A STUDY OF HYDROGEN DENSITY IN EMERGING FLUX LOOPS FROM A COORDINATED TRACE AND CANARY ISLANDS OBSERVATION CAMPAIGN

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ABSTRACT

During an international ground-based campaign in Canaries coordinated with Space instruments (TRACE, Yohkoh) we have observed an active region on September 10, 1998 with high spatial and temporal resolution. New emerging flux has been observed in magnetograms of the GCT, Tenerife and the SVST, LaPalma. The arch filament systems are well developed in Hα (VTT/DPSM, SVST). The multi-wavelength observations (SXT/Yohkoh, TRACE) allow us to analyse the behaviour of 3D loops visible in transition region and coronal temperatures. We discuss on different physical quantities: i.e. temperature, hydrogen column density.

The arch filament systems (AFS) correspond to low emission regions observed in wavelengths 171 Å and 195 Å due to absorption by hydrogen and helium in the cool prominence plasma. The emitting plasma around and above the AFS is at a measurably higher temperature than the large extended loops.

1. Introduction

Emerging solar magnetic flux is frequent in the solar atmosphere. The phenomenon in the chromosphere is characterized by the formation of low-lying dark filament, called arch filament systems (AFS). The matter is compressed by the rising of new magnetic flux and, as it becomes denser, flows down both ends of the loops under the influence of gravity.

Therefore, plasma downflows are commonly observed at the footpoints of the AFS and upflows around the apex of the loops. The loops connect regions of opposite polarity. Above the AFS it is not clear what happens. Generally, as the flux emerges, the X-ray bright loops that overlie the AFS regions are hotter and/or denser than the surrounding plasma (Malherbe et al. 1998). The reason for the heating of the corona is not so well explained. It may be due to reconnection of magnetic field lines leading to the formation of hot loops. The AFS are then formed as these loops cool (Yoshimura et al. 1996). Are hot and cool plasma loops the same structures? Multi-wavelengths coordinated observations and good co-alignment are required for this analysis.

The MSDP spectrograph and SVST telescope for chromospheric lines and TRACE in EUV lines are well suited to study the dynamics of chromospheric and coronal material in different ranges of temperatures. Cool and hot X-ray loops can be compared. Plasma diagnostics of the AFS region can be achieved by comparing at the absorbing features and the surrounding corona in 171 Å line and 195 Å (TRACE). Hydrogen column density is obtained from the analysis of Hα profiles using cloud model method and by interpreting the absorption of the coronal lines by hydrogen and helium continua.

2. Observations and co-alignment

The AR 8331 was observed on Sept 10 1998 by ground based instruments in Canaries and TRACE during an international campaign (see Table 1).
2.1. TRACE

The TRACE instrument is a 30cm aperture Cassegrain telescope intended to observe solar plasmas from 6000 to 1 MK with 1 arc sec spatial resolution and high temporal resolution and continuity (Handy et al., 1999, Schrijver et al., 1999). TRACE was operating in the 2 wavelengths 171 Å and 195 Å every 60 sec from 12:00 UT to 16:00 UT and a white light image was taken every 35 minutes. The field of view is 1024 × 1024 pixels with a pixel size=0.5 arc sec.

2.2. Telescopes in the Canaries Islands

- MSDP
  The Multichannel Subtractive Double Pass spectrophotograph (MSDP) was operating on the German Telescope (VTT) in the Canaries (Mein, 1991). This instrument provides simultaneous data in a 2D area at eleven spectral positions covering the Hα line profile. The slit of the entrance window of the spectrograph is 180'' × 22''. The exposure time is 20 ms - 30 ms for Hα. By adding adjacent elementary areas a larger field-of-view is observed in both directions. Here the typical field is 3 × 180'' × 320 '' ~ 450'' × 320''. In the present study we used only a central part of the field around 170 '' × 240''.

The Hα profiles were reconstructed for each pixel of the region. By locating the bisector position of the line profile and the minimum intensity, maps of Doppler shifts and intensity fluctuations can be obtained. Velocity and intensity images in the Hα line were obtained over a part of the active region.

