The Rate of Emergence of Magnetic Dipoles in Coronal Holes and Adjacent Quiet-Sun Regions

V. I. Abramenko
Big Bear Solar Observatory, 40386 N. Shore Lane, Big Bear City, CA 92314

L. A. Fisk
Department of Atmospheric, Oceanic and Space Sciences, University of Michigan, 2455 Hayward Street, Ann Arbor, MI 48109

V. B. Yurchyshyn
Big Bear Solar Observatory, 40386 N. Shore Lane, Big Bear City, CA 92314

Observations from the Michelson Doppler Imager and the EUV Imager Telescope on the Solar and Heliospheric Observatory (SOHO) are analyzed to determine the rate of emergence of new magnetic flux in coronal holes, and in surrounding regions on the quiet Sun. Coronal holes are regions where the open magnetic flux of the Sun, the component that forms the heliospheric magnetic field, is concentrated. It is determined that the rate of emergence of new magnetic flux is systematically lower, by a factor of ~2, in coronal holes relative to the surrounding quiet Sun. This result is consistent with a prediction in a recent model for the transport of open magnetic flux on the Sun, which demonstrated that open flux tends to accumulate and concentrate in regions where the rate of emergence of new magnetic flux is a local minimum.

Subject headings: (Sun:) solar wind; Sun: magnetic fields; Sun: photosphere

1. Introduction

Coronal holes are regions in the solar atmosphere where the magnetic field that opens into the heliosphere, the so-called open magnetic flux of the Sun, is concentrated. The solar wind escapes easily along the open field lines, and the coronal density is reduced. During solar minimum conditions, large, well-defined coronal holes form near the solar poles. During maximum solar activity, transient coronal holes form elsewhere on the Sun.

One of the interesting questions in solar physics is why do coronal holes form? There are numerous, quite sophisticated models for the evolution of the solar magnetic field (e.g., Wang & Sheeley 1991; Wang, Lean, & Sheeley 2000a; Schrijver 2001; Schrijver & Title 2001; Schrijver, DeRosa, & Title 2002; Schrijver & DeRosa 2003). These models are generally based on the following processes: the emergence of new magnetic flux, particularly in active regions; the subsequent diffusion of the magnetic field due to random convective motions in the photosphere; and flux cancellation when magnetic fields of opposite polarity interact. In most of these models, the presence of open or closed magnetic flux (bipolar loops) is determined, as a separate event, by a potential field source surface model, as pioneered by Altschuler & Newkirk (1969) and Schatten et al.

(1969). The field is assumed to evolve by diffusion in the photosphere; whether it is ultimately open or closed is determined by a potential field source surface model. Such models, however, are intrinsically static, and cannot describe the evolution of the magnetic field. The issue is particularly problematic for the polar coronal holes. New magnetic flux emerges in active regions during solar maximum and diffuses toward the solar poles, where it cancels existing flux of opposite polarity to accomplish the magnetic field reversal during the solar cycle. When the magnetic field emerges, it is closed magnetic flux. Yet, when it is at the solar poles in the well-established polar coronal holes at the next solar minimum, it is open flux. However, there are no aspects in most current models to accomplish this transition.

In a series of papers, Fisk and colleagues have approached the evolution of the open magnetic flux of the Sun from a different point of view (e.g., Fisk 1996; Fisk et al. 1999; Fisk 2001; Fisk & Schwardon 2001). Their approach is based on the observation that the open magnetic flux of the Sun is relatively constant during the solar cycle (e.g., Wang, Sheeley, & Lean 2000b). It does exhibit some temporal variations. Coronal mass ejections drag new magnetic flux outward into the heliosphere, but then this new flux appears subsequently to reconnect, in a process known as interchange reconnection, and does not result in a long-term addition to the total open magnetic flux in the heliosphere (e.g., Crooker, Gosling, & Kahler 2002). The open flux is certainly much more constant during the solar cycle than the total magnetic flux.

