DEACYING POST-FLARE LOOPS SYSTEM OBSERVED BY SOHO/CDS AND YOHKOH/SXT

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ABSTRACT

The results of an analysis of joint SOHO/CDS and Yohkoh/SXT observations of a decaying post-flare loops system resulting from a small flare (GOES class C2.9) with a rapid time evolution are presented. Using the CDS rasters taken in EUV lines with different formation temperatures and a temperature sensitive line pair Fe XVI 360.8/Si XII 520.7 we confirmed the existence of the vertical stratification in the loop system according to the line formation temperature. The analysis of the SXT data showed that the hot part of the observed loop system (T ≃ 2.5 MK) decayed mainly due to a rapid plasma outflow from the loops. The total emission measure of the system dropped more than 4 times in approximately 10^3 s, while its temperature decreased only slightly. On the other hand, in the CDS rasters taken in cool lines (O V, O III) signs of rapid, probably radiative cooling can be identified. Using the density sensitive line pair of Fe XIV 334.2/353.8 and the integrated intensity of Fe XIV 334.2 line we determined the electron densities and emission measures across the top of the loop system. From the results of these measurements, taking all known uncertainties into account, we obtained that the geometrical filling factor at the top of the system in the Fe XIV line lies somewhere in the interval from 0.01 to 0.2.

Key words: post-flare loops; EUV lines; geometrical filling factor.

1. INTRODUCTION

Post-flare loops — PFL systems have been extensively observed particularly in Hα and in soft X-rays, especially after the launch of Yohkoh with its Soft X-ray Telescope — SXT Tsuneta (1991). Hα images show plasma at temperatures around 10^4 K and provide a very good spatial resolution useful for studies of the structural and dynamic properties of PFL (recently for example Wikl et al. 1996). On the other hand, soft X-ray images, which unfortunately miss the spatial resolution of Hα images, show plasma with temperature of the order of 10^5 – 10^7 K and they are useful for approximate temperature and emission measure analysis (recently Schmieder et al. 1996). Observations of PFL systems in EUV lines provide an excellent opportunity to study the behaviour of post-flare plasma at the intermediate temperatures. EUV spectra also allow the application of efficient electron density, emission measure and temperature diagnostic methods (for example Mason & Monsignori Fossi 1994). There have been several studies of this kind published based on the data from Solrad 9, Skylab and SMM (for review see Bray et al. 1991).

The Coronal Diagnostic Spectrometer — CDS on board SOHO is described in Harrison et al. (1995). The analysed data set was taken using the Normal Incidence Spectrometer — NIS with the 2 × 240 arcsec slit oriented in the N–S direction. Two-dimensional images of solar atmosphere (rasters) are built up using a scanning mirror which can move the image created with a Wolter–Schwarzschild type 2 telescope in the focal plane, where the entrance slit is placed, in the direction from west to east with a step size of 1 arcsec. The size of the raster analysed in this work is 244 × 240 arcsec, the spatial dimensions of one raster element are 2 arcsec in the E–W direction and 1.7 arcsec in the N–S direction. The whole raster consists of 120 exposures and the total building time was 1 h 45 min 38 s.

In this paper we analyse CDS and SXT data taken simultaneously to examine a decaying PFL system. The system was taken by CDS as a by-product of an active region observation and the CDS data was found after a systematic search for flare related data in the CDS archive.

2. OBSERVATIONS

The analysed PFL system was a remnant of a small flare (GOES class C2.9) which occurred on 16th December 1996 on the south-west limb of the Sun. GOES X-ray fluxes showed that the flare started at 12:20 UT, its maximum occurred at 12:29 UT and the GOES event finished at approximately 13:00 UT.
There are no direct observations of the flare itself because during the flare Yohkoh was in the shadow of the Earth and the slit of CDS was high above the flare region. The data concerning the PFL system was taken only before and after the GOES event and the time distribution of the available data set is presented on the background of GOES-9 X-ray fluxes in Figure 1.

