WHY ARE CORONAL HOLES INDISTINGUISHABLE FROM THE QUIET SUN IN TRANSITION REGION RADIATION?

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ABSTRACT

Coronal holes have the same properties as quiet Sun regions in chromospheric emission lines, but for coronal lines the average intensity is lower in coronal holes. A key quantity for the understanding of these phenomena is the magnetic field. We use data from SOHO/MDI and reconstruct the magnetic field in coronal holes and the quiet Sun with help of a potential magnetic field model. Our results give evidence that the number of long magnetic loops is reduced by one order of magnitude in coronal holes. We compute the loop temperature with help of the RTV-scaling law ($T \propto L^{1/3}$). Due to this scaling law long loops are hotter than short loops. Thus, one way to explain both the decreased coronal emission and the unaffected transition region emission in coronal holes is by the greatly decreased number of long loops, but an almost equal number of short loops relative to the normal quiet Sun.

Key words: SOHO15, coronal heating, magnetic fields, coronal holes.

1. INTRODUCTION

Coronal holes are regions with a significantly reduced emissivity in all wavelength at coronal temperatures. Coronal holes have been identified as the source region of the open magnetic flux. This does not exclude, however, the existence of partially closed flux in coronal holes. Coronal holes are observed at different wavelengths, e.g. soft X-rays, EUV lines, radio emissions. At the limb coronal hole boundaries can also be determined from an extrapolation of the boundaries of the white light corona onto the solar surface. Emission lines in EUV are formed at temperatures from some $10^4 K$ to several $10^6 K$. The emission of rather cold chromospheric and transition region lines is not significantly reduced in coronal holes (Wilhelm et al., 2000; Stucki et al., 2000, 2002; Xia, 2003). Lines from the upper chromosphere show already a slight difference between coronal holes and quiet Sun regions. For coronal lines the average intensity is lower in coronal holes compared to the quiet Sun. Coronal holes have been also detected in the 1083 He I absorption line (Harvey et al., 1975). This absorption line can be observed from the ground and has been used by Harvey and Recely (2001) at NSO/Kitt Peak to create coronal hole maps, which are available online. Wiegelmann and Solanki (2005) used the corresponding coronal hole map of Carrington rotation 1975 (09.04.-0.6.05.2001) and 56-min average MDI-magnetograms (see Krivova and Solanki (2004) for details of the averaging procedure) to compare loop statistics in coronal holes and on the nearby quiet Sun. The result of this study is a first step towards an understanding of the phenomenon that coronal holes are not detectable in transition region radiation, but well visible in coronal lines. In the following we briefly summarize the main results of our work (Wiegelmann and Solanki, 2005) and provide additional material. (Figs. 1 and 2 provide new material and Fig. 3 highlights results from Wiegelmann and Solanki (2005).)

Table 1. Some properties of coronal holes in comparison with the quiet Sun.

	Coronal holes	Quiet Sun
Net magnetic flux	$7.6 \pm 4.8G$	$0.4 \pm 0.4G$
Unbalanced flux	$77\% \pm 14\%$	$9\% \pm 9\%$
Average Loop length	7.8 ± 3.9Mm	14.1 ± 4.1Mm
Average Loop height	0.9 ± 0.4Mm	3.0 ± 0.7Mm

2. SOME PROPERTIES OF THE SOLAR MAGNETIC FIELD IN CORONAL HOLES COMPARED WITH THE QUIET SUN.

A key quantity for the understanding of most solar phenomena is the magnetic field. The solar magnetic field couples the solar interior with the photosphere and atmosphere. It is therefore important to investigate to which extent the occurrence and properties of coronal holes are related with the solar magnetic field structure. To do so we compute the global coronal magnetic field with help of a potential field model. Fig. 1, top panel shows the coronal magnetic field for May, 04, 2001 and the bottom panel of Fig. 1 contains a corresponding EIT-image (Fe XII, $19.5nm$, formation temperature 1.5 million K). The bright structures in EIT correspond to long closed magnetic loops in the magnetic field model. The hot plasma is trapped on closed magnetic loops and its emission is visible, e.g., in the EIT image. The large scale structure of the coronal magnetic field is open in coronal holes (Altschuler et al., 1972) and the plasma is able to escape along the open field lines. These open field regions show a reduced emissivity in the EIT image. To get more insight regarding the magnetic field structure on smaller scales, we investigate the local magnetic field of a coronal hole and the nearby quiet Sun in Fig. 2. The top panel shows a coronal EIT image in Fe XII. The reduced emissivity corresponds to a coronal hole region. Fig. 2 bottom panel shows the corresponding magnetic field. We computed the magnetic field with help of a Greens function method (see Aly (1989) and Wiegelmann and Solanki (2005) for details.) and display only the closed mag-

