m)^2]$ (Altschuler et al. 1977). Here, g_n^m and h_n^m are harmonic coefficients determined from measurements of the line-of-sight component of the photospheric magnetic field. We used the harmonic coefficients calculated at the Wilcox Solar Observatory (<http://wso.stanford.edu/forms/prgs.html>) for CRs 2045–2085 to examine the dipole and multi-pole components during the 1996 and 2007 minima (Figure 5). From these plots, the difference between the dipole and multi-pole components is larger during the 2007 solar minimum as compared to the similar phase of the 1996 solar minimum, and it may be chiefly attributed to weakening of the dipole component during the 2007 solar minimum. In particular, when comparing data for CRs 1900–1909 and CRs 2048–2057 (similar solar cycle phase), one can see that the dipole component decreased nearly threefold, whereas the sum of all multi-poles decreased only by about 30%. It is also interesting that there is a slight decline in both dipole and multi-pole components during the 2007 solar minimum, which was not the case for the preceding 1996 solar minimum.

3. GENESIS OF THE EQUATORIAL CORONA HOLE N2

We analyzed the most persistent CH, N2, in more details. In Figure 6, we illustrate appearance of N2 by showing three EIT 195 Å images taken on 2007 June 04, 28, and 30. The over-plotted boxes encircle the same area on the Sun. Comparison of the June 04 (top panel) and June 30 (bottom panel) images (they are one CR apart) shows that small active region (AR) NOAA 10958, completely decayed over one solar rotation and that a

vast area immediately northeast of the AR became occupied by a CH (indicated by the box in the bottom panel). The June 28 EIT 195 Å image (middle panel) shows that only two days earlier the CH was not present or, at least, it was in a very early stage of development.

As we mentioned earlier, this CH was observed (having slightly different shapes) for 27 solar rotations. The time difference between consecutive culminations of the center of gravity of the CH was on average 26.9 ± 0.7 days. The latitude of the center of gravity varied between -10° and 8° , which indicates on its near-equatorial location (note that the coordinates of the center of gravity were determined by averaging the corresponding coordinates of the points located along the CH boundary; a technique to outline the CH boundary is described in Abramenko et al. 2009).

To probe the structure of the negative polarity field inside N2, we utilized *Advanced Composition Explorer* (ACE) Solar Wind Electron, Proton, and Alpha Monitor (SWEPAM) measurements of the solar wind speed, V_x , in geocentric solar ecliptic (GSE) coordinate system. We determined the speed of the fast stream, associated with the CH, by accepting that the time interval between the stream arrival time at 1 AU and the injection time (the CH culmination moment) multiplied by a given $V_x(t)$, measured by ACE instrument, produces a distance of 1 AU (for more details see Abramenko et al. 2009). This was performed for 17 solar rotations (CRs 2059–2075) during which N2 has been observed. Since no other solar activity was detected during the period under study, our approach allowed us every time to reliably detect a well-pronounced signature of the CH in the solar wind speed profile. The magnitude of the CH-associated solar wind speed varied between 560 and 670 km s^{-1} with the mean value of $620 \pm 40 \text{ km s}^{-1}$.

Next, we examine whether there is evidence for the N2 CH in coronal models. A three-dimensional MHD model of the solar corona was computed prior to the 2008 August 1 solar eclipse (see <http://www.predsci.com>). A synoptic magnetic field map for CRs 2071–2072 (2008 June 25–July 21) was constructed from Michelson Doppler Imager (MDI) magnetograms and used as the boundary condition. The modeling approach is described