- SVST
  The Swedish telescope in LaPalma provides every minute: Hα images in the line center and ± 0.25 Å. ± 0.45 Å, continuum and magnetic field images computed by using the Fe 6302 Å line. The field-of-view is 1534 × 1032 pixels around 127 '' × 88 '' with a pixel of 0.083''.

- GCT
  The Gregory Coude Telescope (GCT) in Tenerife allows us to obtain maps of the longitudinal magnetic field and of the continuum of the active region covering an area 374 '' × 158'' with a elementary pixel of 0.387''. To compute the magnetic field they size the magnetograms down to the half (xsize=452;ysize=204 with a pixel size of 0.766 '') by taking the average of the relevant pixels in order to fit the arrays to a more realistic resolution. The area was scanned in more than half an hour.

2.3. Co-alignment

The co-alignment was mainly done by using the pixel size of the GCT (0.77 '') and the direction of the GCT observations which is mainly North/South.

The co-alignment between MSDP data and GCT has been obtained by using the white light images of both instruments. MSDP images have been rotated. The co-alignment has been made between TRACE.
Table 1. Observations of the AR 8331 (B = magnetic field, WL = white light)

<table>
<thead>
<tr>
<th>Wavelengths lines</th>
<th>Instrument</th>
<th>Time UT</th>
<th>Δt</th>
<th>Resolution arc sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hα, WL</td>
<td>MSDP/VTT</td>
<td>13:02 - 15:33</td>
<td>17 min</td>
<td>0.25</td>
</tr>
<tr>
<td>Hα, WL B</td>
<td>SVST</td>
<td>13:35 - 16:00</td>
<td>64 sec</td>
<td>~ 0.156</td>
</tr>
<tr>
<td>B, WL</td>
<td>GCT</td>
<td>11:10 - 11:52</td>
<td>80 min</td>
<td>0.77/0.385</td>
</tr>
<tr>
<td></td>
<td></td>
<td>13:30 - 14:10</td>
<td></td>
<td>0.77/0.385</td>
</tr>
<tr>
<td></td>
<td></td>
<td>14:45 - 15:20</td>
<td></td>
<td>0.77/0.385</td>
</tr>
<tr>
<td>171,195, WL</td>
<td>TRACE</td>
<td>12:00 - 16:00</td>
<td>60 sec</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Figure 2. TRACE image in 171 Å and parallel lines over the central part of the region (set A and set B) where the intensity cuts have been made in Fig. 3 and 4.

Figure 3. Intensity slices (DN unit) of set A (left), and set B (right) in TRACE images (see Fig. 2).

and GCT by using also white light images and the GCT magnetic field. Only translation is done: files (512 x 512 pixels (0.77")). Figure 1 shows the co-alignment of TRACE, GCT and MSDP at 13:03 UT.

3. Plasma physical quantities derived from TRACE

3.1. Temperature

Using the observations of TRACE we derive the temperature of the corona in each pixel from the ratio of the intensity of the two lines (171 Å, 195 Å) assuming an isothermal plasma along the line-of-sight. The temperature array in log of TRACE is between 5.8 to 6.25. From the temperature map we find clear evidence that the plasma above and adjacent to the AFS is at a higher temperature (6.15) than the large extended loops (6.05 near the footpoints). This suggests that much of the emission observed over the AFS is due to foreground plasma. The plage region has a similar temperature value than the AFS region. The higher intensity of the

Figure 4. Optical Depth slices along the cuts in TRACE images: set A (left) and set B (right).
plage region would be explained by a higher density.

3.2. Absorption Model

We used the method based on Daw et al., 1995 (see also Northup et al., 1999) to derive the hydrogen column density of the plasma absorbing the coronal lines.

