THE STRUCTURE AND EVOLUTION OF SOLAR CORONAL HOLES OBSERVED BY SOHO DURING AUGUST AND SEPTEMBER 1996

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ABSTRACT

A series of observations of coronal holes and their boundary regions was made with the Coronal Diagnostic Spectrometer on SOHO throughout the month of August 1996. Early in the month a large northern polar hole was a prominent feature, appearing even larger because of the tilt of the solar axis relative to the Earth at that time. Around the 21st August, the character of the northern coronal hole boundary changed dramatically as a large equatorward extension rotated around the East limb. This extension connected across the equator to the magnetic region of like polarity associated with a complex active region. Observations of this large coronal hole on the disc, as it crossed the meridian towards the end of August, have yielded spectra taken along a near-radial line-of-sight. From these spectra (using both NI and GI spectrometers), density and temperature information has been obtained for both cell centre and network regions within the hole and from the adjacent quiet-sun regions. These values are compared with similar results from the northern polar hole, again taken at the meridian. Observations made at the limb provide information about the change in temperature with height which, combined with intensity profiles in different lines taken across the equatorial hole, indicate how the hole expands with height. Magnetogram data taken with the MDI instrument clearly show the magnetic structure associated with the trans-equatorial hole, which exhibits differential rotation, and EIT images show the overall morphology and evolution of the hole. Changes in the trans-equatorial hole over one solar rotation are discussed, comparing the August observations with data taken a month later in September.

Key words: Sun; coronal holes; density.

1. INTRODUCTION

During August 1996 the Coronal Diagnostic Spectrometer (CDS) was used to carry out a series of observations of coronal holes, focusing on the boundary regions. These were supported with observations by EIT and MDI instruments on SOHO. In the first part of August the northern polar coronal hole was large and symmetric with a near-circular boundary while the rest of the Sun appeared quiet. The north pole was tilted towards the Earth at this time, making the hole appear even larger. Towards the end of August the situation changed dramatically as an equatorward extension of the hole appeared around the East limb. As it rotated into view it became clear that this extension had opened right down to southern latitudes (Figure 1), connecting to a region of strong magnetic field associated with an active region just south of the equator. This field had the same polarity as the north polar hole.

![Figure 1. The “Elephant’s Trunk” trans-equatorial coronal hole on the 26th August 1996 – EIT 195Å image.](image-url)

2. OBSERVATIONS

We present here results from an observation of the northern polar coronal hole taken on the 17th Au-
tions with a largely radial line of sight, whereas the polar observations include data taken both on the disc and above the limb, where observations of the corona can be obtained without including emission from the transition region and chromosphere. However, these data still result from integrating along a line of sight and will, above the limb, include contributions from regions higher in the corona but beyond the limb.

MDI observations taken at about the same time show the line-of-sight component of the magnetic field at the photosphere. EIT observations in the Fe XII (195 Å) line made in August and September reveal the short and long-term evolution of the equatorial coronal hole.

2.1. Magnetic structure

Figure 4 is an overlay of an MDI magnetogram on EIT 195Å data, from the 25th August. The two magnetic polarities are represented by blue and red colours. It is evident that the coronal hole lies over a predominantly unipolar (blue) magnetic region which connects to the same polarity region of the large active region at the bottom left. A neutral line appears to run along the prominence channel which lies parallel to the coronal hole to the east. The unipolar nature of the hole becomes less clear at high latitude, where the field (in the line of sight) also appears weaker.

2.2. Variation of coronal hole boundary with height

The monochromatic images of the trans-equatorial coronal hole shown in Figure 5, produced from CDS NI spectra of 26 August 1996, show the difference...
in nature of the coronal hole at different temperatures/heights in the solar atmosphere. The four lines represented here are:

\[
\begin{align*}
\text{He I } 584.3 \, \text{Å} \, (\log T = 4.5) \\
\text{Mg IX } 368.1 \, \text{Å} \, (\log T = 6.0) \\
\text{Mg X } 624.9 \, \text{Å} \, (\log T = 6.1) \\
\text{Si XII } 520.7 \, \text{Å} \, (\log T = 6.3)
\end{align*}
\]

Figure 5. Monochromatic images of the coronal hole on the 26th August with temperature/height increasing from left to right from the chromosphere through the corona.