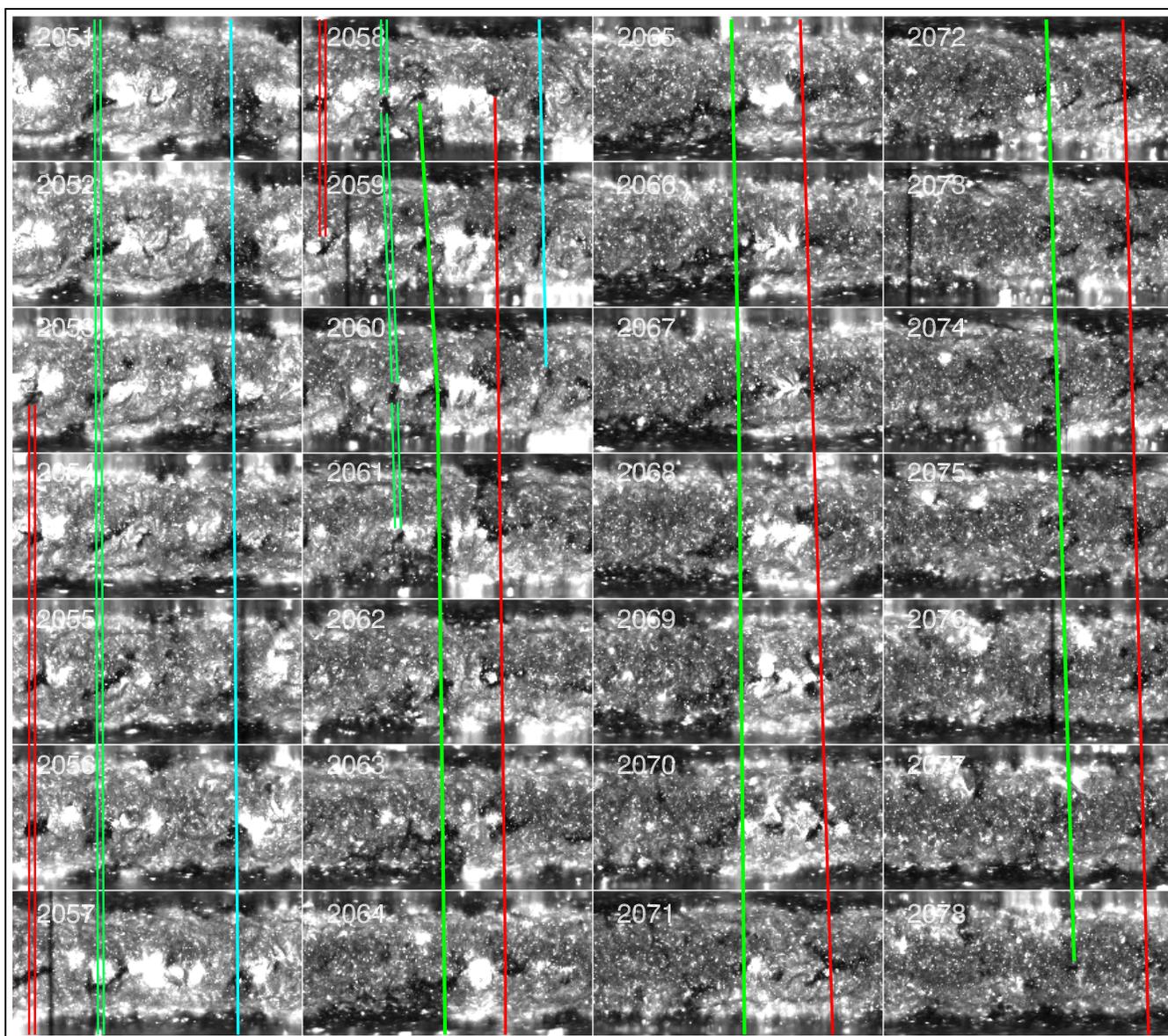


Figure 4. *STEREO-A* SECCHI EUVI 195 Å synoptic maps for 28 CRs ranging from CR 2051 (2006 December 12) to CR 2078 (2009 January 12). Each color lines traces the same CH at subsequent rotations, and it crosses a map from top to bottom in case when the corresponding CH existed during previous and subsequent CRs. The lines have a gap to make small CHs visible. The red lines trace two negative polarity CHs: N1 (double red line), appeared at CR 2053 and existed during 7 rotations; N2 (thick red line), appeared at CR 2058 and was observed during 27 rotations. The double green, blue, and thick green lines trace positive polarity CHs, P1, P2, and P3, respectively. The enlarged version of the synoptic map for CR2059 is shown in Figure 3.