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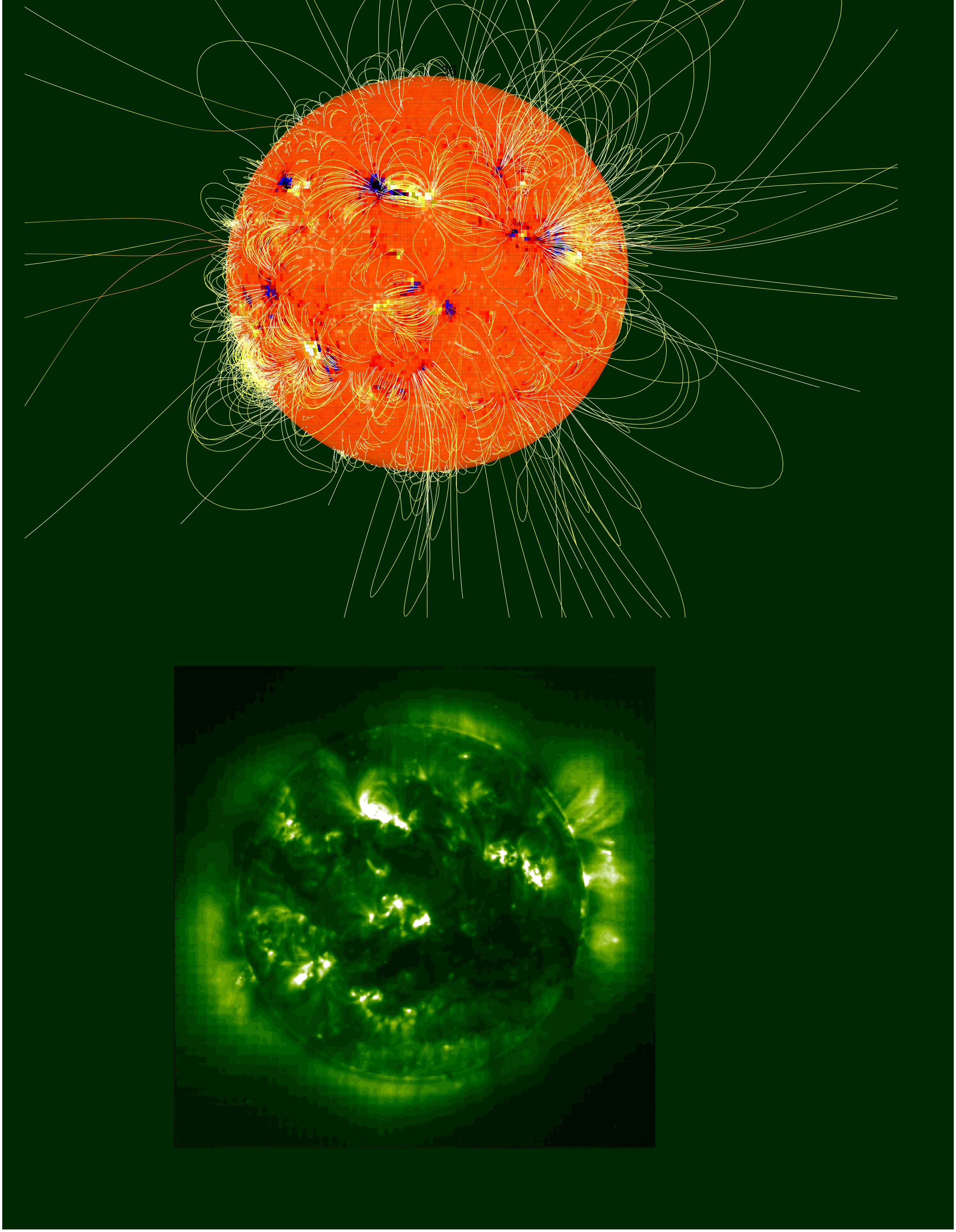

Figure 1. Top: Global potential field model. Bottom EIT Fe XII image.