The time evolution of the hot parts of the PFL system \( (T \approx 2.5 \text{ MK}) \), at approximately the same time when the slit of CDS scanned it, is easily visible in the images obtained by SXT (Figure 2). The PFL system, clearly conspicuous in the first images of the sequence, is quickly disappearing and in the last images is not recognizable at all. The length of the loop determined from these pictures is approximately \( 2.5 \times 10^9 \text{ cm} \). Figure 2 also shows that the examined loop system is surrounded by hot and rare coronal plasma. The influence of this plasma has to be taken into account when the temperature, emission measure and electron density are determined. Apart from the PFL system and the coronal plasma around it, it is also possible to recognize some loops above the PFL and two bright points; one above the northern footpoint of the loop and the second under it. In this study we discuss only the behaviour of the conspicuous loop-like structure visible in the first images of the sequence.

3. STRUCTURE AND SIGNS OF TIME EVOLUTION IN THE CDS RASTER

3.1. Depletion of the PFL system

The CDS raster of the PFL system, taken in eight selected lines which cover the temperature range from \( 2 \times 10^4 \) K to \( 2.2 \text{ MK} \) (see Table 1), are shown in Figure 3. Here, in all lines, roughly only one half of the loop is easily visible. Why it is so in the hot lines \( (T > 1 \text{ MK}) \) is apparent from a comparison of the CDS rasters with the time sequence of images obtained by SXT in Figure 2. The hot loops in the rasters are visible until approximately 13:22 UT, which corresponds to the time when the hot loop observed by SXT starts to disappear as well. It will be shown in the next section that this is mainly due to plasma depletion from the loops system. In the cooler lines this could be explained due to the combined effect of plasma depletion and cooling.

### Table 1. Formation temperatures of the EUV lines used in Figure 3.

<table>
<thead>
<tr>
<th>Ion</th>
<th>Wavelength</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \text{Å} )</td>
<td>( \text{K} )</td>
</tr>
<tr>
<td>He I</td>
<td>584.33</td>
<td>( 2 \times 10^4 )</td>
</tr>
<tr>
<td>O II</td>
<td>509.59</td>
<td>( \times 10^5 )</td>
</tr>
<tr>
<td>O V</td>
<td>630.03</td>
<td>( 2.5 \times 10^5 )</td>
</tr>
<tr>
<td>Ca X</td>
<td>396.84</td>
<td>( 6 \times 10^6 )</td>
</tr>
<tr>
<td>Mg X</td>
<td>394.40</td>
<td>( 1.1 \times 10^6 )</td>
</tr>
<tr>
<td>Fe XII</td>
<td>364.47</td>
<td>( 1.6 \times 10^6 )</td>
</tr>
<tr>
<td>Fe XIV</td>
<td>334.17</td>
<td>( 1.8 \times 10^6 )</td>
</tr>
<tr>
<td>Fe XVI</td>
<td>360.75</td>
<td>( 2.2 \times 10^6 )</td>
</tr>
</tbody>
</table>

3.2. Thermal stratification in the PFL system

It follows from the way the CDS rasters are built that the eight images with the loop-like structures in Figure 3 are exactly cospatial. When the positions of
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Figure 3. Part of the CDS raster with the PFL system in eight chosen lines spanning the temperature range from $2 \times 10^4$ K to $2.2 \times 10^6$ K (image in negative). The times on the $x$-axes correspond to the positions of the CDS slit in the raster. The time goes from right to left because the CDS slit scans from $W$ to $E$ and is oriented in N-S direction.

the tops of the semi-loops taken in different lines are compared, it is apparent that those in the images which are taken in lines having higher formation temperature lay above those formed at lower temperatures. On the other hand, the structures visible in different lines are not spatially separated, but they are overlapping, which is demonstrated in Figure 4. This temperature stratification can be either real, as it is assumed in theoretical models of PFL (Kopp & Pneumann 1976, Forbes & Malherbe 1986, etc.), or mimicked by the combined effect of cooling and scanning the loop system with the CDS slit with a finite speed. When we compare the scanning speed of the CDS slit with the cooling rate obtained from the SXT measurements (see next section) it follows that the cooling of the hot plasma in the system is very slow (if at all). Also the theoretical estimates of PFL plasma cooling rate based on the method of Švestka 1987b do not show any fast cooling in the temperature region above $\pm 1$ MK. So we believe that at least in the lines with formation temperature above 1 MK we are observing a real temperature stratification with height, as a 'snapshot' of the PFL system evolution.