If the open magnetic flux is relatively constant, its evolution during the solar cycle can be treated as a transport problem. To form coronal holes, then, whether at the poles or elsewhere, the open magnetic flux must be transported to these regions, and there must be a physical reason for why the open flux accumulates in coronal holes.

In Fisk (2005) a model for the transport of open magnetic flux is developed. The model assumes that open magnetic field lines are transported by two processes: random convective motions in the photosphere, common to all magnetic flux, and reconnection with coronal loops. If an open field line reconnects at the base of a coronal loop with opposite polarity, the open field will be displaced to lie over the opposite end of the loop. To the extent that the loops are randomly oriented, this is an additional diffusion process; in fact, a more important one than random convective motions, since the size of loops can exceed the linear dimensions of network lanes. This process can also control the sizes of loops since the reconnection process with open field lines destroys loops, and leaves only a small secondary loop at the site of the reconnection.

In Fisk (2005) the interactions of open field lines and coronal loops are modeled, and the diffusive transport coefficients for open field lines are determined in terms of the rate of emergence of new magnetic flux on the Sun. This model makes a very specific prediction: Coronal holes, concentrations of

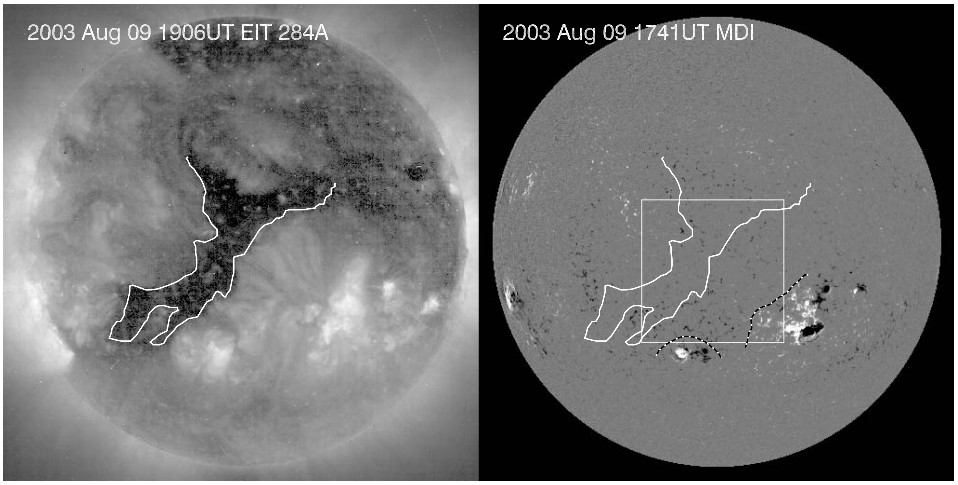

Fig. 1. – SOHO/EIT 284-Å image (left) and SOHO/MDI magnetogram (right) obtained on 2003 August 9. A fitted contour of the coronal hole (thick white line in both panels) was determined as a boundary between dark and gray areas in the left image and then projected on the magnetogram. A part of the coronal hole enclosed by the MDI high-resolution 1024 x 1024 FOV (thin white box in the right panel) was analyzed. The analyzed QS area is located outside the CH, but inside the FOV. We did not take into account areas near active regions marked by dashed black-white lines.

open magnetic flux, will form in regions where the rate of emergence of new magnetic flux is a local minimum.

In this paper, we test this prediction by determining the rate of emergence of new magnetic flux in coronal holes (CH) and in adjacent regions on the quiet Sun (QS), outside of active regions. We find that the dipole emergence rate in coronal holes is twice that of the surrounding quiet Sun, in agreement with the prediction.

We begin by describing our observation technique and then present our results and the conclusion we draw from them.

