K-CORONA POLARIZED BRIGHTNESS AND ELECTRON DENSITY MEASURED WITH THE VISIBLE LIGHT POLARIMETER OF UVCS

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ABSTRACT

The White Light Channel (WLC) of the Ultraviolet Coronagraph Spectrometer (UVCS) on SOHO is a coronagraph polarimeter that measures the polarized brightness (pB) of the K-corona between 1.6 and 5 \( R_\odot \) in the 450–600 nm wavelength range. The WLC is co-registered with the UV spectrometers of UVCS, thus providing a measurement of the electron density (van de Hulst 1950), a key parameter for plasma diagnostics. After a description of the calibration of the WLC, we present the synoptic measurements of polarized brightness for streamers, coronal holes, and mid-latitude regions from August 1996 till May 1997. The electron densities are computed from the synoptic pB measurements using a spherically symmetrical model and an estimate of the maximum to minimum electron density ratio is given for streamers and coronal hole regions.

Key words: solar corona; electron density.

1. INTRODUCTION

The White Light Channel WLC of the Ultraviolet Coronagraph Spectrometer (UVCS) of SOHO is a coronagraph polarimeter operating in the wavelength range from 450 to 600 nm (Kohl et al. 1995, Romoli et al. 1997). WLC measures the polarized brightness (pB) of the corona from 1.5 to 4 \( R_\odot \), with a spatial resolution of 14\text{"}x14\text{"}, in one single point at each time, which is co-registered with the field of view of the ultraviolet spectrometers of UVCS.

The pB is due to Thomson scattering of the photospheric continuum by free electrons in corona. The electron density in the extended corona can be inferred from different spectroscopic diagnostics (for example, from the collisional component of the UV emission lines (Corti et al. 1997)), but this often requires the knowledge of other coronal parameters, such as temperatures, velocities and ion abundances. Under the assumption that the polarized component of the coronal continuum is due solely to electron-scattered K-corona and not to the dust-scattered F-corona, which is valid below 5 \( R_\odot \), the pB measurement provides a direct measurement of the electron density integrated along the line of sight, with no dependence on other plasma parameters.

The computation of the local electron density from the line-of-sight electron density requires an electron density model of the coronal structure, unless a spherical symmetry is adopted. In this case the electron density can be derived analytically.

2. WLC MEASUREMENTS

The polarization brightness (pB) is measured by the WLC in the point shown in Figure 1 relative to the nominal roll angle, PA, and to the heliocentric height, \( r \), of the instrument pointing.

![Figure 1. WLC pointing](image)

The polarimeter consists of a rotating half wave retarder plate (HWRP) and a fixed polarizer. The HWRP is rotated into three positions, which should be \(-30^\circ\), \(0^\circ\), \(+30^\circ\) relative to the polarizer axis to improve the accuracy of the pB measurement, but are slightly different in the WLC because of technical reasons. For each angle of the HWRP, \( \alpha \), the photon counting detector measures a countrate:

\[
N(\theta) = k \cdot B(\theta)
\]
with:

\[ B(\theta) = \frac{I + Q \cos 2\theta + U \sin 2\theta}{2} \]  

(2)

where: \((I, Q, U)\) is the Stokes vector for linearly polarized brightness, normalized to the Sun center brightness; \(k\) is a constant that includes reflectivities and transmittivities of the optical components, the geometry of the optical system, and the integral over the wavelength of the WLC filter bandpass times the detector quantum efficiency times the Sun center specific brightness; and \(\theta = 2\alpha\). In Eq. 1 the assumption is made that the normalized Stokes vector is wavelength independent.

Finally, \(pB\), normalized to the Sun center brightness, is derived by solving the set of linear equations obtained from Eqs. 1 and 2 for three angles of the HWRP, and computing:

\[ pB = \sqrt{Q^2 + U^2} \]  

(3)

3. CALIBRATION AND SYNOPTIC OBSERVATIONS

Data are calibrated according to the most recent calibration:

- Radiometric Calibration: \(k \times \frac{f^2}{2S_S S_T} = (0.4 \pm 0.1)\%

where \(S_S\) and \(S_T\) are the pinhole area and the telescope area, and \(f\) is the telescope focal length.