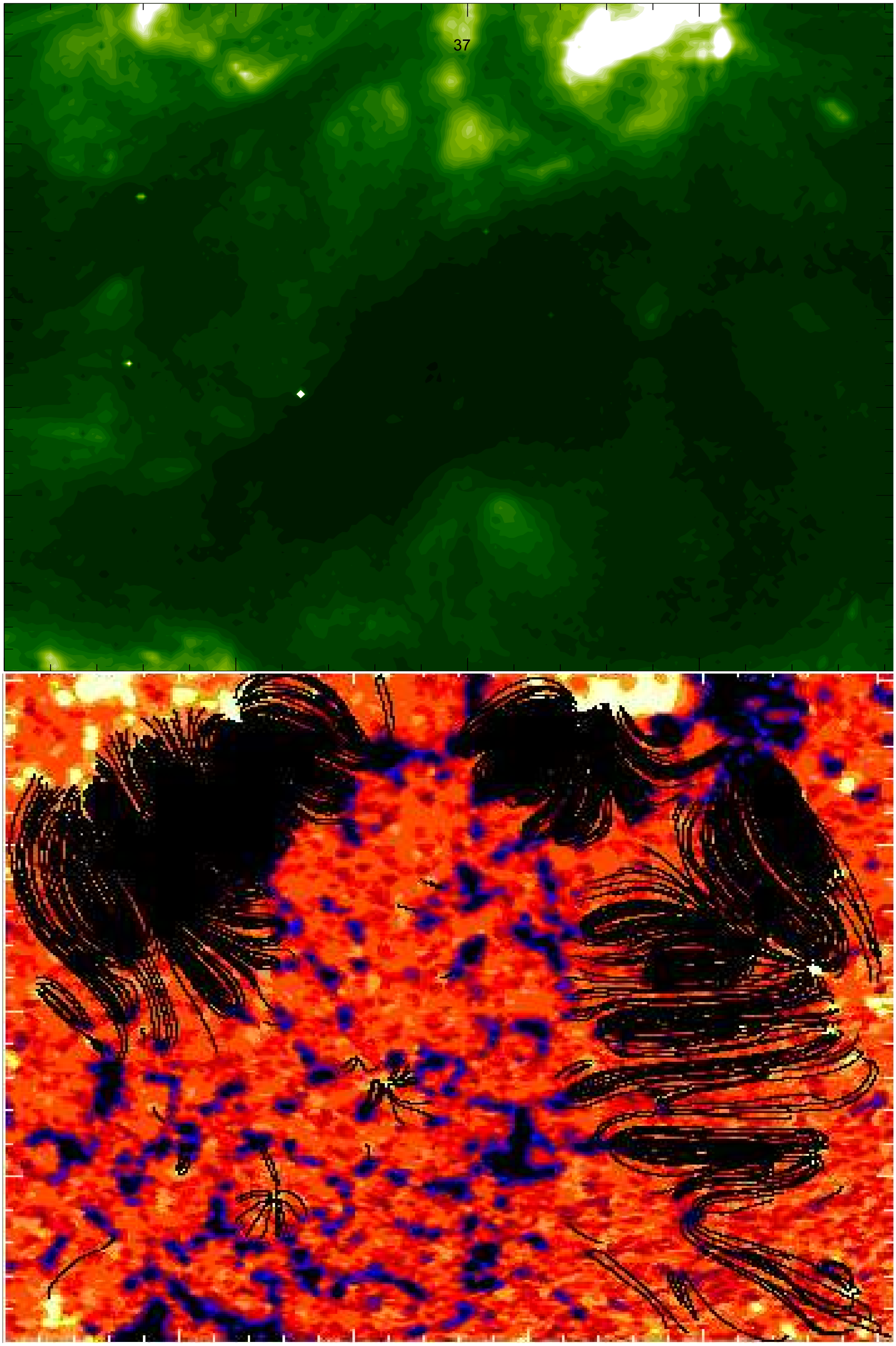

Figure 2. Top: EIT 19.5 *nm image.) Bottom: MDI magnetogram and closed magnetic field lines (*$B \geq 20G$*).*

