Relative Altitude of Hot and Cool Post-Flare Loops

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\textbf{Abstract.} We collected a unique set of data obtained simultaneously at 4 different ground based observatories and with the \textit{Yohkoh} satellite to study the relationship between hot X-ray ($6 - 7 \times 10^6$ K) and cool H$\alpha$ ($1.5 \times 10^4$ K) post-flare loops as they evolved during the long gradual phase of the X3.9 flare which occurred on 25 June 1992 at 20:11 UT. We found reasonably good agreement between the computed ‘theoretical’ cooling times and the ‘observed’ cooling times derived from the relative altitudes of hot and cool loops. Taking into account evolutionary effects, we also found similar shape and configuration of hot and cool loops during the entire observing period and confirmed that at any time hot loops are at higher altitude than cool loops, suggesting that cool loops indeed descend from hot loops. Our results provide support for the reconnection model.

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1. Introduction

Post-flare loops (e.g., Švestka, 1989; Schmieder, 1992) are now widely believed to be the physical evidence of on-going magnetic field line reconnection during the gradual phase of flares which keeps forming new loops at an ever-increasing altitude (Kopp and Pneuman, 1976; Forbes and Malherbe, 1986; Forbes and Acton, 1996). The hot loops then cool down to appear eventually as Hα loops, but by that time newer hot loops are formed at higher altitudes, therefore at any given time hot loops should be observed being at higher altitudes than the relevant cool loops.

Several observations support this scenario (e.g., Moore et al., 1980; Hanaoka et al., 1986; Švestka et al., 1987; Schmieder et al., 1995 (Paper I)). On the other hand, Feldman and Seely (1995) looking at Skylab data expressed strong scepticism towards the reconnection model of post-flare loops. They could not always relate loops of different temperatures (seen at different wavelengths) to each other and they did not always find cooler loops at lower altitudes than hotter loops. Furthermore, according to their interpretation of the model, reconnection should create separated loops, therefore the expansion of the loops should not be smooth and continuous, but should proceed in a step-wise manner, which has not been clearly observed in X-rays.

Using coordinated observations of a large system of post-flare loops on 25–26 June 1992, which produced the longest ever parallel observations of such events in X-rays and in Hα, we study the relative altitudes of hot and cool loops, and we discuss points raised by Feldman and Seely (1995).

### Table 1. Data sets of the post-flare loops of June 25–26, 1992

<table>
<thead>
<tr>
<th>Observatory</th>
<th>Obs. interval</th>
<th>Temporal res.</th>
<th>Spatial res.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hida, Japan</td>
<td>20:25–06:34</td>
<td>5-80 m arc sec</td>
<td>1 arc sec</td>
</tr>
<tr>
<td>MSDP, Pic du Midi, France</td>
<td>07:08–09:37</td>
<td>10 s–90 m arc sec</td>
<td>0.5 arc sec</td>
</tr>
<tr>
<td>Valašské Meziříčí, Czech R.</td>
<td>07:12–14:29</td>
<td>15 m–1 h arc sec</td>
<td>1–2 arc sec</td>
</tr>
<tr>
<td>La Palma, Lockheed group</td>
<td>08:10–08:55</td>
<td>21 s arc sec</td>
<td>0.5 arc sec</td>
</tr>
<tr>
<td>Yohkoh/SXT</td>
<td>22:57–13:18</td>
<td>32 s arc sec</td>
<td>2.46 arc sec</td>
</tr>
</tbody>
</table>

2. Expansion Speed and Relative Altitude of Hot and Cool Loops

A post-flare loop system was observed with the Yohkoh/SXT (after the large X-class flare of June 25 at 20:11 UT) for more than 15 hours, and from ground based observatories in Japan and Europe for more than 19 hours (see Table 1). Unfortunately, Yohkoh missed the first 3 hours of the flare, but covered the rest of the gradual phase. On the other hand, Hα observations started right after the impulsive phase at Hida Observatory, so we could follow the fast early evolution of the loop system. During the entire observing period we see an arcade of loops and we can follow the evolution of 3 main loops (Figure 2), which appear to be very similar in Hα and in X-rays (Figure 1).

In order to get the real expansion speed of the X-ray loops, we measured the positions of the footpoints and the loop tops, then reconstructed the shape of
the loops (for the method, see Wiik et al., 1996, Paper III) taking into account effects of the solar rotation. The expansion speed was found to be 1.1 km s\(^{-1}\) between 02:00 UT and 15:00 UT. Since X-ray loops are faint at their footpoints, the precision of these measurements decreased when smaller-bigger brightenings occurred in the active region. Since in the H\(\alpha\) images the loop legs are (i) covered by an occulting disc, or (ii) hardly visible on the bright disc, such true height reconstruction was carried out for the X-ray observations only.