From our observations we have the following relationships:
for 171 Å
\[ F_1 = E_0 + E_1 \]
\[ F_2 = E_0 e^{-\tau_1} + E_1 \]
for 195 Å
\[ F_3 = E_0 + E_3 \]
\[ F_4 = E_0 e^{-\tau_2} + E_3 \]

where, \( F_1 \) represents the observed 171 Å flux outside of the filaments, and \( F_2 \) is the observed flux over the filament. \( F_3 \) and \( F_4 \) are the flux “outside” and over the filament in 195 Å. This gives 4 equations and 6 unknowns \( (E_0, E_1, E_2, E_3, \tau_1, \tau_2) \). The main uncertainty of the method comes from the estimate of the background. Assuming the faintest emission above the filaments is all due to foreground emission, then:
\[ E_1 = \min(F_2) = 3.37DN/s \] and \( E_3 = \min(F_4) = 4.75DN/s \).

DN is the unit of measurement of the intensity. We choose a characteristic “outside” emission from the regions next to the filaments, \( F_1 = 8.5DN/s \) and \( F_3 = 11.5DN/s \). The equations are now solved at each point above the filament giving \( \tau_1 \) and \( \tau_2 \) as a function of position. The \( \tau_1 \) and \( \tau_2 \) are calculated for 195Å and 171Å (dashed) profiles using a constant background emission with a ratio of 1.3 (195/171) and a constant foreground emission that is equal to the faintest emission seen above the filaments. With these assumptions, upper bound values will be determined.

3.3. Column density

The optical depth \( \tau \) is equal to:
\[ \tau = \sigma_{HI}^t N_{HI} + \sigma_{H_1}^t N_{H_1} + \sigma_{H_1}^t N_{H_1} \]

We follow the method described by Northup et al., 1999 to derive \( N_{HI} \) the hydrogen column density. We take into account only HI and HeI and use the cross sections values \( \sigma_{HI} \) and \( \sigma_{H_1} \) according Osterbrock (1989), West and Marr (1976). The number ratio of hydrogen to helium is 10.1 so we have:
\[ \tau(171\text{ Å}) = 1.1 \times 10^{-19} N_{HI} \text{ cm}^2 \]
\[ \tau(195\text{ Å}) = 1.6 \times 10^{-19} N_{HI} \text{ cm}^2 \]

<table>
<thead>
<tr>
<th>( \tau )</th>
<th>( \Delta\lambda )</th>
<th>( d )</th>
<th>( N_e )</th>
<th>( N_{HI} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>195 Å</td>
<td>0.9 \times 10^{17}</td>
<td>( \Delta\lambda )</td>
<td>1.2 \times 10^{17}</td>
<td>2.5 \times 10^{17}</td>
</tr>
<tr>
<td>171 Å</td>
<td>1.35 \times 10^{19}</td>
<td>1.8 \times 10^{19}</td>
<td>3.6 \times 10^{19}</td>
<td></td>
</tr>
</tbody>
</table>

Table 3. Optical thickness, electron density, and hydrogen column density for two filaments B1 and B2 from Hα data

The ionization ratio of H and He could introduce a factor 2 of uncertainty and lead to upper values of \( N_{HI} \) but nevertheless the correlation obtained between the two determinations is close to the predicted one.

\[ N_{HI} = 0.1 \times 10^{18} \tau(171\text{ Å}) \text{ cm}^{-2} \]
\[ N_{HI} = 0.3 \times 10^{18} \tau(195\text{ Å}) \text{ cm}^{-2} \]

Different cuts have been made through the central part of the active region (Fig. 2). The results of the optical depth are presented in the Figure 4. The values of \( \tau \) are between 1.5 to 4 at the maximum with a mean value of 2. The corresponding values of \( N_{HI} \) are upper limits (Table 2).

