

LARGE-SCALE ACTIVE CORONAL PHENOMENA IN YOHKOH SXT IMAGES

IV. Solar Wind Streams from Flaring Active Regions

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Abstract. We demonstrate limb events on the Sun in which growing flare loop systems are embedded in hot coronal structures looking in soft X-rays like fans of coronal rays. These structures are formed during the flare and extend high into the corona. We analyze one of these events, on 28–29 August 1992, which occurred in AR 7270 on the eastern limb, and interpret these fans of rays either as temporary multiple ministreamers or plume-like structures formed as a result of restructuring due to a CME. We suggest that this configuration reflects mass flow from the active region into interplanetary space. This suggestion is supported by synoptic maps of solar wind sources constructed from scintillation measurements which show a source of enhanced solar wind density at the position of AR 7270, which disappears when 5 days following the event are removed from the synoptic map data. We also check synoptic maps for two other active regions in which existence of these fan-like structures was indicated when the active regions crossed both the east and west limbs of the Sun, and both these regions appear to be sources of a density enhancement in the solar wind.

1. Introduction

In the preceding three papers we discussed *Yohkoh* SXT observations of rising post-flare giant arches (Švestka *et al.*, 1995, Paper I), stationary giant arches (Fárník *et al.*, 1996, Paper II), and enhanced post-flare streamers above growing systems of flare loops (Švestka *et al.*, 1997, Paper III). In this Paper IV we study a more complex kind of large-scale coronal structures imaged by *Yohkoh* and associated with eruptive flares.

We have found several limb events in which growing systems of flare loops were embedded in extensive coronal structures which, for some period of time, looked like a *fan of bright X-ray rays*. One such event, the most conspicuous of those we have discovered, occurred on the eastern solar limb in active region No. 7270 on 28/29 August 1992 and a detailed study of this particular event is the main subject of this paper. In Section 8 we will also briefly discuss other events of similar kind.



2. Activity in AR 7270

Solar-Geophysical Data (SGD, 1992) give the first observation of active region No. 7270 on 29 August at 09° S, 75° E, and Yaji (1994), who studied this region in detail, supposed that it was born on that day. However, in *Yohkoh* images AR 7270 could be first recognized already at about 20 UT on 27 August, when its centroid was still behind the limb. During the whole day of 28 August *Yohkoh* observed various kinds of activity in this active region, of which the most conspicuous event was seen at 18:39 UT, when a large bright jet resembling that studied by Shibata *et al.* (1994) appeared. The jet changed its position, bending gradually to the north. It disappeared after 20 minutes and Enclosure 1 on the accompanying CD-ROM shows its time development. We also enclose a movie in the CD-ROM (courtesy of David E. McKenzie), which covers the whole development of the solar corona above AR 7270 on August 28–29, and in this movie the jet looks like a searchlight moving in the night sky.

The centroid of the region crossed the limb at about 5 UT on 28 August and SGD (1993) reported two subflares in it on 28 August in the position 10°S, 90°E at 07:58 and 15:54 UT. Thus the active region, probably born recently behind the eastern limb, was already quite active when gradually appearing on the solar disk.

3. Coronal Mass Ejection

At 21:22 UT on 28 August an extensive arch-like structure was observed above the region in *Yohkoh* SXT images, which expanded and eventually disappeared from the field of view. Figure 1(b) shows the expanding structure when it was first seen by *Yohkoh* and Figure 1(c) illustrates the situation after its disappearance from *Yohkoh*'s field of view. Figure 2, showing three difference images of the arch, reveals that several loops were expanding, and the direction from dark to bright shows the direction of the expansion. Azimuthal integrations of the coronal brightness in Figure 3 show that between 21:22 UT and 21:48 UT the projected speed of the rise of the arch was about 10 km s⁻¹. Enclosure 2 on the accompanying CD-ROM demonstrates the time development of the arch configuration (also see the movie).