To obtain the relative altitudes of the X-ray and H\(\alpha\) loops utilising the entire data set we had to measure the altitudes of loops from the solar limb, which could be located in all kinds of observations, since the flare in question was a limb event. With error bars due to the determination of the pixel size of H\(\alpha\) data (around 10%) and to the exposure time of different pictures (in overexposed frames the the solar limb appears to be more extended) we find that hot and cool loops are growing continuously (Figure 2). From the H\(\alpha\) (Hida Observatory) observations, which started 15 minutes after the beginning of the flare, it is clear that the expansion of the loop system was very fast at first (\(\approx 8\)–\(10\) km s\(^{-1}\)), it decreased more-or-less exponentially to about 1 km s\(^{-1}\) in about 4 hours, and the loop system was observed to expand with that speed for at least 14 hours.

3. Discussion and Conclusions

In Schmieder et al. (1996, Paper II), using the filter-ratio method for the two Al filters we determined the temperature and the emission measure \(EM\) of the X-ray loops for the entire gradual phase and computed the electron densities of the hot plasma, taking 4000 km for the line-of-sight thickness of the X-ray loops and computed the cooling times taking into account thermal conduction and radiative losses with a starting temperature of \(6.5 \times 10^6\) K.

Table 2. Measured and estimated cooling time of hot post-flare loops

<table>
<thead>
<tr>
<th>Observations</th>
<th>(\Delta t)</th>
<th>(n_e^{hot}(cm^{-3}))</th>
<th>(\Delta t_c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>23:00 UT</td>
<td>(\approx 10) m</td>
<td>(7-8 \times 10^{10})</td>
<td>10 m</td>
</tr>
<tr>
<td>04:00 UT</td>
<td>30 m–2 h</td>
<td>2-3 (10^{10})</td>
<td>30 m</td>
</tr>
<tr>
<td>08:00 UT</td>
<td>1–2 h</td>
<td>(10^{10})</td>
<td>1 h</td>
</tr>
<tr>
<td>13:00 UT</td>
<td>2 h</td>
<td>6-7 (10^9)</td>
<td>2 h</td>
</tr>
</tbody>
</table>

The computed cooling times can be compared to observed cooling times (Table 2), i.e. to values obtained from the relative altitude curves of hot and cool loops (Figure 2). We see in Figure 2 that at any given time hot loops appear higher than the cool loops, and the gap between the two altitude curves becomes wider with time. If we suppose, that loops do not shrink between the ‘mature’ X-ray loop and H\(\alpha\) stage (which doesn’t exclude the possibility that hot loops shrink right after their formation as found by Forbes and Acton (1996)), then the observed cooling time is the time difference between hot and cool loops to
Figure 1. Evolution of the post-flare loops system in soft X-rays (left panels) and in Hα (right panels) during the gradual phase of the X3.9 flare of 25 June 1992 20:11 UT.
reach the same altitude. Looking at Table 2, it is obvious that there is a good agreement between the computed and observed cooling times 3 and 17 hours after the impulsive phase, while the observed cooling times appear to be longer than the computed cooling times 8 to 12 hours after the onset of the flare. This discrepancy may or may not be real, taking into account the difficulties of such relative altitude measurements using data from 5 different sources. It might be possible that hot loops cool slower than indicated by the computations. On the other hand Švestka et al. (1987) suggested that since the density must be increasing during the life of a cooling loop implying that the loop can not stay at the same altitude, but must shrink. Our results do not contradict their suggestion, but, we can not say either that they confirm it. Analysis of other events might prove more decisive (Harra-Murnion et al., 1996).

The expansion rate of the post-flare loop system was found of the order of 10 km s\(^{-1}\) shortly after the impulsive phase, then decreased exponentially and about 4 hours later it stabilised at 1.1 km s\(^{-1}\). Note, that this is the expansion speed of an evolving loop system, not of individual loops. The expansion seems to proceed without ‘jumps’ in the case of the X-ray loops, while in the H\(\alpha\) observations of the Lockheed group taken with high temporal and spatial resolution we do see the formation of a distinct new loop (see also Bruzek, 1964). We feel, that the lack of jumps in the X-ray loop expansion does not contradict the reconnection model, this requirement was only a (mis)interpretation of the model by Feldman and Seely (1995). On the contrary, the reconnection may rather be a smooth, steady process, which does not proceed in impulses forming distinct hot loops (Forbes, private communication, 1996). The formation of distinct H\(\alpha\) loops may rather be due to the cooling process and condensation of material than to a step-wise reconnection.

The shape and structure of the loops are very similar in X-rays and in H\(\alpha\) (Figure 1). On the other hand, we may understand why Feldman and Seely (1995) could not always relate loops seen at different wavelengths to each other.
First of all, post-flare loops normally form an arcade, of which different loops may overlap. Furthermore, during the long gradual phase of a flare new flares and ejections could occur in the same active region, and especially close to the limb spatially different features may appear projected at the same place, and therefore physically unrelated events can be confused.

Our results do not justify the scepticism expressed by Feldman and Seely (1995) towards the reconnection theory of post-flare loops; on the contrary, we find that at any time, the relative altitude and shape of hot and cool loops confirm that cool loops are ‘descendants’ of hot loops of a few minutes (early during the gradual phase) or a few hours earlier (later during the gradual phase), depending on their electron density. Observations of post-flare loops with SOHO will be very important to provide observations at several intermediate wavelengths (i.e., temperatures), which will reveal finer details of the cooling process.

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