POST-FLARE LOOPS OF 26 JUNE 1992

II. Gradual Evolution of Cool and Hot Loops

B. SCHMIEDER
Observatoire de Paris, Section de Meudon, 92195 Meudon Principal Cedex, France

P. HEINZEL
Observatoire de Paris, Section de Meudon, 92195 Meudon Principal Cedex, France; and
Astronomical Institute, 25165 Ondřejov, Czech Republic

L. VAN DRIEL-GESZTELYI
Observatoire de Paris, Section de Meudon, 92195 Meudon Principal Cedex, France

and

J. R. LEMEN
Lockheed Palo Alto Research Laboratory, Palo Alto, CA 94304, U.S.A.

(Received 21 July, 1995)

Abstract. We observed the large post-flare loop system, which developed after the X 3.9 flare of 25 June 1992 at 20:11 UT, in Hα with the Multichannel Subtractive Double Pass Spectrograph at Pic-du-Midi and in X-rays with the yt Yohkoh/SXT instrument. Following the long-term development of cool and hot plasmas, we have determined the emission measure of the cool plasma and, for the first time, the temporal evolution of the hot-loop emission measure and temperature during the entire gradual phase. Thus, it was possible to infer the temporal variation of electron densities, leading to estimates of cooling times. A gradual decrease of the hot-loop emission measure was observed, from $4 \times 10^{30}$ cm$^{-5}$ at 23:00 UT on 25 June 1992 to $3 \times 10^{28}$ cm$^{-5}$ at 13:10 UT on 26 June 1992. During the same period, the temperature decreased only slowly from 7.2 to $6 \times 10^6$ K. Using recent results of NLTE modeling of prominence-like plasmas, we also derive the emission measure of cool Hα loops and discuss their temperature and ionisation degree. During two hours of Hα observations (11–13 hours after the flare) the averaged emission measure does not show any significant change, though the amount of visible cool material decreases and the volume of the loops increases. The emission measure in Hα, after correction for the Doppler-brightening effect, is slightly lower than in soft X-rays. Since the hot plasma seems to be more spatially extended, we arrive at electron densities in the range $n_e^{\text{hot}} \leq n_e^{\text{cool}} \sim 2 \times 10^{10}$ cm$^{-3}$ at the time of the Hα observations.

These results are consistent with the post-flare loop model proposed by Forbes, Malherbe, and Priest (1989). The observed slow decrease of the emission measure could be due to an increase of the volume of the loops and a gradual decrease of the chromospheric ablation driven by the reconnection, which seems to remain effective continuously for more than 16 hours. The cooling time for hot loops to cool down to $10^6$ K and to appear in Hα would be only a few minutes at the beginning of the gradual phase but could be as long as 2 hours at the end, several hours later.

1. Introduction

Complex systems of post-flare loops appear frequently as a development of large, two-ribbon eruptive flares (Bray et al., 1991; Švestka and Cliver, 1992; Schmieder, 1992). The loops develop slowly during the gradual phase of the flare and can persist for hours. Many papers have been devoted to the analysis of post-flare

loops at particular stages of their evolution. Physical parameters like temperature, density, pressure, and velocity field have been derived at specific moments during the lifetime of different flares (Švestka et al., 1987; Bray et al., 1991; Heinzel, Schmieder and Mein, 1992).

Post-flare loop systems have been explained by models of reconnection of magnetic field lines in the high corona with an X-point where plasma is strongly heated. Many observations indeed directly support this model (e.g., Tsuneta et al., 1992).

Such reconnection model, where magnetic field lines are attached to the photosphere and extend into the corona, continuously reconnecting to form magnetic loops, has been proposed first by Sturrock (1968) and later by Kopp and Pneuman (1976). Later, Forbes and Malherbe (1986) studied a complete MHD reconnection model based on this configuration, explaining the replenishment of the loop by chromospheric ablation. Forbes, Malherbe, and Priest (1989) deduced the scaling laws for thermal conduction and radiative cooling of the model and evaluated the relationship between the parameters of the hot and the cool plasmas. Other mechanisms, considered to explain the presence of material in the X-ray loops are waves or a siphon mechanism (Forbes, Acton, and Tsuneta, 1995).

Recently, Schmieder et al. (1995 (Paper I), 1996) studied the relationship between hot X-ray ($T \approx 6 \times 10^6$ K) and cool Hα ($T \approx 10^4$ K) post-flare loops observed on June 26, 1992, using about 40 min long data set of Yohkoh/SXT and one MSDP (Pic-du-Midi) image obtained during this time.

However, there is still a lack of knowledge of the long-term evolution of such loop systems, covering the entire gradual phase, from the impulsive phase of the flare until the time when the loops are fading and becoming invisible. In this paper, we analyse the gradual phase of this large flare from 14 hours in X-rays (Yohkoh/SXT) and 2½ hours in Hα (MSDP) observations in order to study the long-term behaviour of this post-flare loop system on June 25–26, 1992. We derive the emission measure and temperature evolution in both hot and cool loops. Finally, we discuss the electron density values and related cooling times necessary for $\sim 10^7$ K loops to cool down to $10^4$ K.

2. Observations

AR 7205 had a delta-spot and was the seat of recurrent large flares of X and M class (Table I). In addition, many small flares were observed by GOES and ground-based instruments. Note, however, that those occurring during the long gradual phase of the 20:11 UT flare are not well observed by the SXT because their maxima occurred mainly during the satellite night (see Table I and Figure 1).