- Subtraction of a constant polarized stray light contribution, probably due to the telescope edge reflections of the disk radiation diffracted by the UVCS external occultor.

- \(pB = Q\), instead of \(pB = \sqrt{Q^2 + U^2}\), under the assumption that the direction of the K-corona linear polarization is tangent to the limb, and the \(U\) polarization component is a spurious polarization due to fluctuation of the detector dark countrate.

The statistical error for each data point is small, compared to the scale of the plot. The uncertainty in the y-axis scale is \(+25\%\) (due to the radiometric calibration) and \(-100\%\) (due to time variations of the dark counts of the detector, a correction of this effect is now under investigation).

The UVCS synoptic program consists of a daily observation sequence in which a mirror scan of the solar corona is performed at several heights for eight values of the position angle, namely: south and north polar regions \((1.5, 1.75, 2, 2.25, 2.5, \ R_0)\), east and west equatorial regions \((1.5, 1.7, 1.9, 2.2, 2.5, 3 \ R_0)\), and the four mid-latitude regions \((1.5, 1.75, 2, 2.25 \ R_0)\). Figure 2 summarizes the synoptic observations for all 8 position angles and for most of the heliocentric heights. The black squares on map of the Sun show where the WLC measures the \(pB\) during the UVCS daily synoptic observation. Due to an offset in the pointing of the WLC, shown in Figure 1, the heliocentric heights of observation are slightly higher than nominal (from 0.01 to 0.02 \(R_0\)), and the actual position angle is increased in average by \(7^\circ\). The \(pB\) are plotted, one data point per day for different heliocentric heights for the eight position angles of the synoptic observation starting from August 1996 to the end of May 1997. The vertical dotted lines mark the beginning of each Carrington rotation, whose number is written at the top of each interval.

The NE and NW mid-latitude panels display a higher variability and higher values for \(pB\) than the SE and NW panels. This asymmetry is due to the offset in the WLC pointing: the field of view in the NE and the SW observations is closer to the equator, while the field-of-view for the SE and the NW observations is closer to the corresponding pole.

The mid-latitude observations display brightenings once every Carrington rotation, in particular from August to December 1996, with \(pB\) values comparable with those of the equatorial regions. For several solar rotations, these brightenings appear alternatively above the two equatorial limbs, showing that one equatorial region was wider in latitude than the opposite one.

When the mid-latitude regions are quiet, the \(pB\) is about the same of that of the polar regions, except for the last three displayed solar rotations, where a regular increase of the polarized brightness at 1.75 \(R_0\) appears. This is the only evidence that the solar activity is leaving the solar minimum.

4. ELECTRON DENSITY

The electron density in the solar corona can be determined from the measurement of the linear polarization produced by the photospheric continuum radiation Thomson-scattered by the free electrons (van de Hulst 1950), the so called K-corona polarized brightness. The \(pB\) is a function of the heliocentric height of observation, \(\rho\), namely, the distance from the Sun center of the intercept of the line-of-sight (LOS) with the plane of the sky, and is proportional to the LOS integral of the electron density, \(N_e\), according to the equation:

\[ pB(\rho) = \frac{3}{16} R_0 \sigma_T \int_{-\infty}^{+\infty} N_e [(1 - u)A(r) + uB(r)] \frac{r^2}{\rho} dl \]  

(4)

where: \(\sigma_T\) is the Thomson cross-section; \(u\) is the disk limb darkening; \(\tau\) is the distance between a point on the LOS and the Sun center; \(A(r)\) and \(B(r)\) are functions related to the integration of the angular scattering function over the solid angle subtended by the solar disk from a distance \(r\) (van de Hulst 1950); \(l\) is the coordinate along the LOS (in units of \(R_0\)); and the \(pB\) is normalized to the Sun center brightness. The limb darkening function, \(u\), is actually a function of the wavelength, and gives a weak dependence of \(pB\) on the wavelength. The dependence is removed by weighing \(u(\lambda)\) over the WLC response function and the Sun center brightness: \(u = 0.78\) that corresponds to an effective wavelength of 510 nm. This is equivalent to the assumption that the normalized
Figure 2. WLC synoptic data from August 1, 1996 to May 31, 1997. See Section 3. for the description.
Stokes vector is wavelength independent (see description of Eq. 1).