2. Observational Data and Results

In this study we analyzed data obtained from the Michelson Doppler Imager (MDI, Scherrer et al. 1995) and the EUV Imager Telescope (EIT, Delaboudinière et al. 1995) on the Solar and Heliospheric Observatory (SOHO). To identify the location of a coronal hole (CH) and a quiet-Sun (QS) area, relative to the magnetic field, we used MDI's full-disk magnetograms and EIT's Fe XV 284-Å full-disk images. In these images CHs are seen as dark, extended areas of very low intensity, whereas adjacent QS areas (outside active regions) are light gray and spanned by fuzzy loops. A boundary between a CH and a QS was determined by aligning an MDI magnetogram with the closest EIT 284-Å image. An example of a CH and adjacent QS area is shown in Figure 1.

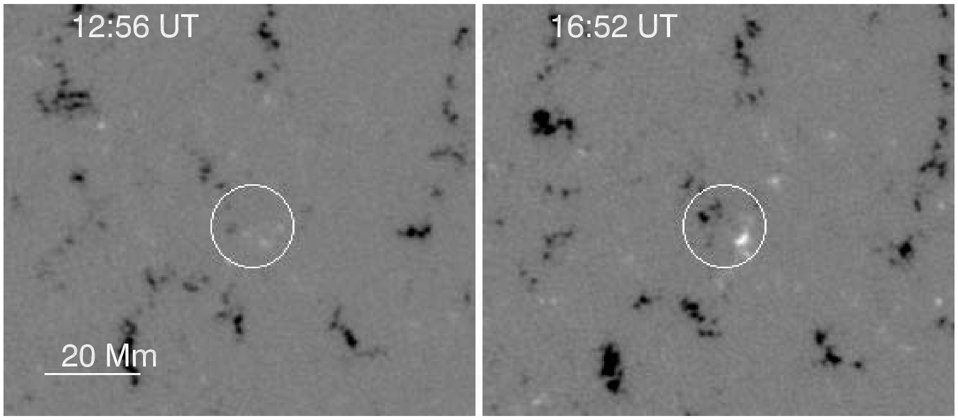

Fig. 2. – SOHO/MDI high-resolution magnetograms obtained on 2003 June 16 covering the same fragment of a coronal hole. The circle indicates the location where emergence of a new dipole was observed. The magnetograms are scaled within a range of ± 200 G.

In order to determine the rate of emergence of new magnetic flux in CHs and QS areas we used line-of-sight MDI magnetograms recorded in the high-resolution mode (spatial resolution 1.25 arcsec and the corresponding pixel size of 0.58 × 0.58 arcsec) in the Ni I 6768-Å spectral line with a 94-mÅ band pass filter. The detection limit for the magnetic flux density is approximately σ =17 G (Schrijver et al. 1997). The dimension of all MDI high-resolution magnetograms was 1024 × 1024 pixel.

In our data set, which covers a period from 2002 June till 2003 December, we identified 34 CHs with adjacent QS areas located at the disk center. For each pair of CH and QS area we used a set of magnetograms so that the evolution of magnetic fields can be studied. In the majority of cases, the MDI high-resolution data sets allowed us to average 3–5 consecutive magnetograms, obtained with 1-minute time cadence, to reduce noise. Usually, for each pair of CH and QS there were no less than 4 averaged magnetograms available that covered a time period, Δt, of about 17–30 hours. A time interval between the averaged magnetograms varied from 2 to 15 hours.

