STUDY OF THE JUNE 30, 1973 TRANS-POLAR CORONAL HOLE

SERGE KOUTCHMY*
AFGL, Sacramento Peak Observatory, Sunspot, NM 88349, U.S.A.

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Abstract. Radially and tangentially polarized pictures of the solar corona obtained near 4500 Å during the 30 June, 1973 solar total eclipse have been used to derive a model of a trans-polar coronal hole. The hole is identified by using OSO-7 EUV spectroheliograms. The line of sight coincides with the privileged plan of the hole over the N-polar region. A new method of absolute calibration is used. The Saito (1970) method is applied to determine the electron densities. Extrapolated values of densities down to the surface are lower than have ever been observed although derived hydrostatic temperatures are certainly not: \( N_e = 1.8 \times 10^7 \) cm\(^{-3}\) and \( T = 2 \times 10^6 \) K. The morphological peculiarities of polar regions are considered.

1. Introduction

The north polar region of the solar corona observed near the total solar eclipse of June 30, 1973 has been recognized as a typical region named a coronal hole. This is clearly shown on the Wagner (1976) maps using Fe xvi spectroheliograms or in the Nolte \textit{et al.} (1976) atlas of coronal holes as observed in soft X-rays. In addition, this hole was observed during many rotations and a 3-dimensional view of the N-polar region can be easily understood. By accepting the conclusions of Wagner (1975) about the rigid rotation of coronal holes, we show in Figure 1 the N-polar region as seen by the GSFC experiment aboard OSO-7 (Fe xvi spectroheliograms) for the eclipse day 'on the disc' and behind. We recognize after inspecting this figure the good coincidence of eclipse day observations and meridian passage (see also the Nolte \textit{et al.} atlas) of this \textit{trans-polar hole}. This means that above the N-pole, the line of sight is almost unaffected by non-hole structures. Therefore, white-light observations furnish a valuable determination of electron densities above this rather typical coronal hole.

2. Method and Observations

A quick look at the order of magnitude values of the most important parameters (geometric and photometric) showed convincingly that the determination of the \( pB \) values (a product of the total intensities and the corresponding polarization rates) is the most reliable method of deducing of \( N_e(r) \), where \( N_e \) is the electron density at the distance \( r \) (in solar radii) from the Sun-center. Indeed the total observed intensity on an eclipse picture is composed of the integrated light along the line of sight coming from the \( K \) corona: \( I^K \), the \( F \)-corona: \( I^F \) and of the scattered light: \( I^S \) (sky background and

* On leave from Institut d’Astrophysique, CNRS, Paris as NRC Research Associate.
Fig. 1. Sketch showing Fe xii 284.5 Å spectroheliograms obtained aboard OSO-7 by the NASA GSFC spectrophotograph operated by W. M. Neupert, R. D. Chapman and R. J. Thomas.
coronal aureola produced by the instrument). Only $I^K$ is polarized since the contribution of the slightly polarized sky background (observations were performed at a solar elevation of 70°) is negligible in the inner corona ($r < 2$).

It is easy to see that

$$pB = p(I^K + I^F + I^S) = I^K - I^K = p^K I^K,$$

where $p^K$ is the polarization rate of only the $K$ corona and $I^K$ and $I^K$ are the tangentially and radially polarized components of $I^K$. In this notation:

$$I^K = I^K + I^K.$$

Since the $K$-corona is produced by Thomson scattering of solar radiation on the free electrons of the solar corona, quantities such as $p^K$, $I^K$ and $I^K$ are model sensitive only to the electron density distribution. The use of the $pB$ method for determining $N_e$ is especially useful when the contribution of the background scattered light is important, as for the $K$-coronometer observations. For the case of eclipse observations, the background is due essentially to the $F$-corona (in the inner corona).

Above the N-polar region this contribution is especially important since the $K$-corona is at a low level: at $r = 1.3$, for example, $I^F \approx 1.5 I^K$. Any method which does not use the $pB$ method will be very sensitive to the adopted model of $F$-corona.

