SPEEDS OF RISING POST-FLARE STRUCTURES

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(Dedicated to Cornelis de Jager)

Abstract. There are basically two kinds of post-flare coronal structures: those rising with decreasing speed, and others which rise with constant speed for a long period of time. As a rule, those structures with decreasing speed are post-flare loop systems, while those rising with constant speed are post-flare giant arches. However, there are exceptions. We demonstrate several cases of post-flare loop systems which rise with constant speed for many hours, three of them observed by *Yohkoh*. These observations imply that the Kopp and Pneuman interpretation of post-flare loops as sequentially reconnecting open field lines cannot be generally valid. The most likely interpretation is that all post-flare loop systems start with the Kopp and Pneuman process, but in some of them later-formed loops begin to be continuously heated; thus they cease to cool and begin to expand into the corona. This kind of post-flare loops might represent an intermediate stage between the ordinary post-flare loops and post-flare giant arches.

1. Introduction

The Hard X-ray Imaging Spectrometer (HXIS) on board the Solar Maximum Mission (SMM) spacecraft, of which Kees de Jager was the Principal Investigator (Van Beek *et al.*, 1980), observed on 21–22 May, 1980 for the first time two different coronal structures associated with a major flare: the commonly known post-flare loop system, observed for a few hours after the onset of the flare, and a much higher large-scale structure which was visible in >3.5 keV X-rays for more than 10 hours and got the name 'post-flare giant arch' (De Jager and Švestka, 1985). While the loops rose into the corona with gradually decreasing speed, the arch appeared to stay above them at the same altitude during the whole period of observation; taking the size of one HXIS pixel and the arch inclination into account, its speed of rise could not exceed 1.1 km s^{-1} (Hick and Švestka, 1985). Other giant arches, discovered later by the SMM instruments, rose with higher speeds (up to 12 km s^{-1}), but in all cases the speed was constant over the whole observing period of several hours (Švestka, 1984). This constancy of speed of rising giant arches has been recently confirmed by observations on *Yohkoh* which show speeds of rise for several post-flare giant arches staying constant for up to 24 hours (Švestka *et al.*, 1995).

Figure 1(a–c) shows three examples of the different behavior of the two structures: (a) the disk event of 21–22 May, 1980, with stationary giant arch and post-flare loops rising below it (both observed by HXIS); (b) the close-to-limb

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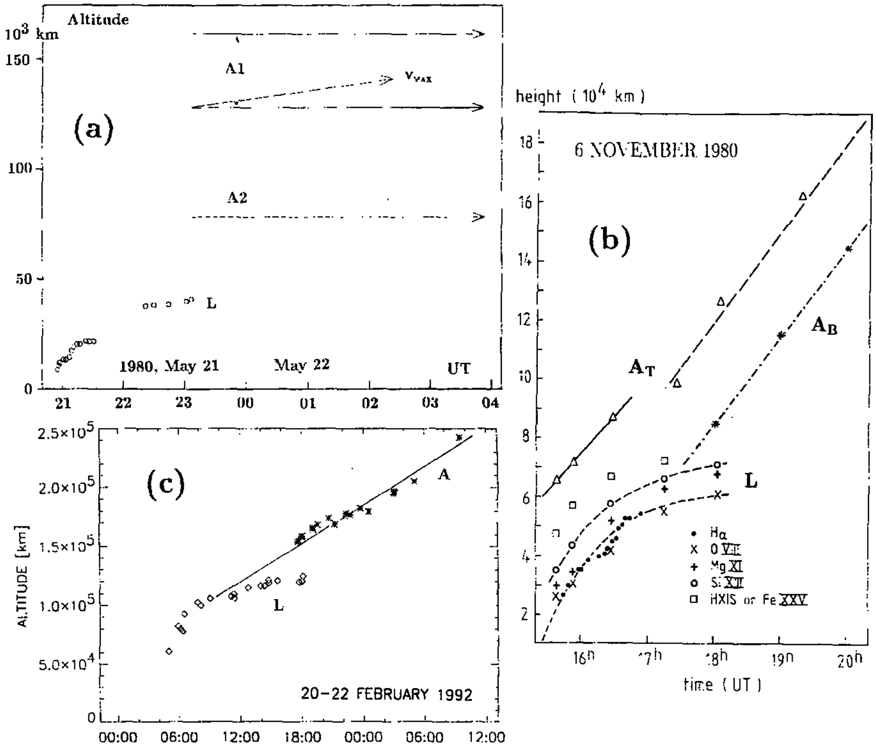