To get other information on the temperature distribution of hot plasma in the PFL system we used a temperature sensitive line pair of Fe XVI at 360.8 Å and Si XII at 520.7 Å. The ratios of Fe XVI and Si XII lines were determined in 13 pixels along the axis $x$ from pixel numbers 22 – 34 (see Figure 5). To improve the $S/N$ ratio the signal was integrated from 6 pixels along the $y$ axis from pixels 52 – 57. The intensities of both spectral lines were obtained by fitting Gaussians into the observed spectra. The error bars correspond to $3\sigma$ probability of the line fits and they do not contain any uncertainties in values of theoretically calculated emissivities. Their very variable length is given by the theoretical dependence of the temperature on the emissivities ratio. The emissivities were calculated using ADAS (Summers et al. 1996). The uncertainties in relative abundance of iron to silicon and the possible systematic error in the CDS calibration prevented us from calibrating the temperature scale using only theoretical data and we had to use another method based on our knowledge of the temperature obtained from SXT data. Therefore, we assumed that the maximum temperature of plasma in the PFL system, measured using the line ratio, corresponds to the plasma temperature measured by SXT at the same time. Of course, the temperatures obtained from SXT can be influenced by a significant systematic error, but when we are interested in the general structure of temperature distribution in the system rather than in single values of the temperature, we believe that this method can be justified. The results of this analysis are presented in Figure 5, where the intensity profile of the Fe XVI loop was also plotted. It is clearly visible that the temperature tends to grow with height up to its maximum, which is placed above the Fe XVI loop. Plasma with lower density is probably located here. This distribution of temperature in the PFL system is in full agreement with the classical formation theory of PFL systems. The course of temperature under the Fe XVI loop reflects the temperature of rare hot coronal plasma surrounding the PFL system rather then the temperature of plasma located in the loops visible in lines having lower formation temperatures.

3.3. Signs of rapid plasma cooling

When the shapes of the semi-loop structures in hot and cool lines are compared it is apparent that they are much smoother in the hot lines while in the cool lines there are some irregularities in their shapes (see Figure 3 structures in the dotted boxes). If we admit that there is a real plasma temperature stratification with height in the observed PFL system, so that hot plasma is above the structures visible in lines O V,
O III and He I, we can easily interpret these irregularities as signs of rapid cooling of PFL plasma visible in the cool lines. We will explain only the origin of the most prominent irregularity in the shape of O V loop (inside the dotted box in Figure 3). It is clearly not a part of the O V loop, so it has to be a result of the time evolution of the PFL system. If there is a real temperature stratification with height in the observed PFL system, then when the CDS slit was pointed above the O V very bright loop top (at 13:20 UT), there was plasma with a temperature higher than that corresponding to the formation of the O V line. This is why this stripe, in Figure 3 (negative), is relatively light. But after CDS had finished taking the spectrum of this light stripe, the image of the Sun on the slit moved one step eastwards (to the left in Figure 3) to the position where the top of the O V loop starts to be seen, but also the irregularity in the loop shape. After one more scanning step of CDS the irregularity protruding from the loop becomes very prominent. This can be explained by the existence of plasma with a higher temperature than when it corresponds to the formation temperature of O V line, which lays above the O V loop and managed to cool down to reach the formation temperature of the O V line in one or two CDS scanning steps and became visible. Because the time necessary for the completion of one N - S stripe exposure is approximately only one minute we can interpret these irregularities as signs of very rapid, probably radiative plasma cooling. Similar features indicating rapid cooling are apparent also in all other available cool lines (O III, He I). Since in hotter lines no similar features are seen, we believe that the plasma visible in these lines cools much more slowly compared to the CDS scanning speed.

4. ANALYSIS OF THE SXT DATA

The SXT data and filter ratio method were used to derive the time evolution of mean temperature and emission measure during the decay of the loop system. The intensity, in each filter (A11, AlMg), was integrated from an area of 189 pixels which lay inside an intensity contour 39% above the background containing the whole loop (see Figure 6). The general behaviour of the mean plasma temperature and emission measure is almost independent of the chosen area of the loop system where the intensity was integrated from.