(A color version of this figure is available in the online journal.)

by Lionello et al. (2009), while Rusin et al. (2010) describes a comparison of the model with observations around the time of the eclipse.

Figure 7 shows CH boundaries, magnetic field lines, and emission at 195 Å as derived from the MHD model and the EUVI instrument aboard the *STEREO-B* spacecraft on 2008 July 9. The open field regions in the model (black areas and red field lines in Figure 7(a)) agree quite well with the *STEREO* observations of N2 (Figure 7(c)). The simulated emission (Figure 7(b)) also agrees reasonably well with the observations, although the CH region is too dark and extensive in the model. This is because the coronal heating mechanism, assumed for the model, produced too little emission overall (see Lionello et al. (2009) for a discussing of the technique for computing simulated emission from coronal models). Nevertheless, it is clear that N2 is revealed to be a CH in the MHD model as well as

the observations. The N2 was detected again prior the 2008 August eclipse in *STEREO-A* observations on July 14, and afterward in *SOHO* EIT observations on August 7. It survived for nearly another year after that. During 2009 May, the N2 began to shrink and it finally vanished one rotation later in June, almost two years after its first appearance on the solar surface.

4. CONCLUDING REMARKS, DISCUSSION, AND OPEN QUESTIONS

We have combined observed data with magnetic field modeling to show that the global magnetic field of the Sun during this 2007 extended solar minimum was not a simple dipole. The area occupied by CHs inside a belt of $\pm 40^\circ$ around the solar equator was found to be considerably larger during the 2007 minimum than that during the similar phase of the previous 1996

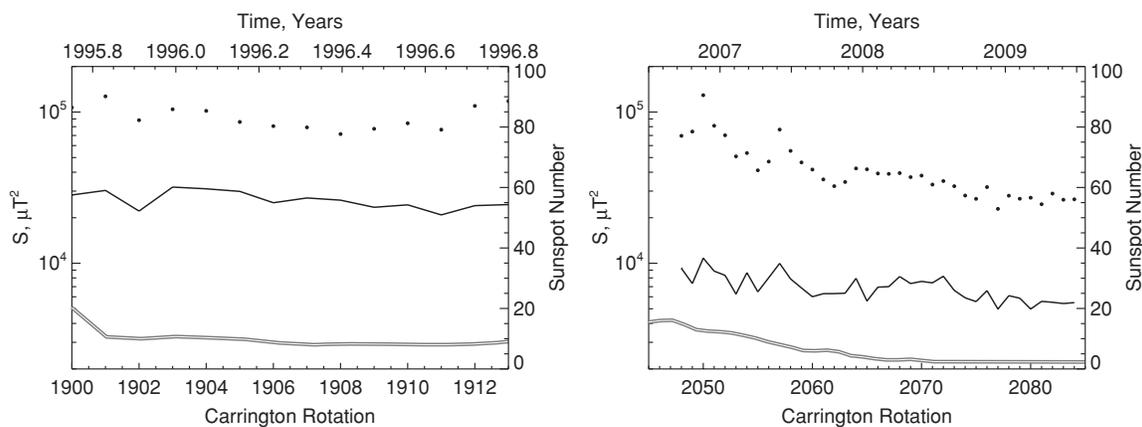


Figure 5. Time profiles of various components, S (in squared micro-Tesla), of the multi-pole power spectrum of the solar photospheric magnetic field during CRs 1900–1913 (left panel) and CRs 2048–2085 (right panel). The solid line shows the dipole component ($n = 1$) and the dotted lines are the sum of all multi-poles from $n = 2$ to $n = 7$. The sunspot numbers are plotted with double gray line (right axis).