A large system of post-flare loops developed close to the west limb on June 25 and 26, 1992 in AR 7205 located at N09 W67, after the X 3.9 class flare on June
TABLE I
List of flares occurring in AR 7205 as detected by GOES on June 25–26, 1992. SFP: flare visible close to the southern footpoint of the loops; NFP: northern footpoint; GBO: ground-based Hα observations

<table>
<thead>
<tr>
<th>Date</th>
<th>UT</th>
<th>Class</th>
<th>SXT observations</th>
<th>GBO</th>
</tr>
</thead>
<tbody>
<tr>
<td>June 25</td>
<td>05:15</td>
<td>C 5.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>06:27</td>
<td>M 1.0</td>
<td>yes</td>
<td>Pic-du-Midi</td>
</tr>
<tr>
<td></td>
<td>14:12</td>
<td>C 7.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>16:23</td>
<td>C 1.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>17:55</td>
<td>M 1.4</td>
<td>yes</td>
<td>Big Bear</td>
</tr>
<tr>
<td></td>
<td>20:11</td>
<td>X 3.9</td>
<td></td>
<td>Hida, Mees</td>
</tr>
<tr>
<td>June 26</td>
<td>04:10</td>
<td>M 1.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>05:20</td>
<td>C 2.5</td>
<td>SFP</td>
<td></td>
</tr>
<tr>
<td></td>
<td>07:00</td>
<td>C 3.4</td>
<td>9 min after the flare: SFP</td>
<td>Pic-du-Midi</td>
</tr>
<tr>
<td></td>
<td>08:00</td>
<td>C 1.8</td>
<td>10 min after the flare: NFP</td>
<td>Pic-du-Midi, La Palma</td>
</tr>
<tr>
<td></td>
<td>12:54</td>
<td>C 2.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>13:04</td>
<td>C 1.8</td>
<td>SFP</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 1. Time evolution of the soft X-ray emission detected by the GOES satellite.

25 at 20:11 UT. The minor flares occurring in AR 7205 during the gradual phase of the big flare did not perturb the arcade of post-flare loops.

This loop system persisted for more than 16 hours after the X-flare and was followed by Yohkoh/SXT (Anwar et al., 1994). The available SXT data began more than two hours after the X-flare maximum, during the decay phase of the flare, at
TABLE II
List of observation times with Yohkoh/SXT

<table>
<thead>
<tr>
<th>Orbit</th>
<th>Time UT</th>
<th>Number of images</th>
<th>Mode of observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>spr920625</td>
<td>22:57:51–23:06:23</td>
<td>130</td>
<td>FLARE mode (loop top only)</td>
</tr>
<tr>
<td></td>
<td>23:56:57–00:41:57</td>
<td>148</td>
<td>loops + limb</td>
</tr>
<tr>
<td></td>
<td>01:51:05–02:26:57</td>
<td>60</td>
<td>loops + AR</td>
</tr>
<tr>
<td>spr920626</td>
<td>03:12:35–04:04:17</td>
<td>64</td>
<td>loops + AR</td>
</tr>
<tr>
<td></td>
<td>04:54:00–05:28:07</td>
<td>64</td>
<td>loops + AR</td>
</tr>
<tr>
<td></td>
<td>06:32:13–07:13:47</td>
<td>64</td>
<td>FLARE mode 06:52–07:09 (top only)</td>
</tr>
<tr>
<td></td>
<td>08:11:55–08:54:05</td>
<td>64</td>
<td>loops + AR</td>
</tr>
<tr>
<td></td>
<td>10:27:55–10:30:35</td>
<td>12</td>
<td>loops + AR</td>
</tr>
<tr>
<td></td>
<td>13:03:19–13:18:15</td>
<td>74</td>
<td>loops + AR</td>
</tr>
<tr>
<td></td>
<td>15:09</td>
<td></td>
<td>loop top out of the field of view</td>
</tr>
</tbody>
</table>

22:57 UT on June 25, and lasted until 13:18 UT on June 26 (Table II). After that, the tops of the X-ray loops expanded out of the SXT observing field of view.

The system of loops was well observed during a ground-based campaign coordinated with Yohkoh/SXT. In this paper we use the observations obtained at Pic-du-Midi observatory with the Multichannel Subtractive Double Pass Spectrograph (MSDP), complemented by Hα images obtained at Valašské Meziříčí (Czech Republic) with a coronagraph.

Through coalignment of MSDP and SXT observations it was shown in Paper I that the cool loops were located just below the hot loops. Using Hα observations from Wrocław taken between 07:35 and 10:46 UT, an ascending apparent velocity of the Hα loops around 1 km s⁻¹ was derived, equivalent to that of the hot SXT loops. The Valašské Meziříčí images presented here provide us with a longer set of Hα data allowing us to follow the development of cool loops. The Hα loops are still visible in the last picture at 14:29:15 UT, but they are very faint (Figure 2). A more extensive study of the altitudes is in progress to derive the variation of the ascending velocity versus time.