Note the expansion of the coronal hole with height. This is also apparent in the intensity profiles shown in Figure 6, which were produced by integrating vertically across the rectangular regions marked in the images in Figure 5.

In Figures 7, 8 and 9 the profiles have been formed from the solar hole data of Figure 3 by integrating along the solar X-direction within the dashed rectangles shown. A similar expansion can be seen, although note that the images are formed by combining two scans so there is a temporal discontinuity near solar Y = 800 arcsecs. To the right, at the limb, the chromospheric emission is seen to drop off rapidly while the coronal emission increases because it includes emission from beyond the limb. This is particularly so in the Mg IX and Mg X lines because the plume which extends high above the coronal hole emits most strongly at these wavelengths. It is therefore difficult to determine the height of peak emission here but the increase in height from the chromosphere to the peak of the Si XII emission appears to be of the order of 5000 km (less than 10 arcsec in solar Y). In the equatorial hole, the expansion appears to be as much as 20 arcsecs in solar X over this height, indicating that the angle between the field and the solar radius is more than 60 deg at the boundary between the open and closed field lines. This is consistent with the angle observed between open and closed field at the boundary of the polar holes, as seen at the limb in EIT images such as Figure 1.

2.3. Densities and Temperatures

Below the intensity profiles we show the corresponding density profile, obtained from the Si IX (349.9Å/341.9Å) line ratio. Beneath the densities are the profiles of the Mg X/IX (624.9Å/368.1Å) line ratio, an indication of the temperature change across the hole.

The spectroscopic diagnostics were derived from the CHIANTI atomic database, developed by Dere, Landi, Mason, Monsignori Fossi and Young (Dere et al, 1997). In particular, the data used to obtain the density dependence of the Si IX ratio was taken from Bhatia and Doschek (1993).

The densities in the quiet sun regions clearly lie between about 4 and 6 x 10^8 cm^-3 and are decreasing at the boundary of the hole. The values measured within the hole on the disc exhibit a much larger variability – an indication of the uncertainty caused by the very low signal within the hole. However, above the limb, there is more signal, enabling a more precise determination of the density ratio here. To obtain better signal-to-noise on the disc, spectra were formed by spatially averaging data over a larger area. O V images were used to distinguish network from cell-centre regions. Mg IX was used to select pixels within the coronal hole. By combin-
Table 1. Table of densities ($\rho$ $10^8$ cm$^{-3}$), derived from Si IX ratio for the equatorial coronal hole on the 25th and 26th August 1996, and the northern polar hole on the 17th August.

<table>
<thead>
<tr>
<th>Region</th>
<th>25 Aug</th>
<th>26 Aug</th>
<th>polar hole 17 Aug</th>
</tr>
</thead>
<tbody>
<tr>
<td>cor hole cell-centre</td>
<td>4.0</td>
<td>3.3</td>
<td>-</td>
</tr>
<tr>
<td>cor hole network</td>
<td>2.8</td>
<td>2.5</td>
<td>-</td>
</tr>
<tr>
<td>cor hole average</td>
<td>4.0</td>
<td>3.3</td>
<td>3.7</td>
</tr>
<tr>
<td>qu sun cell-centre</td>
<td>5.6</td>
<td>6.2</td>
<td>5.3</td>
</tr>
<tr>
<td>qu sun network</td>
<td>6.2</td>
<td>6.2</td>
<td>6.2</td>
</tr>
<tr>
<td>bright point</td>
<td>$\geq$ 10.0</td>
<td>$\geq$ 10.0</td>
<td>$\geq$ 10.0</td>
</tr>
<tr>
<td>plume footpoint</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

These data appear to suggest that the density above a cell centre in the coronal hole is slightly greater than that above the network. However, longer integration is required to be able to determine densities in the very 'darkest' parts of a hole with more certainty.