The time evolution of the mean plasma temperature in the loop (upper graph in Figure 6) looks rather complicated. At the beginning of the observational sequence, from 13:07:28 UT to 13:17:04 UT, a manifestation of slow plasma cooling from the initial temperature 2.8 MK down to 2.5 MK in approximately 600 s can be seen. Then the temperature behaves rather chaotically. We believe that this could be accounted for by the influence of hot rare coronal plasma surrounding the PFL system, the existence of which we mentioned in the previous section and whose influence on the measured plasma temperature grows with the decrease of the emission measure in the PFL system. That means, that plasma inside the
PFL could continue cooling even after 13:17:04 UT because the values of the temperature later on are probably very strongly influenced by the other hot coronal plasma along the line of sight (see Figure 2).

The behaviour of the total emission measure along the line of sight averaged over the area of the whole loop \( < EM_{\text{tot}} > \), presented in the lower graph of Figure 6, looks much simpler. It decreases very quickly (in approximately \( 10^5 \) s) from its original value \( (9.2 \pm 0.3) \times 10^{28} \, \text{cm}^{-3} \) at 13:07:28 UT to its final value \( (2.2 \pm 0.2) \times 10^{28} \, \text{cm}^{-3} \) at 13:23:28 UT. Because such a rapid decrease of \( < EM_{\text{tot}} > \) can be explained only by plasma depletion from the PFL (see also Figure 2), we can expect a strong downflow of hot plasma from the loop to its footpoints along the magnetic field lines. Later on, the behaviour of \( < EM_{\text{tot}} > \) becomes slightly chaotic again, which we believe can be accounted for by rare hot coronal plasma along the line of sight.

From the SXI images and CDS rasters (Figures 2, 3) we determined the apparent diameter of the loop system in the plane perpendicular to the line of sight \( D_{\text{app}} = (4.0 \pm 0.7) \times 10^8 \, \text{cm} \). If we assume the size of the PFL system along the line of sight equals to \( D_{\text{app}} \) and all the plasma emitting along the line of sight is concentrated in the loop system, the maximum mean electron density is \( (1.5 \pm 0.2) \times 10^{10} \, \text{cm}^{-3} \) and the minimum one \( (7.0 \pm 1.0) \times 10^{9} \, \text{cm}^{-3} \). Using the quantities obtained above and the continuity equation, we estimated the velocity of plasma flow along the magnetic field at the base of the loop. If we suppose that the cross-sectional area along the loop is constant, we get, for a velocity of a symmetrical plasma outflow to both footpoints \( \sim 10 \, \text{km s}^{-1} \). Of course, if the cross-sectional area of the loop decreases towards those footpoints, the outflow velocity can be substantially greater. This rather low velocity contrasts with much stronger flows \( (v \sim 10^2 \, \text{km s}^{-1}) \) observed in cool Hz loops (Wiik et al. 1996). This could be explained by quite different pressure scale–heights in these two cases.

5. CDS ELECTRON DENSITY AND EMISSION MEASURE DIAGNOSIS

The CDS data was used to determine the electron density of the hot part of the PFL system, using the density sensitive line pair of Fe XIV (334.2/353.8) (Mason et al. 1997). The theoretical dependence of the electron density on the intensity ratio was calculated using CHIANTI (Dere et al. 1997).

The electron densities were determined in 13 different positions along the axis \( x \) across the loop top, in pixel numbers 22 – 34 (see the raster in Figure 5). To improve the S/N ratio the intensity was integrated from 6 pixels along the \( y \) axis from pixels 32 – 57. The intensities of both spectral lines were obtained by fitting Gaussians into the observed spectra. The error bars correspond to 3\( \sigma \) probability of the line fits. No uncertainties are included in the theoretical dependence of electron density on the intensity ratio. The course of the electron density across the loop top is shown in the left panel of Figure 7.

6. GEOMETRICAL FILLING FACTOR

The results obtained above were used to estimate the geometrical filling factor of the examined PFL system in the Fe XIV line. If we assume an isothermal plasma e.g. filamentary distributed with a typical electron density in the filaments \( n_e \), we can rewrite the formula for emission measure in this way:

\[
EM = n_e^2 D_{\text{real}} = < n_e^2 > D_{\text{app}}
\]

where

\[
D_{\text{real}} = \int_{\text{rad}} dl
\]

In this integral we calculate the total thickness of the radiating elements along the line of sight. Using these quantities we can define the geometrical filling factor as

\[
f \equiv \frac{D_{\text{real}}}{D_{\text{app}}} = \frac{< n_e^2 >}{n_e^2}
\]
Table 2. The geometrical filling factor at the top of the loop system determined using the Fe XIV 334.2 and Fe XIV 333.8 lines.