2.1. INSTRUMENTS

2.1.1. Yohkoh SXT Instrument
The Soft X-ray Telescope (SXT) on board the Yohkoh satellite obtains X-ray images using thin Al 0.1 μm and thick Al 12 μm filters, together with a Be 119 μm filter during flare mode (Tsuneta et al., 1991). The sensitivity of the filters allows observations of material in a log temperature range between 6 to 7 with an accuracy
of 0.1 (Hara et al., 1992). The June 25–26, 1992 data were obtained in the full resolution mode (pixel size = 2.46 arc sec), with 64 × 64 and 128 × 128 pixels field of view in FLARE mode and in QUIET mode, respectively, with the temporal resolution of 2 s and 32 s, respectively. The orbits and their characteristics are presented in Table II and some partial-frame images are displayed in Figure 3. White-light pictures were obtained with the SXT aspect camera with the narrowband filter (Figure 4), which were used for co-alignment (Paper I).

The Yohkoh spacecraft orbits the Earth approximately 15 times per 24-hour period. The daylight portion of each orbit lasts about one hour but the on-board memory can only store 40 min of data when the spacecraft is operated in high-rate telemetry mode.
23:03:55 UT

00:21:57 UT

01:26 UT

08:04 UT

11:11 UT

12:48 UT

Evolution of post-flare loops on June 26, 1992

Fig. 3. The SXT loops obtained by summing up several images for 6 orbits. The time indicates the beginning of the orbit or, for the two first, the mean time of the chosen images. North is left, west is up. The box represents the field of view of the images at 21:03:55 UT and 00:21:57 UT.

2.1.2. MSDP Instrument

The Multichannel Subtractive Double Pass Spectrograph (MSDP) used for these coordinated observations was operating at the Tourelle telescope on Pic-du-Midi. Three sets of observations are available, each lasting for a few minutes. The MSDP
provides 11 different wavelength channels of the same 2-D area, an elementary field of view of the Sun (Mein, 1991, and Paper I).

The data allow us to reconstruct, by interpolation, the H$_\alpha$ line profile for each pixel when the line is visible in more than 3 channels. The standard processing method uses the wavelength shift between the centers of two $\Delta \lambda$ chords (0.6 Å and 0.9 Å) in the active profiles and in the reference profiles to determine the Doppler shifts, and the relative depths of the chords to determine the relative intensities $\Delta I$ for each pixel. Maps of the maximum intensity and the intensity in the wings, obtained by joining 4 to 5 elementary fields of view (124 $\times$ 900 pixels of 0.25$''$ each), were displayed in Paper I (and are also shown for three different observing times in Wiik et al. (1996, Paper III)). The spatial resolution of the images is of the order of 0.5 arc sec.

2.1.3. **Valašské Meziříčí Coronagraph**
This is a 150 mm coronagraph with a 5 Å passband H$_\alpha$ filter (Figure 2).

2.2. **MORPHOLOGY OF THE HOT LOOPS**

For the first time, we have observed X-ray post-flare loops for a period lasting more than 14 hours (Figure 3). Figure 3 shows SXT images that were obtained by summing several images in order to decrease the noise. The loops seem to be nearly perpendicular to the solar surface (Wiik et al., 1994 and Paper III). During
the first orbit we see 3 distinct loops which seemingly intersect in two bright areas near their tops (Figure 3 at 23:03:55 UT). The southern area stays brighter than the other (northern) bright region during the observing period. At 01:26 UT we can distinguish the arcade and the loops are tied along flare ribbons which appeared like bright X-ray elongated areas (Figure 3). The system of loops was visible until about 15:00 UT in Hα and in X-rays. At their feet, various other loops developed continuously (Figure 3 at 08:04 UT), related to minor flares occurring in the same active region (Table I). One of the secondary loops is nearly horizontal and looks very twisted. None of them seemed to affect the gradual evolution of the post-flare loop system, though.

The inner edges of the loops are sharper than their outer edges, which stay diffuse. This indicates that the outer loops are hotter. The SXT filters have a sharp cut-off for the low temperatures, therefore when the loops become cooler than about 1.5 MK, they disappear from the SXT images (Tsuneta et al., 1991, 1992). Such an explanation is consistent with a continuous formation of newly reconnected hot loops at a growing altitude and a cooling of hot loops to become cool loops eventually.

2.2.1. **Comparison with Hα Loops**

In our MSDP images and in the La Palma Hα images (Tarbell, private communication), with a spatial resolution around 0.5 arc sec or even better, we see several thin Hα loops with a typical apparent thickness, $D$, of about 2000 km; the loops are well separated by distances greater than $D$. Since $D \approx 2000$ km corresponds roughly to the resolution of SXT, we could expect to see many hot loops. However, we see only a few rather compact loops, which seem thicker than the Hα ones. This is a common characteristics of the hot loops, which seem to be wider and more diffuse (Hirayama, private communication; Takeda et al., 1994). Thinner Hα loops could be explained by a stochastic (‘fragmented’) cooling in certain elementary flux tubes, while other tubes nearby or along the line-of-sight still contain hotter plasma. Also the plasma along the individual cool loops is highly fragmented. A similar fragmentation of hot loops was not observed, though it was predicted theoretically by Tang, Fang, and Cui (1995).