The solution of the integral equation (Eq. 4) requires the knowledge of the distribution of the electron density along the line of sight. The electron density distribution can be modeled in several ways, from the simple spherically symmetric model (van de Hulst 1950), to an axisymmetric model (Saito 1950), to models that take into account large scale structures, such as polar plumes in the coronal holes, or active streamers in the equatorial regions.

During the solar minimum, the solar corona has a very structured equatorially symmetric streamer belt, about 60° to 100° wide at the base, characterized by closed magnetic field lines, topped and bottomed by an extended coronal hole region, characterized by open magnetic field lines, where the latitudinal dependence of the electron density is very weak. Therefore, there are two situations in which one can easily assume that the electron density has only a radial dependence (Guhathakurta et al. 1996): when the streamer is edge-on, and the LOS is all at the same latitude; when we look through a coronal hole.

For sake of simplicity, spherical symmetry was assumed, in order to derive an estimate of the electron density fluctuations inside streamers and coronal holes.

Using the spherically symmetrical distribution, pB(ρ) is fit with a sum of two power laws of ρ

$$pB(ρ) = a₁ρ^{−β₁} + a₂ρ^{−β₂}$$  \hspace{1cm} (5)

If we write the electron density as

$$Ne(r) = \frac{α₁r^{−β₁} + α₂r^{−β₂}}{[1-u]A(r) + uB(r)]}$$  \hspace{1cm} (6)

we solve Eq. 4 to find α₁ and β₁ as a function of α₁ and β₁:

$$α₁ = \frac{g₁}{S_β}, \quad \text{with} \quad S_β = \int_0^π \sin β dβ$$ \hspace{1cm} (7)

$$β₁ = b₁ + 1$$ \hspace{1cm} (8)

The ratio between the estimated maximum and minimum electron density is given in Table 1. No absolute values for the electron density are given, because of the still high uncertainty in the absolute calibration of the polarized brightness.

In the streamer regions the variations of the electron density are related to the brightness of the streamer structures, and the increase with height of the ratio could tell that at higher heights the streamer belt narrows and, sometime, the WLC monitors the boundary between open magnetic field and closed magnetic field regions.

In a coronal hole the density fluctuation can be attributed to denser plume versus thinner interplume regions. A similar range of fluctuations has been observed by the white light coronograph on Spartan 201-01 (Fisher & Guhathakurta 1995).

### Table 1. ELECTRON DENSITY RATIOS

<table>
<thead>
<tr>
<th>Heliocentric Height</th>
<th>$N_{max}/N_{min}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Streamers</td>
<td></td>
</tr>
<tr>
<td>1.7 $R_⊙$</td>
<td>2.34 ± 0.20</td>
</tr>
<tr>
<td>1.9 $R_⊙$</td>
<td>2.46 ± 0.20</td>
</tr>
<tr>
<td>2.2 $R_⊙$</td>
<td>2.78 ± 0.20</td>
</tr>
<tr>
<td>1.9 $R_⊙$</td>
<td>2.46 ± 0.20</td>
</tr>
<tr>
<td>2.6 $R_⊙$</td>
<td>2.92 ± 0.20</td>
</tr>
<tr>
<td>3.0 $R_⊙$</td>
<td>3.09 ± 0.20</td>
</tr>
<tr>
<td>Coronal Holes</td>
<td></td>
</tr>
<tr>
<td>1.75 $R_⊙$</td>
<td>1.63 ± 0.15</td>
</tr>
<tr>
<td>2.0 $R_⊙$</td>
<td>1.56 ± 0.15</td>
</tr>
<tr>
<td>2.25 $R_⊙$</td>
<td>1.42 ± 0.15</td>
</tr>
<tr>
<td>2.5 $R_⊙$</td>
<td>1.30 ± 0.15</td>
</tr>
</tbody>
</table>

**REFERENCES**