Figure 1. (a) Altitudes of the post-flare loops (L) and stationary post-flare giant arch (A1) on 21–22 May, 1980 in HXIS X-ray images under the assumption that both these structures were inclined by 25° to the south-west (cf., de Jager and Švestka, 1985, Section 7.1). v_{MAX} shows the maximum possible speed of rise of the arch (after Hick and Švestka, 1985). A2 shows the arch altitude deduced by Poletto and Kopp (1988) when modeling the arch in the current-free approximation (with arch footpoints different from those adopted for A1). (b) Projected altitudes of the post-flare loops (L), observed both in Hα and by SMM instruments, and the rising post-flare giant arch (A_T, A_B) observed by HXIS close to the solar limb on 6 November 1980. A_T shows the altitude of the maximum temperature in the arch in the fine (*full line*) and coarse (*dashed line*) field of view of HXIS (after Hick and Švestka, 1987), while A_B is the altitude of the maximum brightness of the arch (after Švestka, 1984). (c) Altitude of the maximum brightness in the loop (L) and arch (A) structures on 21 February 1992, observed by *Yohkoh*. While the speed of rise of the loops decreases with time, the straight line indicates the constant speed of rise of the arch. (After Švestka *et al.*, 1995.)

event of 6 November, 1980 (onset 14 UT), with a rising giant arch observed by HXIS and post-flare loops below it observed both in X-rays (HXIS and Flat Crystal Spectrometer) and in Hα (Big Bear Solar Observatory); and (c) the limb event of 21 February, 1992, observed in X-rays by *Yohkoh*, with post-flare loops ending their rise at an altitute of 120 000 km and a giant arch continuing to rise to twice that altitude.

2. Post-Flare Loop Systems

More than 30 years ago, Bruzek (1964) made a detailed study of Hα observations of many systems of rising post-flare loops, and arrived at the conclusion that their rise is not caused by any expansion of the loops, but by successive formation of progressively higher loops while the lower loops decay. In the initial phase the loop system grows rapidly, but the rise gradually slows down – as can also be seen in the L curves in Figures 1(a–c).

The sequential formation of new loops can be seen clearly only in images with high spatial resolution, whereas in lower-resolution images, e.g., in the X-ray range, the system of loops seems to be expanding. This may explain why, e.g., Feldman and Seely (1995) express doubts about the correctness of Bruzek's observations. Nevertheless, even low-resolution X-ray images actually indirectly confirm Bruzek's conclusion: the observed lifetime of the growing loop system in X-rays is much longer than the radiative cooling time deduced from the loop density (cf., e.g., Moore *et al.*, 1980). Clearly new, higher loops must be successively formed to keep the growing loop system visible in X-rays. It was also observed, by Moore *et al.* (1980), Hanaoka, Kurokawa, and Saito (1986), Švestka *et al.* (1987), Schmieder *et al.* (1995), and Van Driel-Gesztelyi *et al.* (1997), that hotter loops have their tops higher than cooler loops which, because of cooling, implies more recent formation of hot loops at higher altitudes.

Bruzek's observations led to the interpretation by Kopp and Pneuman (1976, based on earlier models proposed by Sturrock (1968) and Hirayama (1974)) that the originally closed magnetic configuration eruptively opens, solar plasma begins to stream upward along the open field lines, and the resulting prevalence of magnetic pressure forces the field lines to close again: first low in the corona, where the magnetic pressure is strongest, and then, with gradually decreasing speed, at progressively higher altitudes. Plasma evaporating into the newly formed closed magnetic tubes forms then the post-flare loops: first hot and gradually cooling.