3. **Data Reduction Methods of the X-Ray Observations**

During each Yohkoh orbit the partial frame images were co-aligned and organized to form two parallel data cubes $(x, y, t)$, ($t$ being the time), of the Al 0.1 and Al 12 filters. Using SXT-prep Yohkoh software, CCD dark current has been subtracted, saturated pixels were flagged, uncertainty of the decompression was computed, exposure normalisation was carried out and images with missing strips were excluded. It was not necessary to carry out an interpolation of time between the image pairs of the parallel data cubes taken with the two different filters, since
the changes both in temperature and emission measure are slow compared to the few seconds time difference between the data pairs. The number of images used is indicated in Table II. To compute temperature, $T$, and emission measure, $EM$, as a function of time we used the Yohkoh software GO – TEEM. The ratio of the signals of the two Al filters is sensitive in the temperature range $\log T$ between 6 and 7 assuming isothermality within a pixel (Hara et al., 1992). The Be filter provides a diagnostics of higher temperature plasmas ($\log T > 6.5$). The pixels where the analysis was done were selected by choosing the choosing mode applied on the third image of the data cube, which defines the threshold of intensities $DN$ (Data Number) that is considered. $DN$ represents the digital camera output. One $DN$ corresponds to 100 electrons and to an energy of $5.8 \times 10^{-10}$ erg at the SXT focal plane (Tsuneta et al., 1991). In all orbits we use the same sub-image regions that were defined by the intensity contours, in order to achieve a good normalisation between individual results for different orbits. The different regions contain 10, 20, 110, 215, or 450 pixels. For each orbit we compute volume emission measure $EM(t)$, temperature $T(t)$, and data number $DN$ in the selected areas using the filter ratio method. After normalisation by the areas we obtain $EM$ in $\text{cm}^{-3}$ per pixel, and $T$ (Figure 5). Both the emission measure and the electron temperature decrease slightly during one orbit. Since the contour is selected by using the third image of the orbit and kept at the same place, and the loops are growing, the decrease of $EM$ may be due to the gradual shift of the brightest point out of the contour in the third image by the end of the sequence. This effect is more important for the smaller areas. The mean velocity of the apparent rise of the loops was estimated to be about 1 km s$^{-1}$ (Paper I), and in 40 min (the mean duration of one orbit’s observations) this corresponds to a rise of 2400 km, which, together with the effect of solar rotation, mounts to a shift of nearly 2 pixels, which is close to the size of the smallest contour area (10 pixels $\sim 3 \times 3$).

To focus on the large-scale variation we divided each orbit into 5 time-intervals and computed the time-averaged $EM$ and $T$ for each contour area. Figure 5(f) shows that for smaller contour areas, the values of the measured $EM$ and $T$ are closer to their maximum value. It is apparent from Figure 6 that the dispersion of the values is larger for the first orbits, closer to the time of the flare when the brightness gradient in the loop is higher. Generally the asymptotic maximum value of the emission measure, corresponding to the brightest 10 pixels, is twice the $EM$ computed over an area of 215 pixels. This is consistent with the idea that the brightest points are due to the superposition of two loops along the line of sight, but it is difficult to define a realistic filling factor.

The 1$\sigma$ errors of $EM(DEM)$ and $T(DT)$ are very small ($\leq 10^{-4}EM$ and $\leq 2 \times 10^{-4}T$, respectively), meaning that the gradients are small and both $EM$ and $T$ change slowly.

During one orbit over a period of about 40 min the temperature decreases slightly by about 5%. Since the contour where we measure the temperature is kept at the same height during the entire orbit, therefore like this we follow the cooling
26 June 1992

Fig. 5. For one orbit between 03:15 UT to 04:05 UT on June 26, 1992: (a) $EM$, (b) $T$ in an area of 22 pixels ($2.46 \times 2.46$ arc sec). (c) and (d) $DN$ intensity for areas of 22 pixels, (c) with Al 0.1 filter, (d) with Al 12 filter, (e) variation of normalized $EM$ versus time for given threshold of intensity defining number of pixels, (f) variation of averaged over time $EM$ versus the size of the area for 3 times.

of a specific loop. The measured temperature decrease is not enough for loops to cool to H$\alpha$ temperatures $10^4$ K, which is in apparent contradiction with the former coalignment and cooling time analysis of hot and cool loops (see Paper I), where the cooling time was found to be about 40 min. The following interpretations can be suggested: (i) the cooling time is much longer than we found in Paper I, (ii) the effect is due to insufficient spatial resolution which mixes different areas, and
Fig. 6. General evolution of the emission measure of hot loops: (a) at the top (in cm\(^{-3}\) pixel\(^{-1}\)), (b) the same in units of cm\(^{-5}\). T indicates the values computed by Tomczak, H by Hara. The two full triangles indicate the \(EM\) computed for H\(\alpha\). The arrows indicate the MSDP observation times. (c) Variation of the temperature at the top, (d) variation of \(EM\) in the ribbons for 3 areas.
(iii) even if the cooling time is correct, we see either other hot loops or hot sheets around cool loops along the line-of-sight.
3.1. \textit{EM} AND \textit{T} DURING 10 ORBITS

The long-term behaviour of the \textit{EM} is a decreasing exponential-like function of
time, from $\log \text{EM} \simeq 47.0-46.7$ on June 25, 1992 at 23 UT to $45.0-44.8$ on
June 26, 1992 at 13 UT (\textit{EM} itself is in units of cm$^{-3}$ pixel$^{-1}$). Therefore,\n\textit{EM} decreases by two orders of magnitude within 14 hours (Figure 6(a)). These
values are in good agreement with the previous \textit{EM} analysis made by Tomczak
(1994) for two orbits starting at 22:11 and 23:49 UT, and by Hara (1994, private
communication) at 06:42 UT. Dividing this \textit{EM} by the pixel area of $2.46 \times$
2.46 arc sec$^2$, we obtain \textit{EM} in units cm$^{-5}$ (Figure 6(b)). This will be compared
with \textit{EM} of cool loops. The temperature of the loop top decreases slowly from 7.2
to $6.0 \times 10^6$ K during the 14 hours of SXT observations.

