A High-Temperature Component in Coronal Holes as Confirmed by a Partial-Eclipse Observation

Hirohisa Hara
National Astronomical Observatory, 2-21-1 Osawa, Mitaka, Tokyo 181
E-mail: hara@solar.mtk.nao.ac.jp

(Received 1997 March 24; accepted 1997 April 25)

Abstract

We confirmed X-ray signals in coronal holes based upon a Yohkoh soft X-ray observation of a partial eclipse on 1993 November 13. The observed X-ray signals cannot be explained by those coming from one-million-degree plasmas alone, which were observed with the Skylab UV and EUV instruments. This suggests that higher-temperature plasmas are necessary to explain the present observation.

Key words: Sun: corona — Sun: coronal hole — Sun: X-rays

1. Introduction

Hara et al. (1994, hereafter Paper I) estimated coronal-hole temperatures to be $2 \times 10^6 \text{ K}$ from Yohkoh soft X-ray images. A broad-band filter-ratio technique was used to evaluate the temperature for coronal holes located at the disk center. A correction for scattered X-rays from bright regions to coronal holes was made. The resulting temperatures are higher by $0.5-1 \times 10^6 \text{ K}$ than those estimated from UV and EUV observations with the OSO (Orbiting Solar Observatory) and Skylab instruments (Munro, Withbroe 1972; Doschek, Feldman 1977; Mariska 1978; Raymond, Doyle 1981; Ichimoto et al. 1996). The emission measure for the $2 \times 10^6 \text{ K}$ plasma is comparable to the reported emission measure for $1 \times 10^6 \text{ K}$. In order to confirm the result presented in Paper I, we give the result of an eclipse observation on 1993 November 13 with the Yohkoh Soft X-ray Telescope (SXT). The eclipse observation provides a direct measurement of the X-ray intensity in coronal holes. We carefully analyzed the eclipse data and confirmed a signal from the coronal hole, as discussed in the following sections.

2. Observation

Until 1992 November the signals detected with the SXT CCD camera consisted of X-rays from the Sun to be measured, scattered X-rays, and dark current to be removed. The pre-filter of SXT completely shuts out any visible light. However, since a small part of the pre-filter was broken in 1992 November, an additional signal due to visible light has been detected. Because a thin metallic filter is located in front of the CCD camera during X-ray observations, the visible light coming through the broken pre-filter region cannot directly reach the CCD. Therefore, the additional signal is visible stray light. In Paper I it was not necessary for us to consider the stray-light problem because the data were obtained before the failure of the SXT pre-filter. Although the amount of scattered X-rays from bright regions to coronal holes in 1993 November was less than that in 1992, the situation for observing coronal holes was not improved because of this stray-light problem. Thus, a measurement of the X-ray intensity in coronal holes is more difficult under a normal, i.e., outside eclipse, condition. In the present study we used occultation by the moon to evaluate the X-ray signals from a coronal hole.

We observed a partial eclipse on 1993 November 13 from space with the Yohkoh SXT. The speed of the moon moving in the SXT field of view was fairly fast, about $3.58 \text{ s}^{-1}$, based upon orbital calculations by M. Soma of National Astronomical Observatory. We used an exposure of 21 s for this observation, considering both the coronal-hole intensities estimated from the method presented in Paper I and the speed of the moon across the solar disk. Since the moon moved during the exposure, a clear edge due to occultation was not expected. An X-ray filter made of Al, Mg, and Mn (hereafter AlMg) was used to take X-ray images.

Figure 1b (Plate 13) shows the partial eclipse on 1993 November 13. The spatial resolution of this image is about $10''$. A coronal hole is located on the disk, as indicated in figure 1a (Plate 13). According to Solar-Geophysical Data, this coronal hole is located above a magnetic cell with negative polarity. As can be seen in figure 1b (Plate 13), a part of the coronal hole located in the southeast quadrant is occulted by the moon. As reported in Paper I, the intensities over the coronal holes seem to be almost constant, except for the locations of X-ray bright points. This fact also applies to the
Table 1. Data* used in the present study and position of the Sun center in image coordinates.†

<table>
<thead>
<tr>
<th>Observing time (UT)</th>
<th>Exposure (s)</th>
<th>Sun center (2″5 unit)</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>DATA 1…………</td>
<td>1993 November 13 19:33:30</td>
<td>21.4</td>
<td>484.06</td>
</tr>
<tr>
<td>DATA 2…………</td>
<td>1993 November 13 20:56:44</td>
<td>21.4</td>
<td>616.12</td>
</tr>
<tr>
<td>DATA 3…………</td>
<td>1993 November 13 21:44–23:11</td>
<td>0.67×32</td>
<td>485.00</td>
</tr>
<tr>
<td>T.I.†</td>
<td>DATA 4 ………..</td>
<td>1993 December 18 12:26:30</td>
<td>5.37</td>
</tr>
<tr>
<td>DATA 5…………</td>
<td>1994 December 15 07:05:25</td>
<td>5.37</td>
<td>626.64</td>
</tr>
</tbody>
</table>

* All images are taken with the AlMg filter.
† Origin is defined at the lower-left corner of images.
† Terminator images (see text).

coronal hole in figure 1a (Plate 13). Figure 1c (Plate 13) shows that the moon occulted the brightest part of an active region at the east limb.