This has been accepted by most solar physicists as the most likely interpretation of the observed post-flare loop systems, in particular when Cargill and Priest (1983), Forbes and Malherbe (1986), Forbes, Malherbe, and Priest (1989), and others filled in some gaps in the original Kopp and Pneuman model. We will see, however, in Section 4 that some problems still remain.

3. Post-Flare Giant Arches

As mentioned in the Introduction, in all cases when post-flare giant arches expanded and the expansion speed could be measured, the speed of rise was surprisingly constant. Eventually, after many hours of observation, very high in the corona the speed began to decrease (example in Figure 2(a)), but in the extreme case on 15–17 March, 1993 the constant rise continued for at least 24 hours (Figure 2(b)). It is

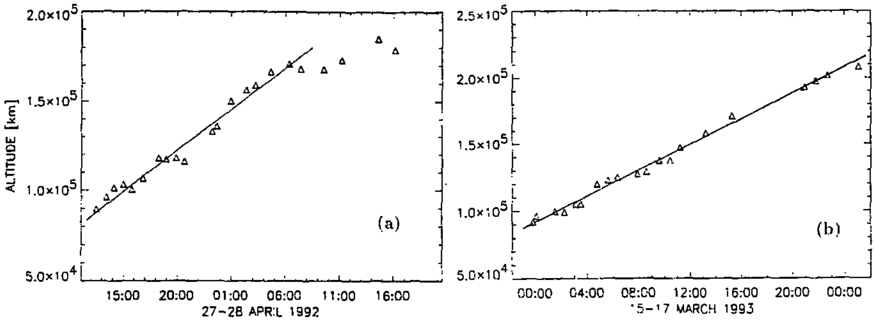

Figure 2. *Yohkoh* SXT observations of post-flare giant arches: (a) Growing altitude of the giant arch of 27–28 April 1992 showing constant speed of rise for 18 hours which began to slow down at an altitude of 170 000 km. (b) Growing altitude of the giant arch of 15– 17 March, 1993, with the speed of rise staying constant for more than 24 hours, up to an altitude of at least 200 000 km. Solar rotation has been taken into account in both events, assuming vertical extension of the loops. (After Švestka *et al.*, 1995.)

not possible that such a rise with constant speed could be caused by successive reconnection of progressively higher loops, as seems to be the case with post-flare loops, because the force driving the reconnection should decrease with the altitude. Therefore, Švestka *et al.* (1995) suggested that in this case we observe real expansion of loops which survived a coronal mass ejection process and rose into the plasma and magnetic-field vacuum left behind the CME.

Still, we encounter here a similar problem of long-lasting cooling which we mentioned in the case of the flare loops. Although the radiative cooling is in this case much slower, because the densities in post-flare arches ($10^8 - 10^9$ cm^{-3}) are lower by one to four orders of magnitude than in post-flare loops ($10^{10} - 10^{12}$ cm^{-3}), the arches still should cool through conduction much faster than observed. In the case of stationary post-flare arches, in which the temperature observed is relatively high (up to 5.5×10^6 K in *Yohkoh* images), frequent activity below the existing arch suggests that there are repeated inputs of energy into the arch structure which keep it visible in X-rays for the long time observed (Fárník *et al.*, 1996). Also in the case of rising arches, quasi-periodic brightness variations were observed in X-rays below the first giant arch of 6 November, 1980 (04 UT) and a series of flaring arches appeared below the second one (14 UT) (cf., Švestka, 1994 and references therein). This activity, again, could feed the arch with an additional supply of energy. Most other rising arches were observed on the limb, where it may be difficult to detect active variations of this kind.