3.2. \textit{EM} OF THE X-RAY FOOTPOINTS

We have made the same study over the region on the disk containing the X-ray
footpoints of the loops which correspond roughly to the H$\alpha$ flare ribbons. The
curves show several enhancements which we interpret as small flares occurring in
the active region during the gradual phase of X 3.9 flare (see Table I and Figure 1).
Corresponding to these subflares, we detected X-ray emissions in the vicinity of the
footpoints of the growing post-flare loops (NFP and SFP in Table I and Figure 7).
Lower X-ray loops were visible from time to time corresponding to these flares.
The most important secondary activity started at 07:00 UT and resulted in a new
system of post-flare loops growing around the northern leg of the big post-flare loop
system.

During the subflares we did not detect changes in \textit{EM} or \textit{T} at the top of big
post-flare loops, and thus, they seemed to be uncoupled loop systems. Apart from
some flaring, the emission measure of the footpoints is relatively stable (around
$2.5 \times 10^{45}$ cm$^{-3}$).

4. Emission Measure in Cool H$\alpha$ Loops

4.1. MSDP LOOPS

We extended the study of the emission measure derived from the H$\alpha$ line (see
Paper I) to all data available from MSDP. We have three sets of MSDP observations
at 07:08 UT, 08:33 UT and at 09:37 UT. In Paper I, we derived the emission measure
of the cool plasma by using the integrated intensity of H$\alpha$ observed in dense knots
near the top of the loops (at 07:08 UT).

Comparing the observations at 07:08 UT and at 09:37 UT, we see that the
individual knots are brighter at 09:37 UT, but we also remark that at 07:08 UT
the whole loop system is more filled-up by the material than later. We have made
a quantitative analysis of these data. Selecting the pixels where profiles can be
Fig. 7. Time evolution of the signal $I(N)$ in Al O.1 filter of sub-flares in the AR measured close to the footpoints of the loops corresponding to the secondary maxima of GOES on 26 June 1992 (Table I): (a) 05:20 UT, (b) 07:00 UT, (c) after 08:00 UT, (d) 13:04 UT.
derived with more than 3 points, we have considered the maximum intensity of the Hα profiles. At 07:08 UT, 10,388 points are taken into account and at 09:37 UT only 5,893 points, which globally reflects the lower amount of visible cold material at 09:37 UT than at 07:08 UT.

4.2. Method of Computation of $EM$ from Hα Data

The basic method for deriving the emission measure $EM$ in cool loops was described in Paper I, where an $EM$ of about $10^{29}$ cm$^{-5}$ was obtained for bright parts of the loop top using the correlation between the Hα integrated intensity $E$ and $EM$, determined by Gouttebroze, Heinz, and Vial (1993) and Heinz, Gouttebroze, and Vial (1994). In the present paper we will use a similar approach to get much better statistics on $EM$ and to derive its temporal behaviour, which can be compared to that of the $EM$ in hot SXT loops. For purely technical reasons, we use here the maximum Hα intensity $I_c$ instead of $E$, which gives similar results. The correlation between $I_c$ and $EM = n_e^2D$ (where $n_e$ is the mean electron density, and $D$ the geometrical thickness) was obtained in the same way as that for $E$ and is shown in Figure 8. Again, we see a weak dependence on the kinetic temperature. This correlation is also almost independent on the height of the structure in the corona. However, to be more precise, we have to take into account certain variation with temperature, which is closely linked to the ionization of hydrogen. The ionization degree of hydrogen versus $T$ (Figure 9) was taken from Heinz, Gouttebroze, and Vial (1994). In Paper I we estimated the Hα Doppler width to be about 0.4 Å, which leads to $T \approx 15000$ K with the microturbulent velocity around 10 km s$^{-1}$. For this (or higher) temperature the hydrogen is almost fully ionized (Figure 9). For lower $T$, the $EM$ will be lower (Figure 8) and for such lower temperatures, the total hydrogen density can then be inferred from Figure 9, where $n_e$ is obtained from $EM$ analysis (see Section 4.4).

4.3. Doppler-Brightening Effect

As discussed in Paper I, we have to take into account the effect of Doppler brightening (DBE) when deriving the $EM$ from Hα line intensities. DBE leads to an emission-measure excess in the loop legs, where large downflow velocities of the order of 50–100 km s$^{-1}$ are observed (Papers I and III, Wiik et al., 1994). Since it is difficult to measure the actual flow velocity in each Hα pixel used for our $EM$ statistics, we have adopted the following scheme: for each pixel in Hα we specify the intensity $I_c$ and the distance from the loop top, and we then evaluate the free-fall velocity of the corresponding blob (assuming zero velocity at the top) at the upper part of the loop, using further the results of Wiik et al. (1994), considering the velocity at the lower part to be almost constant. To the vertical component of this flow velocity we ascribe the corresponding DBE factor, following Heinz and Rompolt (1987), see also Figures 10(a) and 10(c). Then the intensity $I_c$ is divided
by this brightening factor and converted to $EM$, using the correlation in Figure 8 for $T = 8000$ and 15 000 K. Strictly speaking, this procedure can be used provided the individual plasma blobs are not optically thick (this assumption is valid for most points in our statistics, however). In this case the DBE factor is similar or equal for both $E$ and $I_c$ and the results of Heinzel and Rompel (1987) can be applied.