<table>
<thead>
<tr>
<th>z-pixel</th>
<th>$n_e^2 \times 10^{-19}$ cm$^{-6}$</th>
<th>$&lt; n_e^2 &gt; \times 10^{-18}$ f</th>
</tr>
</thead>
<tbody>
<tr>
<td>26</td>
<td>5.25$^{+4.21}_{-2.76}$</td>
<td>4.3 $^{+2.4}_{-2.8}$</td>
</tr>
<tr>
<td>27</td>
<td>9.81$^{+8.87}_{-5.97}$</td>
<td>5.3 $^{+2.8}_{-3.2}$</td>
</tr>
<tr>
<td>28</td>
<td>8.56$^{+6.42}_{-3.76}$</td>
<td>6.1 $^{+3.2}_{-3.5}$</td>
</tr>
<tr>
<td>29</td>
<td>7.21$^{+5.21}_{-3.76}$</td>
<td>6.6 $^{+3.5}_{-3.5}$</td>
</tr>
<tr>
<td>30</td>
<td>5.45$^{+4.58}_{-2.58}$</td>
<td>5.9 $^{+3.2}_{-3.5}$</td>
</tr>
</tbody>
</table>

Because the electron density derived from the density sensitive line pair Fe XIV (335.8/334.2) reflects the collisional rate in plasma, so that it measures the real electron density in radiating elements, we assigned its value to $n_e$ in Eq. 4. On the other hand, from the integrated intensities of allowed lines we can get the emission measure in given line along the line of sight. When we want the value of $< n_e^2 >$ we have to divide EM by the apparent area of the system along the line of sight, which we assume to be equal to $D_{app}$. The quantities $n_e^2$ and $< n_e^2 >$ are identical in the case of homogeneous distribution of plasma along the line of sight. In this case the filling factor would be equal to one. If plasma is not distributed uniformly, the electron density obtained from line ratio is greater than the density obtained from the emission measure and the filling factor is less than one.

Using this method we determined the filling factor in pixels 26 - 30 (z axis) which correspond to the brightest parts of the Fe XIV loop-like structure. The uncertainties in $n_e$ and $< n_e^2 >$ obtained in previous subsections were used to calculate the uncertainty of the geometrical filling factor. The results are summarized in Table 2. Our measurements showed that the geometrical filling factor at the top of the examined PFL system in Fe XIV line (formation temperature $\approx 1.8$ MK) lies somewhere in the interval from 0.01 to 0.2. The great range of its possible values reflects the realistic uncertainties in our knowledge of elemental abundance, integrated intensities, etc.

CONCLUSIONS

In this paper we used CDS and SXT data taken simultaneously to examine a decaying PFL system resulting from a small flare GOES class C2.9. To our knowledge, this is the first detailed analysis of a PFL system observed by CDS.

Using the CDS rasters taken in lines with different formation temperatures and a temperature sensitive line pair of Fe XVI at 360.8 Å and Si XIX at 520.7 Å we confirmed that in the examined PFL system plasma with higher temperature tends to lie over plasma with lower temperature, as it is expected by the PFL formation theory and which was earlier observed by Cheng (1980), Švestka et al. (1987a), etc.

From the SXT temperature and emission measure analysis we obtained that the main role during the decay of the hot part of the loop system was played by a fast plasma outflow from the system. The velocity of the hot plasma ($T \approx 2.5$ MK) at the footpoints was estimated to be approximately 10 km s$^{-1}$, for a uniform cross-sectional area along the loop. In the more realistic case when the area decreases towards the footpoints the velocity can be several times greater, so it could be measurable by CDS. From the CDS data also follows that the rapid outflow of plasma from the system, responsible for its decay, started in all lines at approximately the same moment.

The density sensitive line pair of Fe XIV (334.2/335.8) (formation temperature 1.8 MK) was used to estimate the geometrical filling factor at the top of the loop system. We obtained a broad interval of possible values from 0.01 to 0.2. The great dispersion of possible values of the filling factor reflects the realistic errors of all quantities which influence it.

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