Thus, there is the distinct possibility that the long lifetimes of rising post-flare giant arches are also due to an additional energy supply. If not, then another alternative is an inhibited (or, at least, strongly reduced) conduction. Although this interpretation is contradicted by the observation of Hα footpoints of the 6 November 1980 arches by Martin, Švestka, and Bhatnagar (1989), one could tentatively suppose that inhibition of conductive cooling occurs only in some loop components of the arch, thus keeping these components visible in X-rays for a long time, while in other components conduction works and heats the Hα footpoints in the chromosphere. One should also notice that the longest lifetimes of rising arches (exceeding 24 hours) were observed for relatively cool components of the arch (less than 3×10^6 K in *Yohkoh* data), whereas there is no evidence for lifetimes exceeding 14 hours (and usually much less) in HXIS data for the hot components of the arch. Because of its dependence on $T^{5/2}$ (and even $T^{7/2}$ if $\nabla T = T/L$), classical conductive cooling is much less effective at lower temperatures.

However, one should not forget that also other structures, which exist in the quiet corona, live for a long time and we do not know yet what heats them. With the relatively low temperature in the long-lived rising arches (Švestka *et al.*, 1995), the arch can be heated by the same process which generally heats the quiet corona. In that case, *all considerations about cooling processes are irrelevant, because the arch components are continuously heated by the (unknown) quiet-corona heating process.*

4. Exceptions

Table I lists published events of post-flare loops and post-flare giant arches in which both the altitude and the speed of rise were measured. One can draw from it the following general conclusions:

(i) Giant post-flare arches reach much higher altitudes (up to 250 000 km) than post-flare loops (maximum altitude 140 000 km).

(ii) Giant post-flare arches rise with constant speed to very high altitudes, while the speed of rise of post-flare loops begins to decrease with altitude shortly after the onset of the event.

(iii) Post-flare loops reach larger altitudes in X-rays than in the Hα line.

However, there are clearly exceptions to these general rules. There was one arch (on 13 August, 1973) rising with decreasing speed and, in particular, there were several post-flare loop systems rising with constant speeds. Striking examples are the post-flare loops of 5 April, 1960 (Bruzek, 1964), 21 August 1973 (MacCombie and Rust, 1979) and 26 June, 1992 (Van Driel-Gesztelyi *et al.*, 1997).

The event of 13 August, 1973 (Šimberová, Karlický, and Švestka, 1993) was the only post-flare giant arch identified in *Skylab* images: the identification was based on the time development of its temperature, emission measure, and brightness. While MacCombie and Rust (1979) found its speed of rise more or less constant for 10 hours, a longer-lasting data set analyzed by Šimberová, Karlický, and Švestka clearly show a decreasing speed after 4 or 5 hours of constant rise in its onset phase.

We have shown in Figure 2(a) that the constant speed of rising giant arches generally begins to decrease after some time, high in the corona. According to Švestka *et al.* (1995), in *Yohkoh* images this time was longer than 24 hours on 20–22 February, 1992 and 15–17 March, 1993, 18 hours on 27–28 April, 1992, more