Hudson, Lemen, and Webb (1996) and Hudson and Khan (1996) (also see review by Hudson and Webb, 1997) demonstrated a dimming (cavity formation) associated with this expanding structure which apparently corresponds to a coronal region where field lines got extended due to the expansion moving outwards, probably forming a CME. This dimming high in the corona can be seen very well when comparing Figures 1(a) (before the transit of the arch) and 1(c) (after the transit was over). Figure 4 shows measurements of total soft X-ray flux from two regions, high and low in the corona. It demonstrates that the dimming high in the corona,

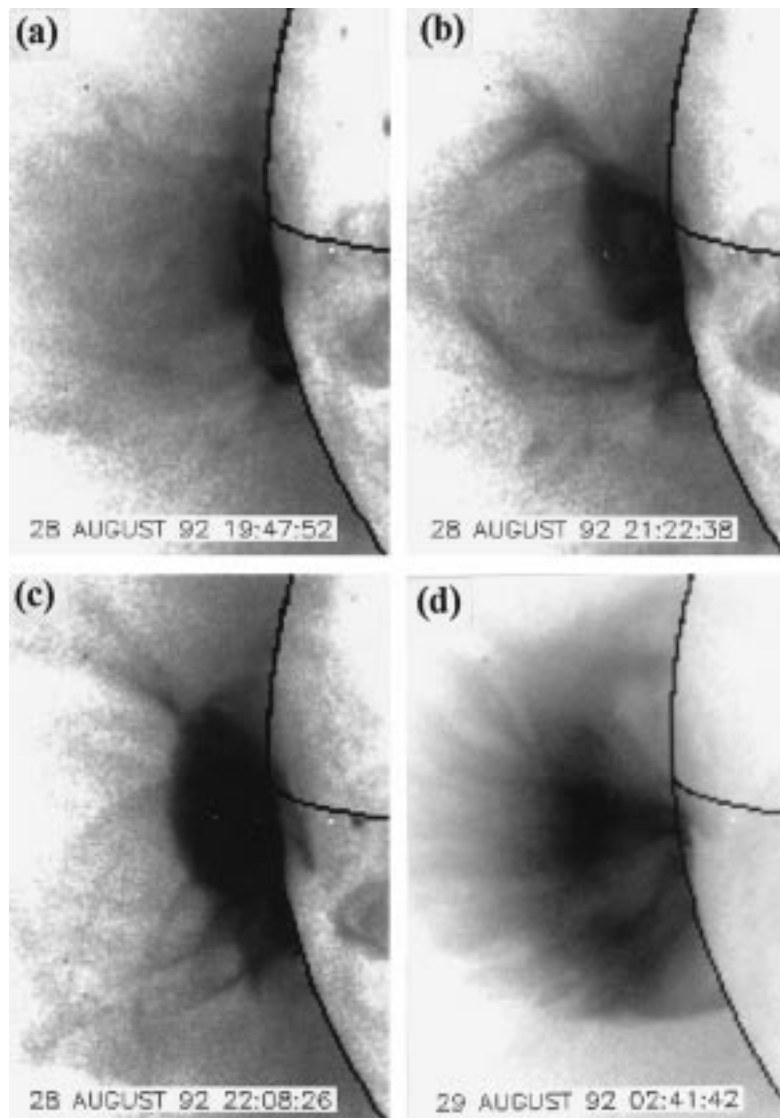


Figure 1. SXT images of the limb event of 28/29 August 1992: (a) Preflare structure of the corona above the active region at 19:48 UT on 28 August. (b) The expanding arch structure preceding the flare event, at 21:23 UT on 28 August. (c) Situation after the arch structure left *Yohkoh's* field of view, at 22:08 UT, three minutes before the onset of a long-duration X-ray event in GOES data (flare behind the limb). (d) The fan of coronal rays created during the flare, as observed at 02:42 UT on 29 August.

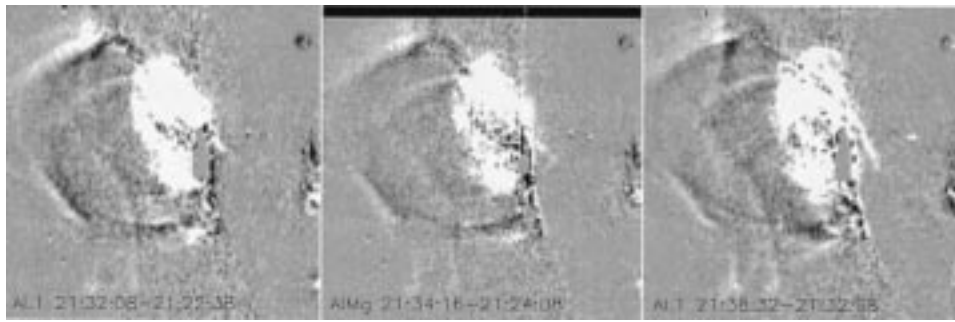


Figure 2. Three difference images of the arch-like structure, which overlap in time because of filter alternation. The outer two are in the Al.1 filter, the middle one in the AlMg filter. Each pair shows a subtraction of the earlier image from the later one, thus the direction from dark to bright shows the direction of the expansion.