It is perhaps not an unexpected result though. The expansion of the coronal hole is obviously still continuing above the height of formation of these silicon lines, so it is unlikely that the field has spread out uniformly by this height. Over the cell centres it will be slightly convergent whereas over the network it should be slightly divergent. This could explain a difference in density between these two regions.

Data obtained from long slit (4'x2') GI observations of the hole on the 24th September indicate densities down to about $3 \times 10^8$ cm$^{-3}$ within the hole, rising to about $10^9$ cm$^{-3}$ in bright regions near the boundary. These data are more uncertain because of the spatial integration along this slit with the GI instrument. They were obtained using the Fe XIII (203.5Å/292.0Å) line ratio.

Assuming an isothermal plasma, the Mg X/IX ratio indicates a minimum temperature in the hole below $8 \times 10^5$ K (the minimum of the temperature sensitive range of this ratio). The temperature is then seen to rise steadily above the limb. However, this ratio can only give an indication of the temperature because the two lines are not from the same ion. If the plasma is not isothermal, the emission will be from slightly different plasma volumes and the apparent temperature will be in error.
Figure 9 shows profiles across a plume. The density clearly peaks at the footpoint, with a value in excess of $10^9$ cm$^{-3}$, the limit of sensitivity of the Si IX density ratio. The temperature appears to peak slightly later, probably an effect of seeing different plasma in the two lines, accentuated because of the high temperature gradient here. Again, above the limb, the density appears to fall and the temperature to rise steadily.

2.4. Rotation

In Figure 2 small changes in the boundaries of the equatorial hole are apparent on a timescale of days, while the overall structure persists. Similar small scale changes may be seen in the two EIT 195Å images shown in Figure 10, taken on the 25th and 27th of August. These have both been 'de-rotated' to the same time, using photospheric rotation rates. No appreciable change in overall shape of the hole is apparent, suggesting that in this case the hole has rotated differentially over the two days.

The low-latitude hole persisted for several rotations. The part to the south of the equator rotated with the active region, which was also persistent. However, in the northern hemisphere, differential rotation appears to have caused the severing of the low-latitude hole from the northern polar hole (see Figure 12). The associated prominence channel can be seen in the September images to be bending round to the East at higher latitudes where the hole has closed. The remainder of the hole appears to have continued to rotate in a quasi-rigid way at the same rate as the active region (with a period of about 27 days) and the prominence channel, suggesting that all three are linked by a common magnetic structure with a rotation rate tied to that of the active region.

The detailed structure of the hole can still be seen to change over a matter of hours, as shown in Figure 11 and also in Figure 12, which shows differences between the images taken on successive days during the September passage.
Densities within the hole are about half those in the quiet sun and less than 25% of those found over bright regions of the network. It is possible that densities in the equatorial hole may be larger over cell centres than over network regions.

Densities in the polar hole are found to be similar to those in the equatorial hole. The density falls off above the limb while the temperature appears to rise steadily.

In the foot-point of a plume the density is high, comparable to that seen in bright points, and is above the sensitivity limit of the Si IX ratio. The density falls off rapidly above the footpoint, but still appears slightly elevated relative to the hole region. The temperature is also seen to peak sharply within the footpoint and appears to fall off with height along the plume.

ACKNOWLEDGMENTS

The authors would like to thank the CDS team for their support in obtaining the observations.

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3. CONCLUSIONS

The magnetic field associated with the equatorial coronal hole is strongly connected to that of the active region at its base, resulting in the two features rotating at almost the same rate. However, differential rotation appears to have had some influence in the short term, distorting the shape of the coronal hole over time and causing the northern parts to separate from the lower latitude regions within one solar rotation.