4.4. $EM$ in Cool Loops

Using the above-mentioned method, $EM$ was derived for a large number of pixels and the results are shown in Figures 10(a) and 10(c). The mean value of $EM$ is seen not to vary too much over the height of the loops (contrary to the values not corrected for DBE). At the top of the loops we obtain $EM \sim 10^{29}$ cm$^{-5}$, as in Paper I. Along the legs the emission measure is of the order of $3-5 \times 10^{28}$ cm$^{-5}$. These values are similar at 07:08 UT and 09:37 UT, but the total emission measure will be lower at 09:37 UT if we take into account the number of pixels where the cool plasma is seen (see the abscissa of Figure 10). At $T = 8000$ K, the hydrogen plasma is only partially ionized and it can be shown, using Figure 10, that the total
Fig. 9. Correlation between total hydrogen $n_H$ and electron $n_e$ density for different temperatures (according to Heinzel, Gouttebroze, and Vial, 1994). The temperature symbols are the same as in Figure 8. The curves join the points where $D = 2000$ km.

hydrogen density is about the same or somewhat higher than the electron density derived assuming $T = 15000$ K. This implies that even when cooler ($T < 10^4$ K) loops exhibit a lower $EM$, the amount of material contained in them is comparable to that in hotter, fully ionized loops.

5. Electron Densities

To derive the mean electron densities from $EM$, we must estimate the line-of-sight geometrical thickness $D$ of the loops. Fortunately, an error of factor $\delta$ in $D$ only leads to an inaccuracy in $n_e$ of $\delta^{1/2}$ since $EM$ is proportional to $n_e^2$.

Note, that to distinguish between the physical parameters of cool and hot loops we label them with ‘cool’ and ‘hot’, respectively.

5.1. Cool Loops

The thickness of the cool loops, $D_{cool}$, does not exceed 2000 km, as derived from high-resolution images of MSDP and La Palma Hα observations (Tarbell, private communication; see also Wiik et al., 1995). The real $D_{cool}$ can be still lower,
Fig. 10. Variation of the $EM$, flow velocity, and DBE-factor along the loop. (a–b) At 07:08 UT, (c–d) at 09:37 UT. In the emission measure panel, the solid line corresponds to $T = 8000$ K, the dotted line to $T = 8000$ K with corrections to Doppler brightening, the dashed line is for $T = 15000$ K when the hydrogen is almost fully ionized.

however, due to unresolved fine structures. In fact, some blobs are very bright and it seems that those with an apparent $D_{\text{cool}} \approx 2000$ km are filled completely by plasma. On the other hand, it is sometimes difficult to resolve closely packed and
superposed loops — in such cases $D_{\text{cool}}$ will be higher. Such a complicated situation occurs particularly around the looptops, where we look along the ‘backbone’ of the loop arcade. This may explain the generally lower $EM$ measured in the legs. With a loop-top $EM_{\text{cool}}$ of $10^{29}$ cm$^{-5}$ and $D_{\text{cool}} = 2000$ km we obtain an electron density $n_e^{\text{cool}} = 2.2 \times 10^{10}$ cm$^{-3}$, like in Paper I. If the filling factor is less than 1, i.e., $D_{\text{cool}} = 500$ km, the density will be twice as high. Along the legs of cool
loops we expect densities similar to densities at the loop tops, but a $D_{\text{cool}}$ can be smaller due to a high degree of fragmentation and since we usually see individual loop legs, which are not superposed as it is the case near the loop top. Therefore, the mean $EM_{\text{cool}}$ will be lower along the legs, as we measured (Figure 10).

5.2. HOT LOOPS

To derive the electron densities in the hot loops, we use $EM_{\text{hot}}$ from Figure 6(b). In Paper I we introduced a ratio $\alpha$, as follows:

$$\alpha = \frac{n_{e,\text{hot}}}{n_{e,\text{cool}}}.$$  \hspace{1cm} (1)

Assuming $D_{\text{hot}} = D_{\text{cool}}$ and using the $EM$ derived in Paper I, we obtained $\alpha \approx 0.32$ indicating a lower density inside the hot loops. However, the $EM_{\text{hot}}$ used in Paper I was more uncertain than $EM_{\text{cool}}$ and we therefore could not exclude values of $\alpha \approx 1$ (see Section 6.2 of Paper I). In the present work we re-examined the values of $EM_{\text{hot}}$ using the GO–TEEM Yohkoh software; the results are shown in Figures 6(a) and 6(b). Note, that $\alpha$ depends also on the different filling factor of the hot and the cool material. The following discussion on the ratio of the thickness of hot and cool loops may depend on the ratio of their fragmentation. Furthermore, H\(\alpha\) loops are inhomogenous, the cool material is condensed into bubbles, while we have no indication of bubbles along hot X-ray loops.