By comparing subsequent magnetograms we detected newly emerged dipoles in both a CH and a QS area. For that, we adopted the technique proposed by Hagenaar (2001). First, we detected the appearance of new unipolar magnetic-flux concentrations with flux density above the threshold level of $3\sigma = 50$ G and with the magnetic flux exceeding 10^{19} Mx. According to Hagenaar (2001), this magnitude of the magnetic flux in magnetic-flux concentrations is sufficiently high to be reliably detected and identified from one magnetogram to another. Our choice of such a high threshold was determined by the low time cadence of the averaged magnetograms that we use in this study: indeed, given the long time intervals between the magnetograms, we had a better chance to detect

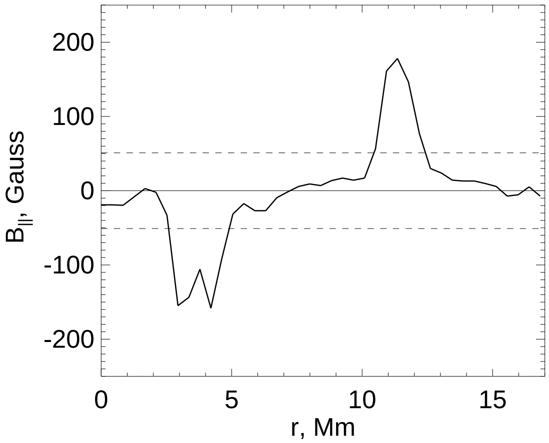

Fig. 3. – Variations of the magnetic-flux density along the axis of the dipole shown in Fig. 2. The dashed lines show the 3σ level of the magnetic-flux density in the magnetogram. The magnetic flux in the positive and negative parts of the dipole, integrated over the pixels with magnetic-flux density exceeding this level, is $+10.2 \times 10^{18}$ *and* -10.0×10^{18} *Mx, correspondingly.*

stronger dipoles as long as there existed a positive correlation between the lifetime of dipoles and their magnetic flux (Hagenaar et al. 1999). When we observed two new flux concentrations of opposite polarity appearing inside a circle with a radius of 10 Mm (as suggested by Hagenaar 2001), we counted this case as an event of new dipole emergence.

A typical example of an emerging dipole is shown in Figure 2. A profile of magnetic-flux density along the line connecting the negative and positive flux concentrations in this dipole is presented in Figure 3.

From the total number of dipoles, n, that emerged inside a given area S during a time period Δt, we determined the dipole emerging rate, m, as the number of dipoles that emerged inside an area of 200 × 200-Mm per day:

$$m= Cn/(S\,\Delta t), \qquad (1)$$

where C is a constant defined by the dimensions of the parameters. We thus obtained 34 values of the dipole emergence rate inside CHs, m_{CH}, and, for each CH, we obtained the dipole emergence rate inside the adjacent QS area, m_{QS}. We then compare them in Figure 4. In all cases, the dipole emerging rate for CHs is lower than that for adjacent QS areas (all data points are above the bisector).

Distributions of m_{QS} and m_{CH} are presented in Figure 5. The peak of the distribution of the emergence rate for CHs is in the range of 0.4–0.5, whereas for QS areas the peak of distribution is clearly displaced to m = 1.0–1.2. The mean value of m_{QS} is about 1.14 ± 0.41 and it exceeds approximately twice the mean value of m_{CH} ($< m_{CH} > = 0.52 \pm 0.23$). Note that the dipole emergence rate estimated here is significantly lower than that reported by Hagenaar (2001). The