For $pB$ determinations we used 2 pictures obtained during the total eclipse in Republic of Tchad by the Institut d’Astrophysique, CNRS, team. A description of the experiment has already been published (Koutchmy, 1973) and we give here only the most important parameters: photographic techniques were used near 4500 Å; the focal length was 3 m and we covered a $5 R_\odot$ field through a radial neutral filter which compensated for the radial gradient of intensity variations. Polarization pictures were also obtained by using rotating axially symmetric polaroids (Koutchmy and Schatten, 1971) which permitted us to register directly the tangentially or the radially polarized component of light. Pictures were also calibrated by using conventional methods; in particular, a small portion of each picture was exposed to attenuated solar light. Because of the great difficulties involved when this method is used for absolute calibration (see, e.g., Elmore et al., 1970) and despite the fact that our pictures show details on the moon background with good enough signal to noise ratio for checking the absolute calibration, we decided to use a completely different and apparently new method. Indeed our pictures achieved a good spatial resolution and more than 30 stars were readily identified in the $5 R_\odot$ field of view. As the relative photographic photometry of these stars can be easily performed by using conventional methods (e.g., Koutchmy and Lamy, 1975) the absolute value of coronal intensities will be related to the average brightness of the Sun, $\bar{B}_\odot$, provided the relative magnitudes of the stars and the Sun are known. More details will be given in a forthcoming publication devoted to the detailed photometry of the entire solar corona.

The determination of electron densities from the measured $pB$ values has already been described by many authors. The method has been exhaustively refined recently by
Saito (1970) who has given numerous graphs and tables which simplified considerably our work of determining $N_e$ from $pB$. As suggested by Figure 1 and Figure 4, we chose to restrict our analysis to the spherically symmetric case, or of 'homogeneous stratified layers'. Obviously, this approach is valuable only near the 'axis' of the trans-polar hole which coincides, approximately, with the N-polar axis. It is not our purpose to derive a 3-D model of the hole but rather to try to derive a reliable value of $N_e$ over the 'privileged plane' of the hole.

Fig. 2. Radial variation of the measured values of $pB$. Values predicted by the Saito (1970) model, along the polar axis, are also indicated. The straight full line shows the adopted model. The Pic du Midi values, Leroy (1976), have been converted into the same units as ours by using the formula: $B_\odot(0.9 \mu) = 1.145 \ B_\odot(0.9 \mu)$ (Allen, 1973).
3. Results

In Table I we give the important parameters used for the absolute calibration, including the measured one. Star identifications are from the Star Catalog (1971 Edition) of the Smithsonian Astrophysical Observatory. The five stars selected gave us a very reliable absolute calibration since the precision achieved was limited only by the knowledge of the absolute magnitude of the Sun. Further, intensities measured above the N-polar region on both polarized pictures were converted to pB values. Figure 4 shows the precise azimuthal position of the measurements not to be critical since the polar region shows only small intensity variations for \( r = \text{const} \) over a sector of \( \pm 10^\circ \) near the polar axis (see also Figures 1 and 4). In Figure 2, we compare our derived pB values with values measured above the N-polar region on June 29th at the Pic du Midi Observatory (Leroy, 1976). A good agreement is apparent. We also compared values for all azimuthal positions around the Sun. The persistent agreement shows our absolute scales to be the same. For comparison, we show also the values predicted by the Saito (1970) model on the polar axis. As expected, our values for the pole are definitely lower, in the inner corona, than those values obtained by averaging over many observations.

### TABLE I

Values of stars and coronal intensities and parameters used for the absolute calibration: SAO Number is the star number of the Smithsonian Astrophysical Observatory Star Catalog; \( m_v \) is the visual magnitude and \( m_{ph} \) the photographic one; \( SP \) is the spectral class; \( \theta_\odot \) is the heliographic angle of the star in the eclipse picture and \( r \) the radial distance of the star; \( A \) is the attenuation factor of the radial neutral filter; \( I \) is the coronal intensity measured near the star and \( I_0 \) the central intensity of the star alone, in relative units; \( HW \) is the full half-width of the star image.