3. Analysis

We used the data tabulated in table 1. The size of the CCD is 1024 × 1024 pixels in 2″5 pixel size. An on-chip summation of 16 (4 × 4) pixels was used in the present observation for DATA 1 and DATA 2 given in table 1. As shown in this table, the position of the Sun in the field of view changed with time. This was due to an intentional offset pointing of the Yohkoh satellite. The offset pointing changes the stray-light condition. In order to check this effect, we used images taken during a transition from day to night of the satellite. X-rays were almost perfectly absorbed by the atmosphere of the Earth during the transition; as a result, only stray light and dark current were detected. We call such images terminator images. Two terminator images (DATA 4 and DATA 5) are listed in table 1. They were used as calibration data to confirm the level of stray light for DATA 1 and DATA 2, respectively. An on-chip summation of 4 (2 × 2) pixels was used for these images. These were chosen because the position of the Sun in the field of view was close to that of DATA 1 and DATA 2. DATA 3 was made from 32 images taken with a short exposure of 0.67 s. This image was used to confirm that the signal levels of the coronal hole and its surroundings did not change before or after the eclipse observation.

In order to estimate the soft X-ray intensity from the coronal hole in figure 1 (Plate 13), we analyzed the five images given in table 1 as follows:

1. Subtract dark signals from the raw images.
2. Align the dark-subtracted images to DATA 2 by a cross-correlation analysis of their signals.
3. Rotate the aligned images by 53° clockwise in order to set the analysis regions in the horizontal direction (figure 2 (Plate 13)).
4. Take an average of the signals in the analysis regions between the two horizontal lines in figure 2 (Plate 13) in order to derive one-dimensional signal profiles in the horizontal direction (asterisk, filled circle, and plus sign in figure 3).

To create DATA 3 before going to the second process, 32 dark-corrected images were integrated and aligned. For aligning the terminator images (DATA 4 and DATA 5), coordinates of the Sun center estimated from data of the Yohkoh attitude control system were used.

Figure 3 shows five signal profiles along the analysis region. DATA 1, DATA 2, DATA 3, DATA 4, and DATA 5 correspond to asterisk, filled circle, plus sign, dotted line, and thick solid line, respectively. The dark levels were subtracted in these profiles through the first process described above. The unit DN (Data Number) corresponds to about 100 electrons, which is equivalent to 365 eV in X-ray photon energy. For an isothermal plasma with a temperature of two million degrees, a single X-ray photon through the AlMg filter produces a signal of about 2 DN. Although the edge of the moon is located between X = 100 and 110, no clear edge can be seen in the signal profile of the eclipse data (DATA 2; filled circle). One reason for this is that the moon moved during the exposure, and the other is that the horizontal direction of the analysis region is not perpendicular to the edge of the moon.

4. Result

The following results were obtained from figure 3 during the course of the analysis:
1. The signal level of the pre-eclipse data (DATA 1; asterisks) in the coronal hole was almost equal to that of the post-eclipse data (DATA 3; plus signs). This shows that the signal level in the coronal-hole region did not change much with time between two observations.

2. The signal level of DATA 4 (stray-light data for DATA 1) was almost equal to that of DATA 5 (stray-light data for DATA 2) near the edge of the moon ($X = 100-110$). The statistical noise of these stray-light data was higher than that at the occulted part of the eclipse data (DATA 2) by a factor of four. This is because shorter exposures and the $2 \times 2$ on-chip summation were used for these stray-light data.

3. The fraction of visible continuum flux occulted by the moon was estimated to be 19% of its total flux by using continuum images taken with the SXT in 1992. Therefore, an 81% level of stray light in DATA 5 should be equivalent to the level of stray light in the occulted part of DATA 2. Since the signal level of DATA 2 was close to that of DATA 5 in the occulted part, the contribution of scattered X-rays to the observed signal in this portion was much smaller than that of stray light.