Table I
List of events with rising loops or arches

Date	Max. altitude (km)	Speed	Type	Energy range	Position	Ref.
1991 Nov. 5	250 000	constant 16h	arch	X-rays	limb	[1] (*Yohkoh*)
1992 Feb. 21	240 000	constant >12h	arch	X-rays	limb	[1] (*Yohkoh*) [a]
1991 Nov. 2	230 000	constant 11h	arch	X-rays	limb	[1] (*Yohkoh*)
1993 Mar. 15	210 000	constant 24h	arch	X-rays	limb	[1] (*Yohkoh*)
1980 Nov. 6, 04 UT	>180 000	constant 2.5h	arch	X-rays	limb	[2] (SMM)
1980 Nov. 6, 14 UT	>180 000	constant 5h	arch	X-rays	limb	[2] (SMM) [b]
1980 Nov. 7	>180 000	constant 2h	arch	X-rays	limb	[2] (SMM)
1991 Apr. 27	170 000	constant 18h	arch	X-rays	limb	[1] (*Yohkoh*)
1968 Nov. 18	140 000	decreasing	loops	Hα	limb	[3]
1957 June 28	126 000	decreasing	loops	Hα	limb	[5]
1986 Feb. 14	121 000	decreasing	loops	Hα	limb	[4]
1992 Feb. 21	120 000	decreasing	loops	X-rays	limb	[1] (*Yohkoh*) [a]
1992 June 26	115 000	constant 14h	loops	X-rays	limb	[6] (*Yohkoh*) [c]
1973 Sep. 7	103 000	decreasing	loops	X-rays	limb	[7,8] (*Skylab*)
1973 July 29	100 000	decreasing	loops	X-rays	limb	[7] (*Skylab*) [d]
1991 June 15	100 000	decreasing	loops	Hα	limb	[9]
1962 Feb. 19	98 000	decreasing	loops	Hα	limb	[5]
1973 Aug. 13	95 000	decreasing	arch	X-rays	limb	[7,10] (*Skylab*)
1992 June 26	90 000	decreasing	loops	Hα	limb	[6] [c]
1960 Apr. 5	88 000	constant 8.5h	loops	Hα	disk	[5]
1962 May 13	82 000	decreasing	loops	Hα	disk	[5]
1957 Apr. 16	75 000	decreasing	loops	Hα	limb	[5]
1973 Aug. 21	>70 000	constant 7h	loops	X-rays	limb	[7] (*Skylab*)
1980 Nov. 6, 14 UT	70 000	decreasing	loops	X-rays	limb	[11] [b]
1961 July 20	68 000	? [e]	loops	Hα	limb	[5]
1962 Feb. 3	>60 000	constant 3h	arch	5303 Å	limb	[12]
1981 Apr. 27	60 000	decreasing	loops	Hα	limb	[13]
1973 July 29	55 000	decreasing	loops	Hα	disk	[8,14] [d]
1980 Nov. 6, 14 UT	55 000	decreasing	loops	Hα	limb	[11] [b]
1980 May 21	41 000	decreasing	loops	X-rays	disk	[15] [f]
1980 Feb. 16	>18 000 [g]	decreasing	loops	Hα, Ca XV	limb	[16]

References: [1] Švestka *et al.* (1995), [2] Švestka (1984), [3] Roy (1972), [4] Smith *et al.* (1994), [5] Bruzek (1964), [6] Van Driel - Gesztelyi *et al.* (1997) [7] MacCombie and Rust, 1979, [8] Moore *et al.* (1980), [9] Akimov *et al.* (1996); [10] Šimberová, Karlický, and Švestka (1993), [11] Švestka *et al.* (1987), [12] Bruzek and Demastus, 1970, [13] Gu *et al.* (1983), [14] Martin (1979), [15] De Jager and Švestka (1985), [16] Hanaoka *et al.* (1986).

[a] Same event (cf., Figure 2(c)). [b] Same event (cf., Figure 2(b)). [c] Same event. [d] Same event. [e] Constant 2h, then an indication of decrease. [f] Stationary arch above the loops (cf., Figure 1(a)). [g] Event behind the limb.

than 16 hours on 5–6 November, 1991, and about 11 hours on 2–3 November, 1991. The lowest altitude where the decrease of speed started was 170 000 km (on 28 April, 1992). HXIS observations only showed that the constant speed could last more than 5 hours. The event of 13 August, 1973 seems to be an extreme case when the speed began to decrease already after 4–5 hours, at the low altitude of about 70 000 km.

However, it is more difficult to explain the behavior of the post-flare loop events for which the speed of rise has been found constant.

The post-flare loops of 5 April, 1960 were rising with a constant speed of about 2 km s^{-1} for more than 8 hours up to an altitude of 88 000 km. This could not be a giant arch, because the observations (Bruzek, 1964; Slonim, 1963) were carried out in the Hα line and the description ('a row of bright points connected to the flare by thin threads') convincingly describes a post-flare loop system. The loops of 21 August, 1973 rose with a constant speed of about 1.8 km s^{-1} for 7 hours to an altitude of about 70 000 km. X-ray pictures of this event (Smith *et al.*, 1977; MacCombie and Rust, 1979) show an arcade of post-flare loops on the limb.