To estimate $\alpha$, one should use $EM_{\text{hot}}$ at $t - \Delta t_c$ for a comparison with $EM_c$ at time $t$ (where $\Delta t_c$ corresponds to the cooling time). For $\Delta t_c \approx 2000$ s (Paper I), we obtain an only slightly higher $EM_{\text{hot}}$ at times of the H\(\alpha\) observations (see Figure 6(b), 10-pixels resolution).

In this paper with $EM_{\text{hot}} > EM_{\text{cool}}$ we would get $\alpha > 1$, assuming $D_{\text{hot}} = D_{\text{cool}}$ (Figure 6). More precisely we take the values $3 \times 10^{29}$ and $1.5 \times 10^{29}$ cm\(^{-5}\) pertinent to 07:08 UT and 09:37 UT, time of H\(\alpha\) observations, respectively. Keeping $\alpha \approx 1$, we arrive at $D_{\text{hot}} \approx 2D_{\text{cool}}$ for mean loop-top emission measures. This is consistent with our detailed analysis of SXT and H\(\alpha\) images. Indeed, the hot loops seem to be more extended than the cool loops, and the factor of two between $D_{\text{hot}}$ and $D_{\text{cool}}$ can therefore be considered a lower limit. This means that $\alpha$ can be lower than unity. Therefore, around 07:00—09:30 UT we estimate the electron densities as $n_{e,\text{hot}} \leq n_{e,\text{cool}} \approx 2 \times 10^{10}$ cm\(^{-3}\). The electron density $n_{e,\text{hot}} \approx 10^{10}$ cm\(^{-3}\) requires about ten times more extended hot plasma seen in soft X-rays than cool plasma seen in H\(\alpha\), which gives us a rather strong constraint on the electron density. The higher density observed in cooler loops is consistent with conductive evaporation taking place during the cooling process (Zarro and Lemen, 1988; Schmieder et al., 1987).
5.3. **Gradual Evolution of Densities**

From the temporal behaviour of $EM_{\text{hot}}$ displayed in Figure 6, we can estimate the gradual evolution of electron densities in post-flare loops. Since the loop volume increases with time (loop system is growing in height) and $EM$ decreases, we also expect to see a gradual decrease of density. The density decrease could also be due to the expected decrease in the efficiency of the reconnection process, which leads to decreased chromospheric ablation (see Section 3).

Assuming a fixed value of $D_{\text{hot}}$ and comparing values of $EM_{\text{hot}}$ measured at 00:00 UT and 09:00 UT, we obtain a density at 00:00 UT which is about a factor of 5 higher than derived above (in fact, the density may be even somewhat greater, as the loops are smaller at 00:00 UT). The corresponding range of densities at 00:00 UT is thus $5 \times 10^{10} < n_e^{\text{hot}} < 10^{11} \text{ cm}^{-3}$.

On the other hand, an interesting constraint on these values can be provided by Hα images taken around 22:00 UT (on June 25) at Hida Observatory (Kurokawa and Kitai, private communication). There, the loop-legs are visible in absorption against the disk close to the limb, which provides an upper limit to the density due to DBE present along the legs (Heinzel and Karlický, 1987). A quantitative analysis of the Hida Observatory images would be valuable.

Using the same procedure we derive an $n_e^{\text{hot}}$ which is about a factor of 2 lower at 13:00 UT than at 09:00 UT. Again, this factor can be even larger due to the expansion of the loop system which increases the emitting volume. Therefore, the electron density at the end of the gradual evolution may be as low as $10^9 \text{ cm}^{-3}$, reaching non-flaring loop values. The reconnection and ablation is assumed to be decreasingly effective. Around 13–14 UT, Hα loops are also very weak (Figure 3), again indicating low mean densities.

### Table III

<table>
<thead>
<tr>
<th>$n_e$ ($10^{10} \text{ cm}^{-3}$)</th>
<th>5</th>
<th>2.2</th>
<th>1</th>
<th>0.5</th>
<th>0.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta t_e$ (s)</td>
<td>780</td>
<td>1660</td>
<td>3000</td>
<td>4400</td>
<td>8300</td>
</tr>
</tbody>
</table>

6. **Cooling Time**

Cooling times have been computed using the method presented in Paper I, taking into account radiative losses and thermal conduction. With the temperature of hot loops $T^{\text{hot}} = 6.5 \times 10^6 \text{ K}$, we obtained the cooling times shown in Figure 11 and in Table III.

© Kluwer Academic Publishers • Provided by the NASA Astrophysics Data System
Fig. 11. Cooling time for a loop with the semi-length of 100 000 km. Initial temperature is $6.5 \times 10^6$ K, the electron densities are (from left to right): $5 \times 10^{10}$, $2.2 \times 10^{10}$, $10^{10}$, $5 \times 10^9$, and $10^9$ cm$^{-3}$.