netic field lines with $B \geq 20G$ at the footpoints. Long closed loops are absent in the coronal hole, but present in the nearby quiet Sun. Some short loops are present also within the coronal hole. The top and bottom image in Fig. 2 shows a clear correspondence between the reduced emissivity and the absence of long closed loops. (See also Wiegelmann and Solanki (2005) Fig. 3 where we present an EIT-image and the local magnetic field structure for another coronal hole (April, 24, 2001), which has been detected also during Carrington rotation 1975.)

An understanding for the absence of long closed loops in coronal holes might be connected with properties of the photospheric magnetic field. The magnetic field strength in coronal holes (on the photosphere) has been measured by several authors, e.g. Levine (1977); Bohlin and Sheeley (1978); Harvey et al. (1982); Belenko (2001) and according to these papers the magnetic flux in coronal holes clearly shows a dominant polarity. This is consistent with coronal holes being the source region of the fast solar wind flowing on open magnetic field lines. The magnetic field is, however, not unipolar in coronal holes and consequently coronal holes should contain also locally closed coronal loops besides the open flux (Levine, 1977). The amount of opposite magnetic flux in coronal holes varies. In a statistically study (11 coronal holes during Carrington rotation 1975) Wiegelmann and Solanki (2005) found an unbalanced flux of $77\% \pm 14\%$ (see table 1 and table 1 in (Wiegelmann and Solanki, 2005) for properties of the individual coronal holes and the nearby quiet Sun regions.).

3. LENGTH DISTRIBUTION OF CLOSED MAGNETIC LOOPS IN CORONAL HOLES AND THE QUIET SUN.

Here we briefly summarize some results of a statistically study presented in Wiegelmann and Solanki (2005). We used coronal hole maps prepared by Harvey and Recely (2001) for our study. Table 1 shows the net magnetic flux, the unbalanced flux and the averaged loop length and height in coronal holes and the nearby quiet Sun. The averages and standard deviations have been computed from 11 coronal hole and 7 quiet Sun region during Carrington rotation 1975 (See Wiegelmann and Solanki (2005) for details.). Coronal holes contain a small amount of opposite flux. Consequently, small closed loops form and connect this opposite magnetic flux with the dominating flux of the coronal hole. Long and high reaching loops cannot form in coronal holes, because the magnetic field becomes unipolar and open above a certain height. In the normal quiet Sun the magnetic flux is almost balanced and consequently the average loop heights and length are larger than in coronal holes. Fig. 3, top panel shows the length distribution of loops (normalized to the area of the region on the photosphere) for coronal holes (black, CH) and the quiet Sun (red, QS). Coronal holes contain about 60% the number of small loops (≤ 2Mm), but only $5-10\%$ the number of long loops (≥ 30Mm) per area compared with the quiet Sun.