<table>
<thead>
<tr>
<th>SAO Number</th>
<th>( m_v )</th>
<th>( m_{ph} )</th>
<th>( SP )</th>
<th>( \theta_\odot )</th>
<th>( r )</th>
<th>( A )</th>
<th>( I )</th>
<th>( I_0 )</th>
<th>( HW'' )</th>
</tr>
</thead>
<tbody>
<tr>
<td>78610</td>
<td>7.6</td>
<td>7.6</td>
<td>F5</td>
<td>36°</td>
<td>2.35</td>
<td>1.72</td>
<td>2.04</td>
<td>0.84</td>
<td>5.32</td>
</tr>
<tr>
<td>78623</td>
<td>8.6</td>
<td>8.7</td>
<td>F5</td>
<td>44°</td>
<td>2.37</td>
<td>1.68</td>
<td>2.01</td>
<td>0.53</td>
<td>4.81</td>
</tr>
<tr>
<td>78637</td>
<td>8.5</td>
<td>8.9</td>
<td>K2</td>
<td>42°</td>
<td>3.83</td>
<td>1.0</td>
<td>1.22</td>
<td>1.12</td>
<td>4.53</td>
</tr>
<tr>
<td>78568</td>
<td>6.8</td>
<td></td>
<td>K0</td>
<td>343°</td>
<td>1.99</td>
<td>3.17</td>
<td>2.25</td>
<td>0.87</td>
<td>4.96</td>
</tr>
<tr>
<td>78586</td>
<td>6.3</td>
<td></td>
<td>K0</td>
<td>185°</td>
<td>4.275</td>
<td>1.0</td>
<td>0.96</td>
<td>3.30</td>
<td>5.92</td>
</tr>
<tr>
<td>( \odot )</td>
<td>-26.74</td>
<td></td>
<td>G2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Following Saito (1970), the observed intensities were plotted as \( \log I - \log r \) (the Baumbach approximation) in order to determine a value for \( n \) which best fits the data. It was found in the limited range \( 1.12 \leq r \leq 1.83 \) that a satisfactory fit was obtained for \( n = 5.45 \). For these observations at 4500 Å, \( q = 0.75 \) and from formula (52) of Saito (1970), we define:

\[
f(n, r, q = 0.75) = \frac{1}{q}(I_T - I_R)_{q=0} + \frac{2}{3}(I_T - I_R)_{q=1},
\]

(2)

where \( f(n, r, q = 0.75) \) is an interpolation from his Table 5 (we used his formulae for the spherically symmetric case). Now at any radial distance, the electron density

\[
N_e(r) = N_0 r^{-n}
\]

(3)
at this distance $N_0$ may be calculated using formula (44) of Saito for the observed
\[ pB = cN_0 f(n, r, q = 0.75)k^{n+1}, \]
where \( c = \frac{3}{8}B_\odot \sigma R_\odot = 1.736 \times 10^{-14} B_\odot \). The values of $N_0$ deduced from (4) and $N_e$ from (3) are shown in Table II.

By inspecting the Figure 8 of Saito (1970) it is interesting to notice the goodness of our approximation (3) (Baumbach approximation). We found our approximation to be especially good for the values $n = 6$ and $k^2 \leq 0.8$ (or, $r \geq 1.12$).

Finally, in Figure 4 we compare our radial variations of $N_e$ with some well known models. In addition, we include hydrostatic temperatures deduced from the formula
\[ T_{\text{hyd}} = 6.08 \times 10^6 \{ d(\log_{10} N_e) \times [d(r^{-1})]^{-1} \}^{-1} \text{ (K)} \]
and an abundance ratio: $H \times H_e^{-1} = 10$ (Brandt, 1970).

Fig. 3. Computed values of electron densities per cm$^3$ (full line) as a function of radial distances, in units of solar radii. $M$ shows values for the Van de Hulst (1953) model of solar activity maximum, $m$ – for the polar-minimum of activity model and $S$ – for the Saito model (polar axis), $N$ – for the present work. The lower part of the graph shows values of hydrostatic temperatures (in millions of K) derived for each model.
Table II

Values of electron density $N_e$ as a function of radial distance. $\rho$ is the projected radial distance, in units of solar radii. $pB$ values are given in units $10^{-10} B_\odot$ and $f(n, r, q)$ in the same units as given for Table 5 of Saito (1970) and computed with our formula (2).

<table>
<thead>
<tr>
<th>$k^2$</th>
<th>$\rho$</th>
<th>$f(n, r, q)$</th>
<th>$pB$</th>
<th>$N_0 \times 10^{-6}$</th>
<th>$N_e \times 10^{-6}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8</td>
<td>1.120</td>
<td>0.131</td>
<td>355</td>
<td>15.7</td>
<td>8.44</td>
</tr>
<tr>
<td>0.7</td>
<td>1.195</td>
<td>0.0936</td>
<td>235</td>
<td>14.5</td>
<td>5.49</td>
</tr>
<tr>
<td>0.6</td>
<td>1.290</td>
<td>0.0619</td>
<td>145</td>
<td>13.5</td>
<td>3.37</td>
</tr>
<tr>
<td>0.5</td>
<td>1.414</td>
<td>0.0371</td>
<td>79</td>
<td>12.2</td>
<td>1.85</td>
</tr>
<tr>
<td>0.4</td>
<td>1.580</td>
<td>0.0192</td>
<td>39</td>
<td>11.7</td>
<td>0.97</td>
</tr>
<tr>
<td>0.3</td>
<td>1.830</td>
<td>0.0080</td>
<td>15</td>
<td>10.8</td>
<td>0.40</td>
</tr>
</tbody>
</table>