In Figure 11 we present several cooling curves for the estimated range of electron densities during the evolution of the post-flare loop system, between 00:00 UT and 13:00 UT. Around the times of MSDP H$\alpha$ observations, the cooling time is consistent with that derived in Paper I. However, at the beginning of the gradual phase, the cooling time will be shorter (due to higher densities). Just after the impulsive phase of the flare, the cooling time will be only several minutes, while it will be longer, more than 2 hours, around 13:00 UT. Presented curves give lower-limit cooling times, since no additional heating is imposed in the energy-balance equation. But these limits can be even lower if we would consider the density increase due to a conductive evaporation.
7. Discussion and Conclusions

The main goal of the present paper is to study the gradual behaviour of the post-flare loop system observed on 25–26 June, 1992. We have used the Yohkoh/SXT data for 10 satellite orbits about 14 hours and derived the temporal evolution of the temperature and emission measure of the top parts of hot loops. We find that during 14 hours $T$ decreased slowly from about $7.2 \times 10^6$ K to $6.0 \times 10^6$ K, while the emission measure of hot loops decreased by almost two orders of magnitude from $4 \times 10^{30}$ cm$^{-5}$ to $3 \times 10^{28}$ cm$^{-5}$.

The observed temperature range is determined by the two Al filters used. An almost constant temperature indicates that during the entire gradual phase of the flare we see continuously sufficient amount of plasma at this temperature region, while cooling. Probably (much) hotter loops ($T \geq 10^7$ K) form and cool down, they are visible for a certain time in the above temperature range, and finally appear as H$\alpha$ loops. Indeed, such high-temperature regions have been recently found by LaBonte (private communication), who obtained temperature maps during the orbit starting at 22:11 UT using a three-filter-ratio method to compute the temperature and summing up 60 images to get better signal/noise ratio. It was shown that the temperature maximum around $T \approx 2 \times 10^7$ K was located above the brightest loops. Because the SXT filter ratios are not sensitive to even higher temperatures, this value indicates only a lower limit of $T$ at the reconnection site. Later, such hot spot was still present above the loops as we demonstrated in Figure 12.

However, due to a significant decrease in the emission measure of the hot loops $EM_{\text{hot}}$ (two orders of magnitude during the gradual phase) and an increase of the loop volume, electron density decreased from about $5 \times 10^{10}$ cm$^{-3}$ at 00:00 UT to $5 \times 10^9 - 10^9$ cm$^{-3}$ around 13:00 UT. Between 07:00–09:30 UT, during the MSDP H$\alpha$ observations, the density was around $10^{10} - 2 \times 10^{10}$ cm$^{-3}$. Since the cooling time of the loops depends very strongly on the electron density, this means that the hot X-ray loops cool down to a temperature of $10^4$ K quickly (in a few minutes) at the beginning of the gradual phase but substantially slower (in a few hours) by the end of the evolution of the post-flare loop arcade.

The somewhat higher $EM$ found in hot loops (as compared to cool loops) seems to be related to a larger geometrical extension we see in SXT images. This leads to similar electron densities in both hot and cool loops. The uncertainties in the geometrical thickness and the filling factor are not so critical for density determination since $EM$ is proportional to $n_e^2$. This gives rather tight constraints on the density, which seems to be well estimated to within a factor of two or even better (i.e., for cool loops). Note however, that even if we here find similar densities in hot and cool loops, these correspond mainly to the top parts. But since the H$\alpha$ loops are continuously being depleted due to high-velocity downflows (while the hot ones can still be replenished during the cooling phase by the conductive evaporation), the total mass of cool loops can be lower (also Pneuman, 1981).
Fig. 12. Temperature (in log scale between 6 and 7) and EM (in log scale between 40 to 48) maps of the loops during the orbit of 04:41 UT. The arrow indicates the hot region.

Our comparison of cool Hα loops and X-ray loops fairly supports the post-flare loop reconnection model of Forbes, Malherbe, and Priest (1989). The observed ‘hot spot’ just above the X-ray loops is supposedly related to the high temperature plasma created during the magnetic reconnection. The presence of this ‘hot spot’ during the entire gradual phase supports the idea of a continuously effective reconnection process. The individual hot loops cool down, disappear from the X-ray images and eventually appear as cool Hα loops, but there are always new loops formed at a somewhat higher altitude which keeps up the image of a slowly changing expanding loop system. The cool loops appear just below the hot ones, as we showed in Paper I. The gradual decrease of the EM is interpreted as due to an increasing volume of the magnetic loop system due to the growing height of the reconnection site and a gradual decrease of the efficiency of the reconnection process which drives the chromospheric evaporation. The observed $1.2 \times 10^6$ K decrease in the temperature at the top of the soft X-ray loops might also be due to the falling intensity of the magnetic reconnection.

**Acknowledgements**

The authors wish to thank the team of *Yohkoh*SXT and the team of *Yohkoh* data center at MSSL for providing them with SXT data. The observers at Pic-du-Midi involved in the campaign were Drs T. Roudier and J. E. Wiik. L. Lenža from
Valašské Meziříčí Observatory kindly provided us with a series of Hα images and Drs H. Kurokawa and R. Kitai with a series of Hida Observatory high-resolution Hα filtergrams. The comments by Drs P. Démoülin and E. Tandberg-Hanssen are highly appreciated. We thank Dr W. van Driel for a critical reading of the paper. P.H. acknowledges the support of the French Centre National de Recherche Scientifique (CNRS) during the course of this work and also partial support from the Grant Agency of Czech Republic. MSDP data were digitalized at the Observatory of Paris (MAMA). L.v.D.G. acknowledges the grant of the French Ministry of Foreign Affairs (No. 147569K). J.R.L. is supported by NAS8–37334.

References