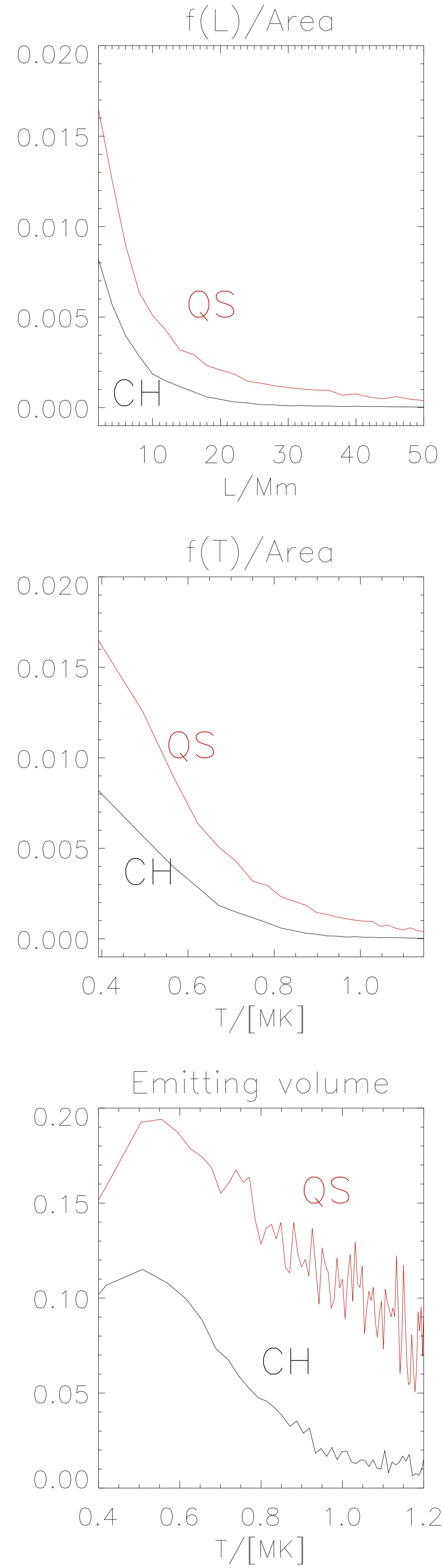

Figure 3. Top: Distribution of loop length. Center: Distribution of loop temperatures. Bottom: Emitting volume. The red lines correspond to quiet Sun regions and the black lines to coronal holes.

4. ESTIMATION OF LOOP TEMPERATURES.

To draw quantitative conclusions about the temperatures in loops is not straight forward. We use a hydrostatic model by Rosner, Tucker and Vaiana (1978) (RTV-model) to estimate the temperatures. The RTV-model assumes no plasma flow, zero gravity, uniform heating and a constant loop cross section and provides the scaling law

$$T_{max} = 1400 \cdot (pL)^{1/3}, \quad (1)$$

where T_{max} is the maximum temperature, L the loop length in cm and p the pressure in $dyn\ cm^{-2}$. We use this scaling law to approximate the temperatures of the loops calculated here. We assume that the temperature along the loops equals $T_{\max}$ and use a constant pressure of $p = 0.11\ dyn\ cm^{-2}$ found by Maxson and Vaiana (1977). For simplicity we have neglected any dependence of p on T or L.

Fig. 3, center panel shows the temperature distribution in coronal holes (black) and the quiet Sun (red) computed with help of the RTV-scaling law from the length distribution (upper panel of Fig. 3). We find that the number of cool loops in coronal holes is about 60% compared with the quiet Sun, but hot coronal loops are almost absent in coronal holes. One has to consider, however, that long loops have a higher volume than short loops and for an estimation of the emissivity knowledge regarding the number of loops is not sufficient. The emitting volume at a given temperature is more relevant than the number of loops for the emissivity. We show this quantity in Fig. 3, bottom panel. The fraction of emitting volume in coronal holes compared with quiet Sun is about 70% for cool (transition region) temperatures, but drops to 10% at coronal temperatures.

Let us remark, that the the RTV-scaling law and the assumption of a constant pressure can give only a rough approximation of the loop temperature. Possible improvements of the model can be achieved by including non uniform heating and gravity (Serio et al., 1981), scaling laws derived from numerical computations (Aschwanden et al., 2000), taking into account the inherent dynamics of loops (Winebarger et al., 2002) and details of the coronal heating mechanism (Schrijver et al., 2004). Such extensions are outside the scope of this work.

5. CONCLUSIONS

We undertook a step towards a better understanding why coronal holes occur in the solar corona, but are almost indistinguishable from the normal quiet Sun in transition region radiation. A key quantity for the understanding of this phenomenon seems to be the magnetic field. Coronal holes have a large net magnetic flux on the photosphere (about 80% of the magnetic flux in coronal holes is not balanced.). The small amount of opposite flux in coronal holes closes with the dominating flux at low heights. These loops are short, low lying, cool and do not reach into the solar corona. Their number is only slightly reduced compared with normal quiet Sun regions. Consequently the (rather cool transition region) plasma trapped on these small loops radiates with nearly the same emissivity as in the quiet Sun. Longer closed loops do practically not exist in coronal holes, because the small amount of opposite flux has been compensated already at lower heights. As a consequence high reaching field lines in coronal holes are open. The absence of long, high reaching and hot closed loops in coronal holes might give an explanation for the strongly reduced emissivity in coronal lines.

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