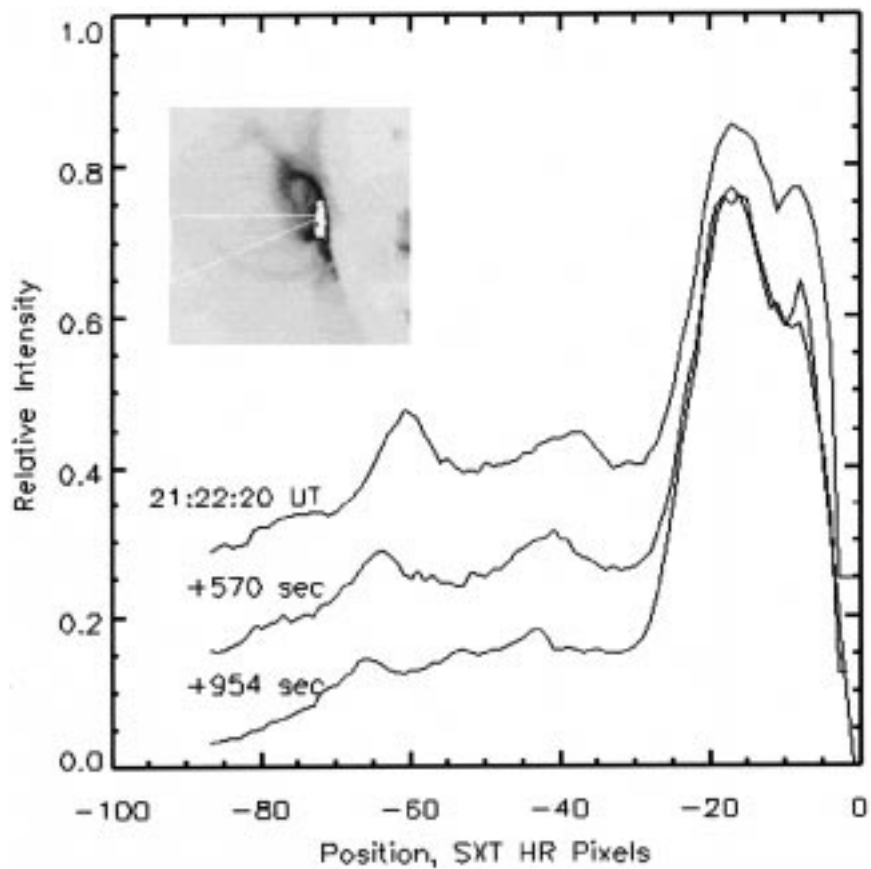


Figure 3. Azimuthal integrations of the coronal brightness above the flare, summing pixels above the limb between the two lines, for three Al.1 images during the development of the arch structure shown in Figure 2. The east limb of the Sun is at coordinate 0. The vertical scale has been modified for clarity. The rising arch-loops show up as local maxima moving progressively outwards (to the left). The projected velocity is about 10 km s^{-1} .