The post-flare loops of 26 June, 1992, observed both in X-rays and Hα (Figure 3(c)) showed a decrease of speed of rise for the first 3–4 hours, but thereafter the speed stayed constant at 1.5 km s^{-1} for about 14 hours up to an altitude of 110 000 km (Van Driel-Gesztelyi *et al.*, 1997).

The 26 June, 1992 event was observed in X-rays by *Yohkoh*, and *Yohkoh* SXT data show several other examples of anomalous behavior of post-flare loop systems. On August 28–29, 1992 the speed of rise of post-flare loops, observed on the east limb of the Sun, remained constant for 10 hours (Figure 3(a)). And on October 28–30, 1992, close to the east limb, the speed of rise of post-flare loops slightly slowed down in the onset phase, but thereafter stayed almost constant for 38 hours (!) (Figure 3(b)). During that time the loops reached an altitude of at least 230 000 km if they were inclined by 45° to the vertical, and their altitude was still larger if the loop inclination was smaller (Švestka *et al.*, 1997). In both cases the limb structures looked in soft X-ray images like 'ordinary' post-flare loop systems (Figure 4).

One might argue that these events could actually be post-flare giant arches, because we still do not know well what the detailed structure of giant arches looks like. However, these systems really look like other post-flare loops observed in X-rays. Besides, the 5 April, 1960 event observed by Bruzek (with more than 8 hours of constant speed) and the 26 June, 1992 event shown in Figure 3(c) were observed in the Hα line where post-flare giant arches are not visible.

5. Discussion

Kopp and Pneuman's (1976) model fits very well the behavior observed in ordinary post-flare loop systems which grow in the corona with decreasing speed of rise. However, it cannot explain the growth of giant arches and anomalous post-flare