4. The signal profile of the eclipse data (DATA 2) in the occulted part seems to have a similar shape to that of the corresponding stray-light data (DATA 5), and the profile of DATA 5 shows no large change over the coronal-hole region. This implies that both the scattered X-rays and stray light did not change much in a short-scale length ($\Delta X \sim 10$). Therefore, the level of scattered X-rays plus stray light in the non-occulted part near the edge of the moon ($X = 110$) can be well estimated by a linear extrapolation of the signal level at the occulted part (solid line in figure 3) or by a quadratic extrapolation (dashed line in figure 3) based upon the reasonable

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Table 2. Soft X-ray intensities in coronal holes located near the disk center.

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<tbody>
<tr>
<td>(the present observation)</td>
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</tr>
<tr>
<td>X-ray intensity</td>
<td>0.29–0.36*</td>
<td>0.33–0.41*</td>
<td>0.32–0.35*</td>
<td>0.19 ± 0.01† ± 0.03‡</td>
</tr>
</tbody>
</table>

* Soft X-ray intensities in coronal holes estimated in Paper I. Unit is DN s⁻¹/2'5-pixel.
† Systematic error.
‡ Statistical error.

Fig. 4. Relation between the temperature and emission measure of the coronal hole as constrained by the X-ray intensity estimated through the Al Mg filter in the present observation (hatched mask). The filled circles are results of Paper I in the case of $\alpha = 1.0$ (see in Paper I). The emission-measure distributions of quiet regions (QR) and coronal holes (CH) derived from the Skylab observation (Raymond, Doyle 1981) are also shown for comparison.

assumption that the signal profile of the stray-light level in the non-occulted part of DATA 2 is determined by the corresponding profile of DATA 5, which is well approximated by the fit.

5. We estimated the X-ray intensity of the coronal hole from the difference between the observed signal in the non-occulted part of the eclipse data (DATA 2) and the signal level extrapolated from the occulted part to the non-occulted part by a linear or quadratic function of $X$. The observed X-ray intensity of the coronal hole through the AlMg X-ray filter was $0.18 (0.20) ±0.03$ DN s⁻¹/2'5-pixel in the case of the linear (quadratic) extrapolation.

Table 2 lists the X-ray intensities of the coronal holes located near the disk center. We compared the intensities estimated through the correction method for scattered X-rays in the previous work (Paper I) with that derived from the present observation. Since the correction method included a parameter [$\alpha$; see equation (3) in Paper I] whose determination was not free from uncertainty, the corrected X-ray intensities listed in table 2 inevitably have a certain level of uncertainty. If the parameter could be well specified, the measured X-ray intensities would have much smaller uncertainty. The X-ray intensities (after subtracting the scattered X-rays from active regions and quiet regions) in Paper I are about twice as great as those estimated in the present observation. There is a possibility that the X-ray intensity in coronal holes may decrease in the declining phase of the 11-year solar activity cycle.

The present observation puts a constraint on the relation between the coronal hole temperature and emission measure. This restriction is independent of the
results given in Paper I. For an isothermal plasma, the X-ray intensity observed with the SXT is described by the product of a function of temperature $f(T)$ and emission measure $EM$ (Hara et al. 1992). Once the X-ray intensity is determined, it gives a trajectory in temperature–emission measure space under an isothermal approximation. The hatched mask in figure 4 shows such a trajectory for the present eclipse observation. The emission-measure distributions for quiet regions (QR) and coronal holes (CH) derived from the Skylab EUV observation at the disk center (Raymond, Doyle 1981) are also shown for comparison. If the X-rays in the present study originate from one-million-degree plasmas or less than one-million-degree plasmas, the emission measure becomes greater than $10^{27}$ cm$^{-5}$. Such a large emission measure has never been reported in the Skylab observations. The X-ray intensity of 0.2 DN s$^{-1}$/2″5-pixel detected in the coronal hole observed with the Yohkoh SXT is therefore direct evidence for the existence of higher-temperature plasmas in coronal holes.

5. Conclusion

The present study supplements the previous work (Paper I) on the determination of coronal-hole temperatures by accurately estimating the X-ray intensity of the coronal hole observed during the partial solar eclipse on 1993 November 13. Because of the single-filter observation, we cannot uniquely specify the coronal-hole temperature from the present eclipse observation alone. However, the observed X-ray signals cannot be explained by only one-million-degree plasmas, which were observed with the Skylab UV and EUV instruments. This suggests that higher-temperature plasmas are necessary to explain the present observation.

We would like to thank M. Soma for calculating the trajectories of the moon, which are seen from the Yohkoh satellite relative to the Sun. We are also grateful to H. Hudson, T. Kosugi, J. Lemen, S. Masuda, and T. Shimizu for their help in the special observation.

References

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