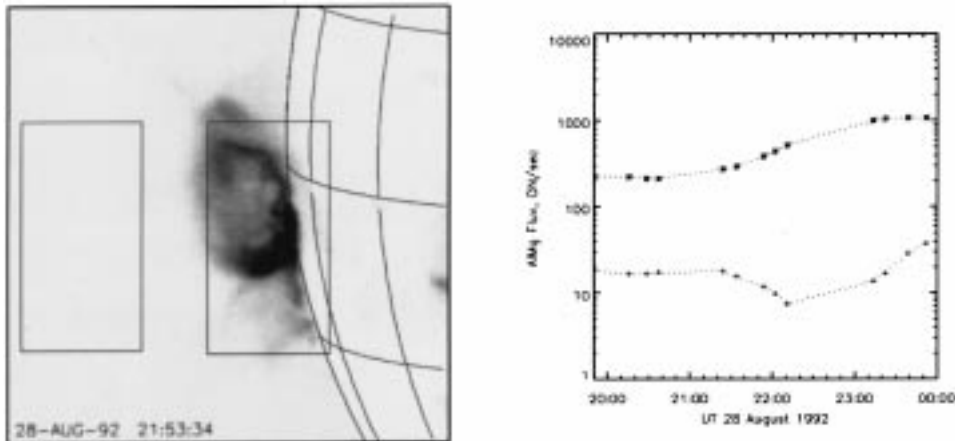


Figure 4. Time series of total SXT flux (AlMg filter) from two regions: the 'dimming' in the corona above the flare (left rectangle and + in the graph) and the flare itself (right rectangle and * in the graph). Note the near-simultaneity of the variations.

and the flare below it (apparently originating slightly behind the limb) started at about the same time.

In *SGD* (1993) Holloman AFB reports an eruptive prominence at the limb in the position of AR 7270 starting at, or before, 21:34 UT. This eruption, in comparison with *Yohkoh* SXT data, was studied by Watanabe *et al.* (1997). The filament eruption and the observed dimming make it indeed very likely that we have seen here the onset of a CME (also see Hudson, Lemen, and Webb, 1996).

4. Eruptive Flare behind the Limb

Behind this expanding structure, a system of flare loops began to grow and rise into the corona (Figure 5 and Enclosure 3 in the CD-ROM). Figure 6 shows the altitude of the tops of the loops (for two different positions) as a function of time, under the assumption that the loops grew in the vertical direction. In that case the loops reached an altitude of 125 000 km, rather typical for extensive 'post'-flare loop systems (cf., e.g., Smith *et al.*, 1994). However, the growth did not decelerate with the altitude as is usually the case with post-flare loops. (The constant speed of rise, in the vertical direction, was 1.65 km s^{-1} .) Although such cases of constant speed of growth of flare loop systems were observed before, they are rare and may indicate that the Kopp and Pneuman (1976) mechanism of the loop formation through sequential reconnection gradually changes into expansion of the reconnected loops (cf., Švestka, 1996).

No $\text{H}\alpha$ flare was reported in *SGD* (1993), but GOES showed a C1.5 long-duration X-ray event starting at 22:11 UT on 28 August, peaking near 00:18 UT on 29 August, and ending at about 09 UT on that day (cf., top graph in Figure 8).

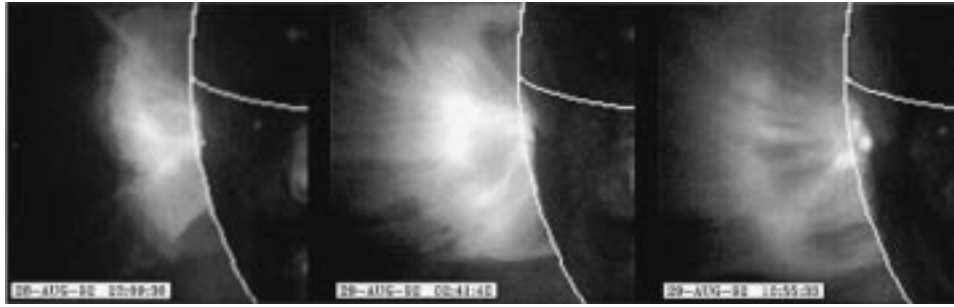


Figure 5. The development of the flare loop system.