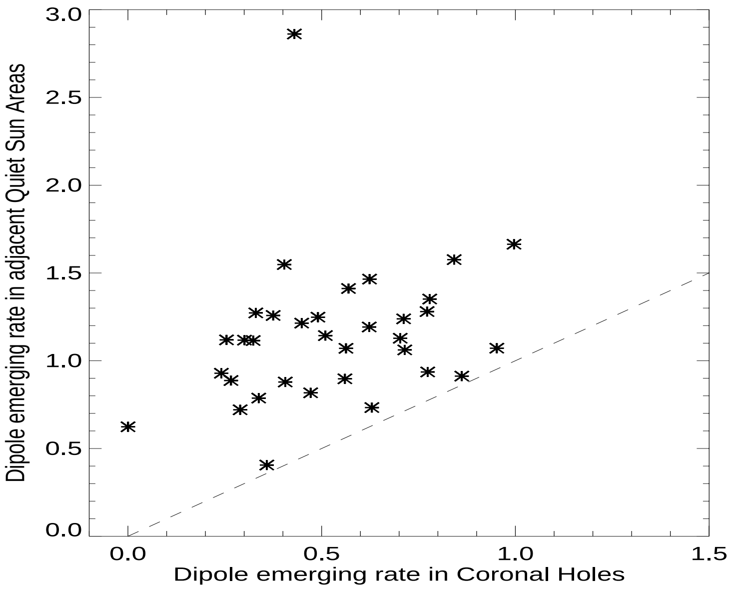

Fig. 4. – The dipole emergence rate (per 200 × 200-Mm area per day) for coronal holes (horizontal axis), m_{CH}*, versus the dipole emergence rate (per 200 × 200-Mm area per day) for adjacent quiet-Sun areas (vertical axis),* m_{QS}*. The dashed line shows the bisector where* $m_{CH} = m_{QS}$*. For all events,* $m_{QS} > m_{CH}$ *.*

reason for that is the lower time cadence of the magnetograms and a higher threshold for detection of magnetic dipoles that we used in our study as compared to Hagenaar (2001).

There could be concern, of course, that our low cadence might influence our conclusions, e.g. if the emerging flux cancels promptly and preferentially within a CH, as opposed to on the QS, it might be missed between samples, reducing the apparent rate of emergence within the CH. To evaluate this possibility, we analyzed the CH and QS area observed on September 15-16, 2003 at a higher cadence of 5 minutes, using 286 magnetograms obtained during 26 hours. The dipole emergence rates, m_{QS}, and m_{CH} are higher than those derived from our usual routine on the basis of 4 magnetograms. However, the ratio m_{QS}/m_{CH} did not change significantly: instead of 4.4 we obtained 3.6.

It is interesting to note that Zhang et al. (2006) analyzed a 7 hour long sequence of Big Bear Solar Observatory longitudinal magnetograms taken with 1 minute cadence in a quiet sun area and in a coronal hole and found that the ratio of the dipole emergence rate in the QS area and in the CH is about 1.76. Therefore, our choice of time cadence and sensitivity does not significantly affect the conclusion that the dipole emergence rate is lower in CHs.

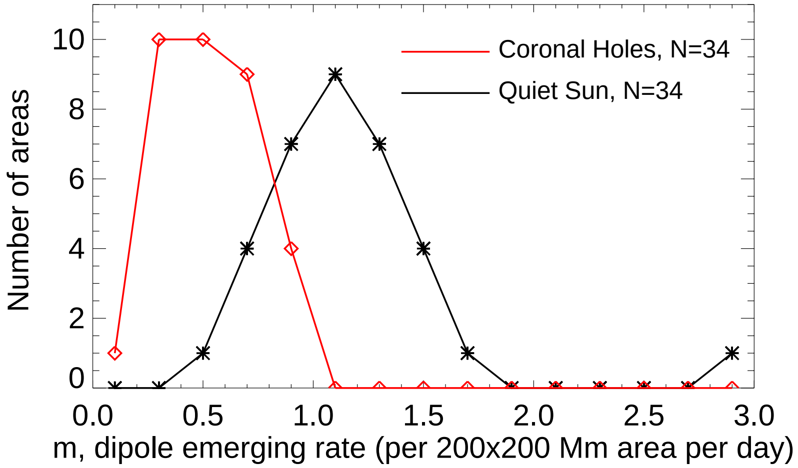

Fig. 5. – Distributions of the dipole emergence rate (per 200 × 200-Mm area per day) for coronal holes (red line), m_{CH} *, and for adjacent quiet-Sun areas (black line),* m_{QS} *.*

3. Concluding Remarks

We compared the magnetic-dipole emergence rate in coronal holes and adjacent quiet-Sun areas, by using the SOHO/MDI magnetograms and EIT 284-Å full-disk images. An analysis of 34 pairs of coronal holes and quiet-Sun areas showed that, on average, the dipole emergence rate in QS areas exceeds twice that in CHs. This implies that a coronal hole is a region with a local minimum in the rate of emerging dipoles.