4. Analysis of Hα profiles

4.1. Cloud Model Method

With the MSDP spectrograph we obtain the profiles of the Hα line in each pixel within the field-of-view. We focus our study on the cool structures which appear in the middle of the active region, the arch filament system. We calculate different parameters of the filaments by considering the cool plasma overlying the chromosphere. We use the method "cloud model" well documented by Mein et al. (1996) and, based on the relationship between the source function and the opacity of the cloud, derived from a non-LTE modeling. For the background profile (dotted line on Fig. 6), we take the mean value of two profiles (noted background 1 and background 2 ) taken at 2° on each side of the axis of the filament (dotted line on Fig. 6). The optical thickness \( \tau_0 \) of the structure at Hα wavelength and the width of the line (including the Doppler width and the microturbulence \( \Delta\lambda \) can be derived by the method using theoretical variable source function in a dynamical model (Heinzel et al., 1999), the width of the structure along
the line-of-sight $d$ can be deduced from the measured width of the structures and the position on the solar image. To determine the electron density in the structures we use the formulae given in Tsiropoulou and Schmieder (1977):

$$n_e = 7.26 \times 10^7 \frac{\Delta \lambda}{d} \text{cm}^{-3}$$

where $n_e$ is the density of hydrogen atoms in the second level, $\Delta \lambda$ in Å and $d$ in km. The relation between the electron density $n_e$ and $n_2$ could be approximated by the formulae proposed by Yakovkin and Žel'dina (1975) for a vertical slab:

$$n_e = 3.2 \times 10^8 \sqrt{n_2} \text{ cm}^{-3}$$

$$n_e = 2.73 \times 10^{12} \sqrt{n_2 \Delta \lambda/d} \text{ cm}^{-3}$$

Poland et al. (1971) show that there is a single-valued relation between $n_H$ the total particle of hydrogen (i.e. neutral plus ionized) and $n_2$ using a vertical slab model atmosphere irradiated from both sides and a model atom of two bound levels and a continuum. In the linear part of the curve we have:

$$n_H = 5 \times 10^8 \sqrt{n_2} \text{ cm}^{-3}$$

The hydrogen column density is $N_{HI} = n_H \times d \text{ cm}^{-2}$

4.2. Electron density and density of hydrogen

We limit our computation to the observation obtained at 12:03 UT and concentrate on two filaments that are denoted B1 and B2 (Fig. 5) which correspond nearly to the points crossed by the B lines on TRACE image (Fig. 2) and more precisely to pixels around 340 in Figure 4 (set B, low right panel). We compare the profile observed in the middle of B1 or B2 with two adjacent profiles at both 2 edges of the filament (background points).

The cross section of the structures is approximately equal to 2 arc sec. Assuming that the structure cross section is a circle, $d$ can be considered as the geometric distance of the structure observed on the disk plan multiplied by a factor taking into account of the position of the filaments on the disk. The filaments are directed towards the Sun center in a direction of 45 degrees so the factor is about $\sqrt{2}$. The geometric distance in the disk plane of the section of the filament is around 1500 km, $d \sim 2100$ km.
According to the cloud model method using the profiles shown in Fig. 6, τ₀ is for B₁ ~ 0.8 and for B₂ ~ 0.4. The results are presented in Table 3. We have to keep in mind that the limited resolution leads to an underestimation of τ but an overestimation of d.

5. Conclusion

The results concerning the hydrogen column density of arch filament systems measured from the analysis of the Hα profiles observed by the VTT/MSDP at Canaries have been compared to those obtained by the formulae: \( N_H = 9.1 \times 10^{14} \tau \) cm⁻² and using the TRACE data. Comparing Tables 2 and 3 we see that the values calculated by using the Hα profiles are lower than the maximum values given by TRACE as far the optical depth at 171 Å is larger than 1.5. That is the case of absorbing features in set B, they have an optical thickness reaching 3 at 171 Å.

The TRACE temperature map gives really a 3D picture of the region. The low X-ray loops in the middle of the AR have a higher temperature than the large extended overlying loops. This was already observed with Yohkoh by Malherbe et al., 1998. The loop temperature over the AFS was estimated to 2.5-5.7 \( 10^6 \) K. These values are larger than the formation temperature of 171 and 195 Å. So it means that over the AFS we have a relatively low system of coronal loops from \( 10^5 \) to 5.7 \( 10^6 \) K temperature.

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