Discussion

By making the assumption of hydrostatic equilibrium in the very low corona $1 < r < 1.3$ (few deviations are expected in this region if no wave input of energy is assumed), we can extrapolate our values of $N_e(r)$ and $T(r)$ down to the surface and make a comparison between different published values, see Table III.

Fig. 4. Composite of the solar corona picture obtained on June 30, 1973 and of the Hα picture obtained simultaneously. The coronal picture has been processed in order to enhance small scale intensity gradients.
TABLE III

Derived parameters for different models of coronal holes. The values by Fisher and Musman (1976) have been recently improved (Fisher, 1976) which lowers the values of $N_e$. Electron density $N_e$ is given per cm$^3$.

<table>
<thead>
<tr>
<th>Model (r = 1 $R_\odot$)</th>
<th>Munro and Withbroe (1972)</th>
<th>Lantos and Avignon (1975)</th>
<th>Fisher and Musman (1975)</th>
<th>Present, extrapolated</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_e$</td>
<td>$3.0 \times 10^8$</td>
<td>$1.2 \times 10^8$</td>
<td>$&lt;6.8 \times 10^7$</td>
<td>$1.8 \times 10^7$</td>
</tr>
<tr>
<td>$T$(K)</td>
<td>$1.05 \times 10^6$</td>
<td>$9 \times 10^5$</td>
<td>$1.8 \times 10^6$</td>
<td>$2 \times 10^6$</td>
</tr>
</tbody>
</table>

We do not believe our extrapolated hydrostatic temperature to be an accurate determination, but its radial behaviour (see Figure 4) is rather interesting. It may be mentioned that the decreasing part of the curve, for $r > 1.5$ provides an indication of a large hydrodynamic expansion since in this case, an increasing part of the kinetic energy would have to be transformed into convective energy, producing the observed effect. This explanation might easily reconcile (Adams and Sturrock, 1975) the concept of a coronal hole as a very low density region and of a coronal hole as a source of solar wind (Noci, 1973; Watanabe, 1975).

Finally, let us comment about the morphological characteristics of the hole. Figure 4 is a photographic composite used for this purpose; the coronal picture was processed in order to enhance the high spatial frequencies. By using this picture, several characteristic features can be noticed:

(a) Number and especially contrast of polar rays in the N-polar region is definitely surpassed by the number and contrast of rays in the S-polar region, where superposition effects could be present (the number ratio is the order of $2^3$). Furthermore, polar rays in the N-region (where the coronal hole was located), are quasi-straight although S-polar rays show the well-known ‘curved signature’. Extensions of polar rays intersect the rotation axis in a characteristic location which is displaced from the Sun center by a distance $q$, in solar radii. For N-polar rays, $q \approx 0.65$; for S-polar rays, $q \approx 0.12$ for this eclipse. Let us point out that a more detailed analysis of the N-pole morphology, taking into account the form of polar rays, has already been published by Waldmeier (1974).

(b) By identifying the N-polar rays with ‘stream lines’ above the hole, it is obvious that the expansion is faster than an $r^2$ expansion. At $r = 2$, for example, the ratio of the ‘hole cross-section’ to the radial one is $2.3$; at $r = 3$, it reaches $2.9$.

One remembers that many authors interpreted polar rays as materialized magnetic field lines of an hypothetical general magnetic field of the Sun. Apart from this concept, the deviation from the radial direction of polar rays might be interpreted as due to the combined effect of rotation and expansion (Koutchmy, 1972). By assuming the expansion to start at the surface of the Sun, the velocity field might be deduced. This oversimplified image is nevertheless contradicted by the obvious curvature of S-polar
rays, which suggests far stronger dynamic effects above this region. Further study of polar rays is clearly needed but is beyond the present analysis.

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References