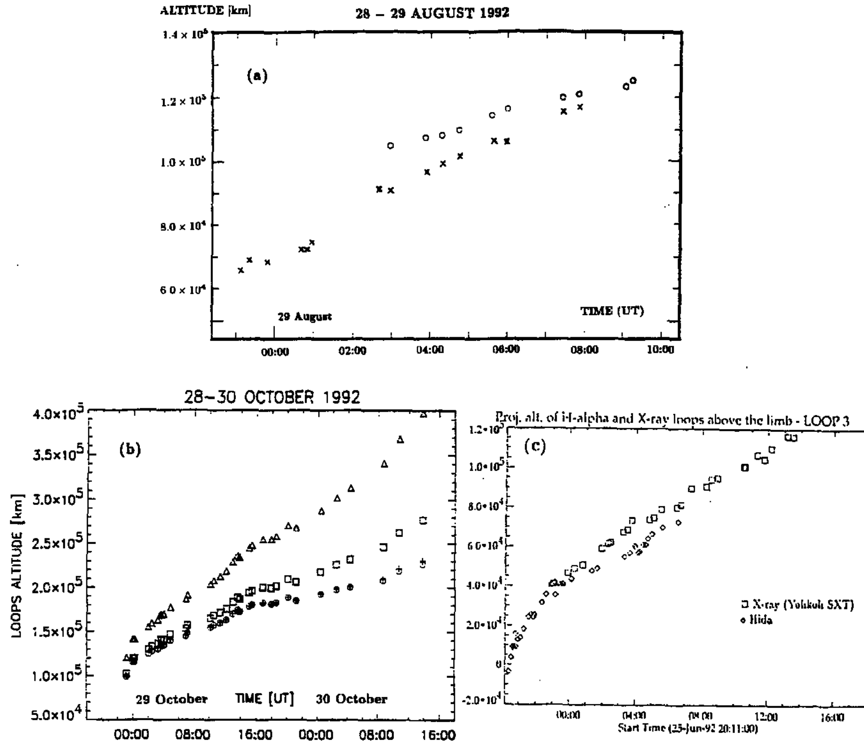

Figure 3. *Yohkoh* SXT observations of anomalous post-flare loop systems: (a) Altitudes of the post-flare loops of 28 – 29 August, 1992, with solar rotation taken into account under the assumption of vertical extension of the loops. Circles and crosses correspond to two different parts of the loop system. (b) Altitudes of the post-flare loops of 28—30 October 1992, with solar rotation taken into account. The altitudes observed are marked by circles. Under the assumption of vertical extension of the loops, their real altitudes are shown by triangles. Squares show the real altitudes under the assumption that the loops were inclined by 20° to the east, and crosses under the assumption that the inclination was 45°. (After Švestka *et al.*, 1997.) (c) Projected altitudes of the post-flare loops of 25—26 June 1992 observed in X-rays (squares, *Yohkoh* SXT data) and in Hα (diamonds, Hida Observatory). (After Van Driel-Gesztelyi *et al.*, 1997.)

loops with constant speed for many hours, because the Lorentz force that drives the reconnection in the Kopp and Pneuman model decreases with altitude.

On the other hand, an expansion of loops left or reconnected behind a CME could proceed with constant speed. It is well known that solar loops tend to expand. Thus as soon as they get a chance to do so (as behind a CME), they just use this opportunity and rise. We do not understand why the speed of rise stays constant for such a very long time, but we see similar behavior at rising filaments and CMEs. Of course, in those cases the speeds are significantly higher, exceeding the escape velocity in the solar corona. In the case illustrated in Figure 2(b) the speed, 1.34 km s^{-1}, was more than two orders of magnitude lower.

In any case, the post-flare loops which grow with constant speed cannot be formed by the process proposed by Kopp and Pneuman (1976). This implies that

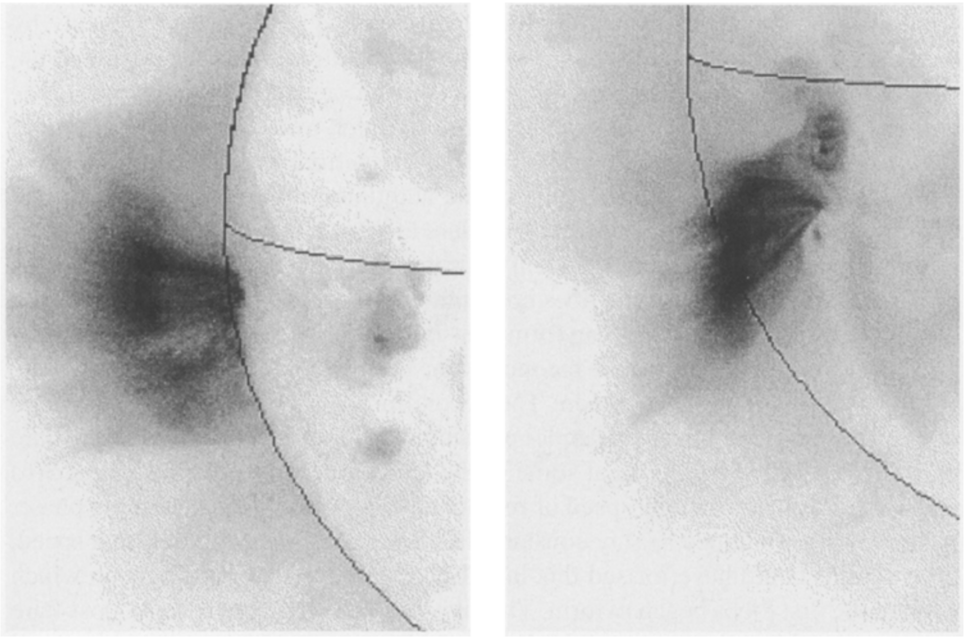

Figure 4. *Yohkoh* SXT images of the post-flare loop systems for which the altitudes were measured in Figures 3(a,b): (a) On 29 August 1992 at 04:24 UT. (b) On 29 October 1992 at 02:01 UT.