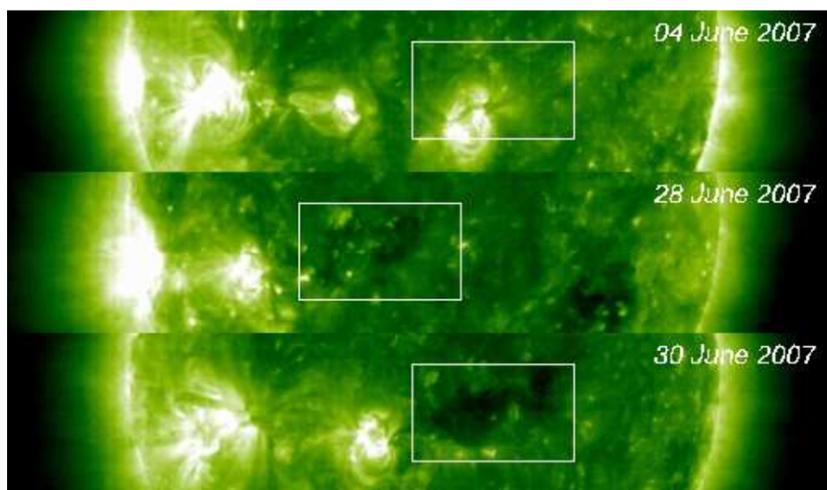


Figure 6. Appearance of the CH of negative polarity, N2, as captured by EIT Fe xii 195 Å instrument. Boxes enclose the same area on the Sun during two consecutive rotations on 2007 June 4 and 30 (CRs 2057 and 2058). A small AR (NOAA 10958, inside the box in the top frame) completely disintegrated and N2 formed on its place. Middle panel shows data on June 28, which indicates that the CH fully developed in less than 2 days and survived for almost 27 solar rotations. (A color version of this figure is available in the online journal.)

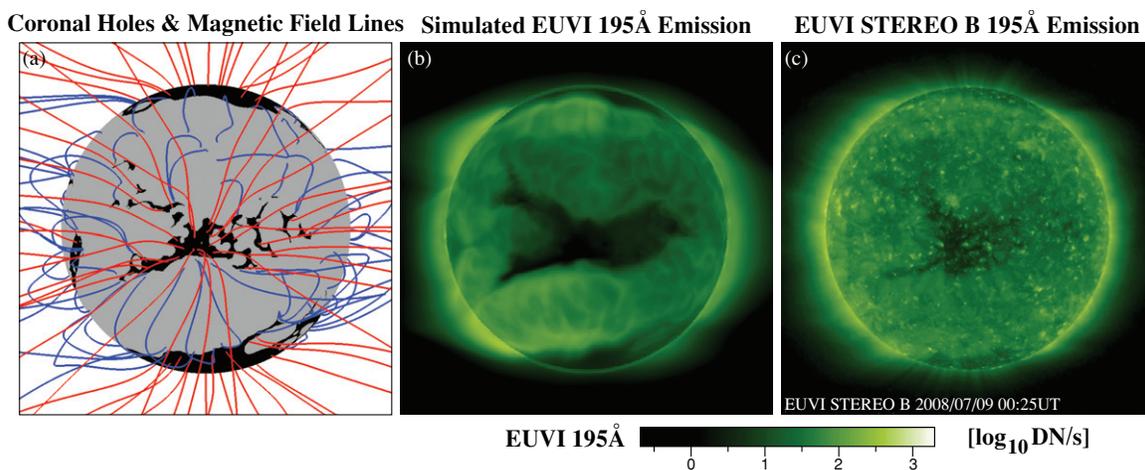


Figure 7. Left panel: CH boundaries and magnetic field lines from an MHD model of the solar corona prior to the 2008 August 1 solar eclipse. Black regions shown on the surface are open field regions computed from the model; and gray areas are closed field regions. Closed magnetic field lines are colored blue and open field lines are red. Middle panel: simulated *STEREO* EUVI 195 Å emission from the MHD model and observed EUVI 195 Å emission from the *STEREO-B* spacecraft on 2008 July 9 (right panel). Comparison of the three images shows that the N2 CH is clearly captured as an open field region in the MHD model during this time period. (A color version of this figure is available in the online journal.)

solar minimum. Our results are confirmed by the CH-modeling results recently reported by Luhmann et al. (2009).

Thus, the global magnetic field of the Sun had a multi-pole configuration, at least in the time period between 2006 September and 2009 May. The harmonic power spectrum of the solar magnetic field shows a greater prevalence of higher multi-pole moments over the dipole moment relative to the previous 1996 solar minimum. The large difference between these two parameters is probably due to a very low (three times lower than that in the 1996 solar minimum) magnitude of the dipole component.