This result is consistent with the prediction of Fisk (2005), who argues that open field lines are transported by both random convective motions and reconnection with coronal loops, and subsequent random displacement. In this model, the transport of open flux is coupled to the properties of the loops, which in turn are dependent on the rate of emergence of new magnetic flux. In regions where the rate of emergence of new flux is a local minimum, open flux will accumulate and form coronal holes.

The observational evidence presented in this paper supports the concept that reconnection of open field lines with coronal loops is an important transport mechanism on the Sun, and needs to be included in models for the evolution of the solar magnetic field. For example, Cohen, et al. (2006) have included the interactions of open field lines with loops in a numerical model for magnetic-field diffusion on the solar surface, and showed that the additional transport model modifies the consequences of meridional flow on the solar surface.

This work was conducted as part of the Targeted Research & Technology (TR&T) program of the NASA Living with a Star program. V. Abrmenko and V. Yurchyshyn were supported, in part, by NASA grant NNG05GN34G. L. Fisk was supported, in part, by NASA grant NNG05GM53G.

References

Altschuler, M. D., & Newkirk, G., Jr. 1969, Sol. Phys. 9, 131

Crooker, N. U., Gosling, J. T., & Kahler, S. W. 2002, J. Geophys. Res., 107, 1028, doi:10.1029/2001JA000236

Cohen, O, Fisk, L. A,, Roussev, I. I., Toth, G., & Gombosi, T. I., ApJ, 2006, submitted.

Delaboudinière, J.-P., et al. 1995, Sol. Phys. 162, 291

Fisk, L. A. 1996, J. Geophys. Res., 101, 15,547

_________, 2001, J. Geophys. Res., 106, 15,849

_________, 2005, ApJ, 626, 563

Fisk, L. A., & Schwadron, N. A. 2001, ApJ, 560, 425

Fisk, L. A., Zurbuchen, T. H., & Schwadron, N. A. 1999, ApJ, 521, 868

Hagenaar, H. J. 2001, ApJ, 555, 448

Hagenaar, H. J., Schrijver, C. J., Title, A. M., & Shine, R. A. 1999, ApJ, 511, 932

Schatten, K. H., J. M., Wilcox, J. M. & Ness, N. F. 1969, Solar Phys., 6, 442

Scherrer, P. H., Bogart, R. S., Bush, R. I., Hoeksema, J. T., Kosovichev, A. G., Schou, J., Rosenberg, W., Springer, L. Tardell, T. D., Title, A., Wolfson, C. J., Zayer, I., and the MDI engineering team, Sol. Phys., 162, 129.

Schrijver, C. J. 2001, ApJ, 547, 475

Schrijver, C. J., & DeRosa, M. L. 2003, Sol. Phys., 212, 165

Schrijver, C. J., DeRosa, M. L., & Title, A. M. 2002, ApJ, 577, 1006

Schrijver, C. J., & Title, A. M. 2001, ApJ, 551, 1099

Schrijver, C. J., Title, A. M., Hagenaar, H. J. & Shine, R. A., 1997, Sol. Phys., 175, 329

Schrijver, C. J., Title, A. M., van Ballegooijen, A. A., Hagenaar, H. J., & Shine, R. A. 1997, ApJ, 487, 424

Wang, Y.-M., Lean, J., & Sheeley, N. R. 2000a, Geophys. Res. Lett., 27, 505

Wang, Y.-M., & Sheeley, N. R. 1991, ApJ, 375, 761

Wang, Y.-M., Sheeley, N. R., & Lean, J. 2000b, Geophys. Res. Lett., 27, 621

Zhang, J., Wang, H., Ma, J., Yurchyshyn, V.B. 2006, in preparation.