either (1) this model is incorrect in all cases, or that (2) there must exist two entirely different processes that produce post-flare loop systems, or that (3) the Kopp and Pneuman process, while producing the loops in the initial phase of an event, is substantially modified in the later phase of the loop-system development. If the Kopp and Pneuman model is wrong, one has to suppose that all post-flare loop systems are formed by expanding loops, of which a few expand with constant speed for many hours, while the majority begins to decelerate within a short time after the loop formation. This need not necessarily contradict observations of post-flare loops in X-rays, because – as we mentioned earlier – X-ray loops could be kept long-lived by the same process (not yet known either) which keeps loops hot in the quiet corona. Also, the fact that hotter X-ray loops are higher than cooler loops might be explained by a combined process of loop expansion and cooling. However, this interpretation also completely contradicts the well-known Hα observations made by Bruzek (1964) in Freiburg and at Sacramento Peak that new loops are sequentially formed at higher altitudes while the previous loops disappear. In addition to the fact that Bruzek was an outstanding observer, his conclusions have been confirmed by Big Bear Hα movies with high spatial resolution (Martin, 1979, 1989). In the 1989 paper, Sara Martin also mentions new flare elements forming on the outer boundaries of the flare ribbons concurrently with the formation of the coronal post-flare loops in X-rays. Generally, the increasing separation of the Hα ribbons at the footpoints of the loops is hard to explain within the context of an expanding loop, whereas it is explained very nicely by the Kopp and Pneuman model. One should also mention that even before 1964, when Bruzek published his paper, other observers recognized that '*the knots (at the tops of Hα loops) are continuously replaced by others, which form anew after and during the disappearance of the old knots*' (quotation from de Jager, 1959). Indeed, the Kopp and Pneuman model, with all the additional improvements mentioned before, explains so well the 'regular' post-flare loop systems with decreasing speed of growth, that one feels very reluctant to drop it completely.

Thus this first interpretation does not seem to be acceptable and there should be two different processes which can form post-flare loop systems in the solar corona. The first process of sequential reconnection, proposed by Kopp and Pneuman, is obviously much more common. The second process of continuous expansion occurs less frequently in post-flare loop systems, but is quite common in post-flare giant arches. When one looks at some of the altitude plots (see, e.g., Figures 3(b) and 3(c)), it appears that the speed of rise actually declined in the beginning phase, but thereafter continued to stay constant. In other events showing constant speed, observations could have missed this initial phase, and we do not know on which altitude the first loops began to form. Thus it is possible that even in those post-flare loop events with constant speed the Kopp and Pneuman model was working well at the beginning, sequentially forming new loops, but it was eventually replaced by another, expanding model. One can suppose that while in 'regular' post-flare loop systems new, progressively higher loops are sequentially formed, subsequently cool, and eventually disappear, in some events, after a short period of the 'regular' Kopp and Pneuman process, newly formed loops begin to be continuously heated from below (through the 'quiet corona heating mechanism' or another process). In consequence of that they begin to expand and cease to cool for a long period of time. Although this interpretation is purely hypothetical, it seems to interpret best the anomalous events observed.

Thus we apparently encounter two different kinds of behavior of the phenomenon called 'post-flare loops': short-lived flare loops which are sequentially created through reconnection and subsequently cool, and long-lived loops which stay hot and expand into the corona (from the beginning of the event or starting only in a later phase of the event). Smith *et al.* (1994) pointed out that some very high post-flare loop systems are not accompanied by any giant arch above them, but that they themselves gradually take over some characteristics of post-flare giant arches. Thus those post-flare loops that expand might represent an intermediate stage between the post-flare loops and post-flare giant arches, a good example being the event of 28 October 1992, shown in Figures 3(b) and 4(b), where an apparent post-flare loop system reached an altitude in excess of 230 000 km, typical for post-flare giant arches. So far we do not know which conditions in an active region lead to the formation of these two different kinds of loops.

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