The observed diminution of the polar magnetic field also implies reduction of the dipole component relative to the rest of the multi-pole components in the solar magnetic field harmonic spectrum (Luhmann et al. 2009). This, in turn, might result in re-enforcement of the multi-pole magnetic configuration in the global solar magnetic field, which can be observed as persistent CHs along the low- and mid-latitudes on the Sun.

From 2006 September to 2009 May, there were at least five long-lived CHs associated with patches of open field inside the near-equatorial $\pm 40^\circ$ zone. Three of them were of positive magnetic polarity CHs, and the other two were of negative polarity CHs. They lasted from 7 to 27 solar rotations. The longest lived CH, N2, formed on the solar disk during a time interval of nearly 2 days and existed for 27 rotations at solar latitudes between S10 and N08. N2 was associated with a fast solar wind stream at 1 AU of approximately $620 \pm 40 \text{ km s}^{-1}$, which may in part be responsible for the heavy tail in the solar wind speed distribution (Luhmann et al. 2009). An MHD model of the corona that used *SOHO* MDI synoptic maps from 2008 June 25–July 21 for the boundary condition, predicted an open field structure and dark emission in the N2 CH region.

A possible mechanism for the formation of this global solar multi-pole is a new challenge for solar dynamo theory. How do these persistent low- and mid-latitude CHs form during a deep solar minimum? They are most likely not transient CHs because there were no coronal mass ejecta during these quiet times that could have created them. It is also very unlikely that these CHs separated from the polar CHs and migrated to the solar equatorial region during one rotation (see Section 3).

Very often a low latitude CH originally forms in association with an AR (e.g., Bohlin & Sheeley 1978; Harvey & Recely 2002; Bilenko 2004; Karachik et al. 2010). Recent analysis of CH formation (Karachik et al. 2010) showed that appearance of a CH in association with an AR is not unique. Authors discuss four cases observed during 2009 when an isolated CH appeared on the place of decaying ARs (similar to the N2 CH case). These isolated CHs might form *in situ* as a result of a large-scale reconnection between the remnant fields of a decaying AR and strongly diverged global open field lines (Wang & Sheeley 2004). Then, as the AR decays, the CH may or may not survive—depending on the rate of AR field decay, whether there is new flux emerging in the same place (e.g., a long-lived “nest” or “active longitude”), or just an extremely slow decay of the AR fields, perhaps due to very little new flux emergence going on. Anyway, the isolated CHs, being very persistent during the current 2007 solar minimum, contribute significantly into the total solar magnetic field balance, equilibrium between the multi-pole and dipole magnetic components and, eventually, might play a role in the onset of the next solar activity cycle.

We are thankful to A. Pevtsov and G. deToma for very helpful discussions. We highly appreciate the efforts of the anonymous

referee whose comments and criticism led to improvement of the manuscript. V. Abramenko and V. Yurchyshyn were supported by NSF ATM-0716512 and NASA *STEREO* NNX08AJ20G grants. J. Linker and Z. Mikić were supported by the LWS Strategic Capabilities program (jointly funded by NASA, AFOSR, & NSF), NASA’s Heliophysics Theory Program, the NSF CISM program, and the *STEREO* IMPACT and SECCHI teams. Computational resources were provided by the TACC on the Ranger supercomputer and by NAS on the Columbia and Pleiades supercomputers. We thank the *ACE* MAG and SWEPAM instrument teams and the ACE Science Center for providing the *ACE* data. We acknowledge the Wilcox Solar Observatory staff for providing the harmonic coefficients. *SOHO* is a project of international cooperation between ESA and NASA. The SECCHI data used here were produced by an international consortium of the Naval Research Laboratory (USA), Lockheed Martin Solar and Astrophysics Lab (USA), NASA Goddard Space Flight Center (USA), Rutherford Appleton Laboratory (UK), University of Birmingham (UK), Max-Planck-Institut für Solar System Research (Germany), Centre Spatial de Liege (Belgium), Institut d’Optique Theorique et Appliquee (France), and Institut d’Astrophysique Spatiale (France).

REFERENCES

- Abramenko, V. I., Yurchyshyn, V., & Watanabe, H. 2009, *Sol. Phys.*, 260, 43
 Altschuler, M. D., Levine, R. H., Stix, M., & Harvey, J. 1977, *Sol. Phys.*, 51, 345
 Arge, C. N., & Pizzo, V. J. 2000, *J. Geophys. Res.*, 105, 10465
 Bilenko, I. A. 2002, *A&A*, 396, 657
 Bilenko, I. A. 2004, in IAU Symp. 223, Multi-Wavelength Investigations of Solar Activity, ed. A. V. Stepanov, E. E. Benevolenskaya, & A. G. Kosovichev (Cambridge: Univ. Press), 373
 Bohlin, J. D., & Sheeley, N. R., Jr. 1978, *Sol. Phys.*, 56, 125
 Delaboudiniere, J.-P., et al. 1995, *Sol. Phys.*, 162, 291
 Harvey, K., & Recely, F. 2002, *Sol. Phys.*, 211, 31
 Hathaway, D. H. 2009, *Space Sci. Rev.*, 144, 401
 Hofer, M. Y., & Storini, M. 2002, *Sol. Phys.*, 207, 1
 Howard, R. A., et al. 2008, *Space Sci. Rev.*, 136, 67
 Karachik, N. V., Pevtsov, A. A., & Abramenko, V. I. 2010, *ApJ*, submitted
 Lee, C. O., Luhmann, J. G., Zhao, X. P., Liu, Y., Riley, P., Arge, C. N., Russell, C. T., & de Pater, I. 2009, *Sol. Phys.*, 256, 345
 Linker, J. A., & Mikić, Z. 1997, in *Geophys. Monograph 99, Extending Coronal Models to Earth Orbit, Coronal Mass Ejections: Causes and Consequences*, ed. N. Crooker, J. Joselyn, & J. Feynman (Washington, DC: AGU), 269
 Linker, J. A., Mikić, Z., & Schnack, D. D. 1996, in *ASP Conf. Ser. 95, Solar Drivers of the Interplanetary and Terrestrial Disturbances*, ed. K. S. Balasubramaniam, S. L. Keil, & R. N. Smartt (San Francisco, CA: ASP), 208
 Linker, J. A., et al. 1999, *J. Geophys. Res.*, 104, 9809
 Lionello, R., Linker, J., & Mikić, Z. 2009, *ApJ*, 690, 902
 Luhmann, J. G., Li, Y., Arge, C. N., Gazis, P. R., & Ulrich, R. 2002, *J. Geophys. Res. (Space Phys.)*, 107, A8
 Luhmann, J. G., et al. 2009, *Sol. Phys.*, 256, 285
 Mason, G. M., Desai, M. I., Mall, U., Korth, A., Bucik, R., von Roseninge, T. T., & Simunac, K. D. 2009, *Sol. Phys.*, 256, 393
 McComas, D. J., Ebert, R. W., Elliott, H. A., Goldstein, B. E., Gosling, J. T., Schwadron, N. A., & Skoug, R. M. 2008, *Geophys. Res. Lett.*, 35, L18103
 Mikić, Z., & Linker, J. A. 1996, in *AIP Conf. Proc. 382, Solar Wind*, ed. D. Winterhalter et al. (Melville, NY: AIP), 104
 Mikić, Z., Linker, J. A., Schnack, D. D., Lionello, R., & Tarditi, A. 1999, *Phys. Plasmas*, 6, 2217
 Rusin, V., et al. 2010, *A&A*, in press
 Schrijver, C. J., & Liu, Y. 2008, *Sol. Phys.*, 252, 19
 Smith, E. J., & Balogh, A. 2008, *Geophys. Res. Lett.*, 35, L22103
 Storini, M., Hofer, M. Y., & Šýkora, J. 2006, *Adv. Space Res.*, 38, 912
 Wang, Y.-M., & Sheeley, N. R., Jr. 2004, *ApJ*, 612, 1196
 Zhao, X. P., Scherrer, P. H., & Hoeksema, J. T. 1999, *J. Geophys. Res.*, 104, 9735