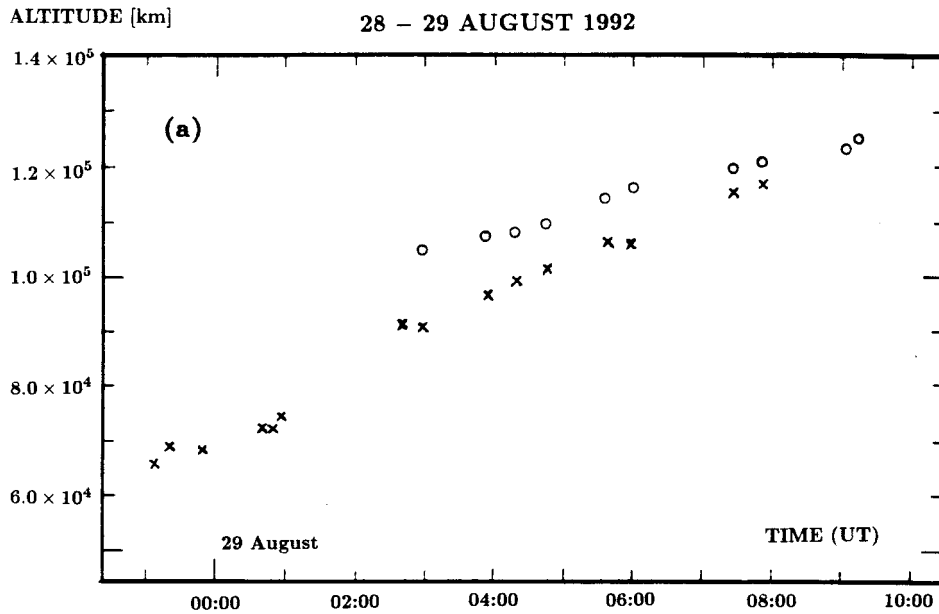


Figure 6. Growing altitude of the bright tops of the flare loops under the assumption of vertical extension, with solar rotation taken into account. Crosses and circles refer to the northern and southern components of the central part of the loop system.

Thus there are several different observations showing that an eruptive flare occurred in the active region behind the eastern limb: the filament eruption and the CME preceding the event, the appearance of growing flare loops below it, and the GOES record of a long-duration event in soft X-rays.

5. Hot Fan of Rays Surrounding the Loops

As Figures 1 and 4 demonstrate, the CME passage essentially removed the coronal material existing above the active region prior to the event – it swept it out.

Thereafter, however, during the rise of the flare loops (Figure 5), a completely new coronal configuration gradually developed, which looked like a fan of coronal rays in which the rising flare loops were embedded (Figures 1d, 5, and 7. The whole development of this coronal structure is shown in Enclosure 4 and in the movie in the accompanying CD-ROM).

The individual elements of the fan look like rays extending from the active region. We have measured the time development of brightness, emission measure, and temperature in one of the rays (area indicated by a rectangle in Figure 7) and the results are shown in the middle part of Figure 8. The temperature was found as high as 8.8×10^6 K at the beginning of our measurements at 23:10 UT, slowly decreasing thereafter. The emission measure was only 4.3×10^{42} cm⁻³ at that time and reached its maximum of 5.6×10^{43} cm⁻³ at the time of maximum brightness in the Al.1 filter, at about 04:45 UT. Thereafter, the structure slowly faded, but maintained its fan shape at least until 15 UT on 29 August.

Combining Al.1 and AlMg images close to the time of Figure 7, we have made maps of temperature and emission measure shown in Figure 9. To get statistically reliable data, we have smoothed 4×4 pixels of the half (4.9 arc sec) resolution of *Yohkoh* SXT, so that the resolution on these maps is 20 arc sec. Enclosure 5 on the accompanying CD-ROM shows Figure 9 in color.

Both Figures 8 and 9, as well as the CD-ROM Enclosure 5 demonstrate that the fan structure had very high temperature, during our period of observation as high, or higher, as the loop tops embedded in it. On the other hand, the emission measure of the fan of rays is very low, by about three orders of magnitude lower than in the loop tops. Thus the fan of rays represents a very hot and very rarefied coronal configuration.

6. Nature of the Fan Structure

One might suspect that the fan structure is some image artifact related to the emission from the tops of the loops. Therefore, we checked the mutual positions of the loop tops and rays in the fan. We made photometric scans along two circles: one going through the tops of the loops (**L**) and the other one running through the higher region occupied by the fan (**F**). Along each circle the brightness was measured in 60 coinciding points and the result is shown in Figure 10: there is no clear and obvious correlation between the brightness maxima in the loop system and in the rays creating the fan. Also, as the lowest graph in Figure 8 demonstrates, the brightness, temperature, and emission measure at the tops of the loops was decreasing monotonically during the period when the fan of rays (middle graph in Figure 8) reached its maximum brightness and emission measure. The GOES record in the upper graph in Figure 8 obviously mirrors this fading of the loops.

Therefore, the fan-like structure is real. The individual elements of the fan might represent very high loops projecting in their planes, i.e., with footpoints oriented

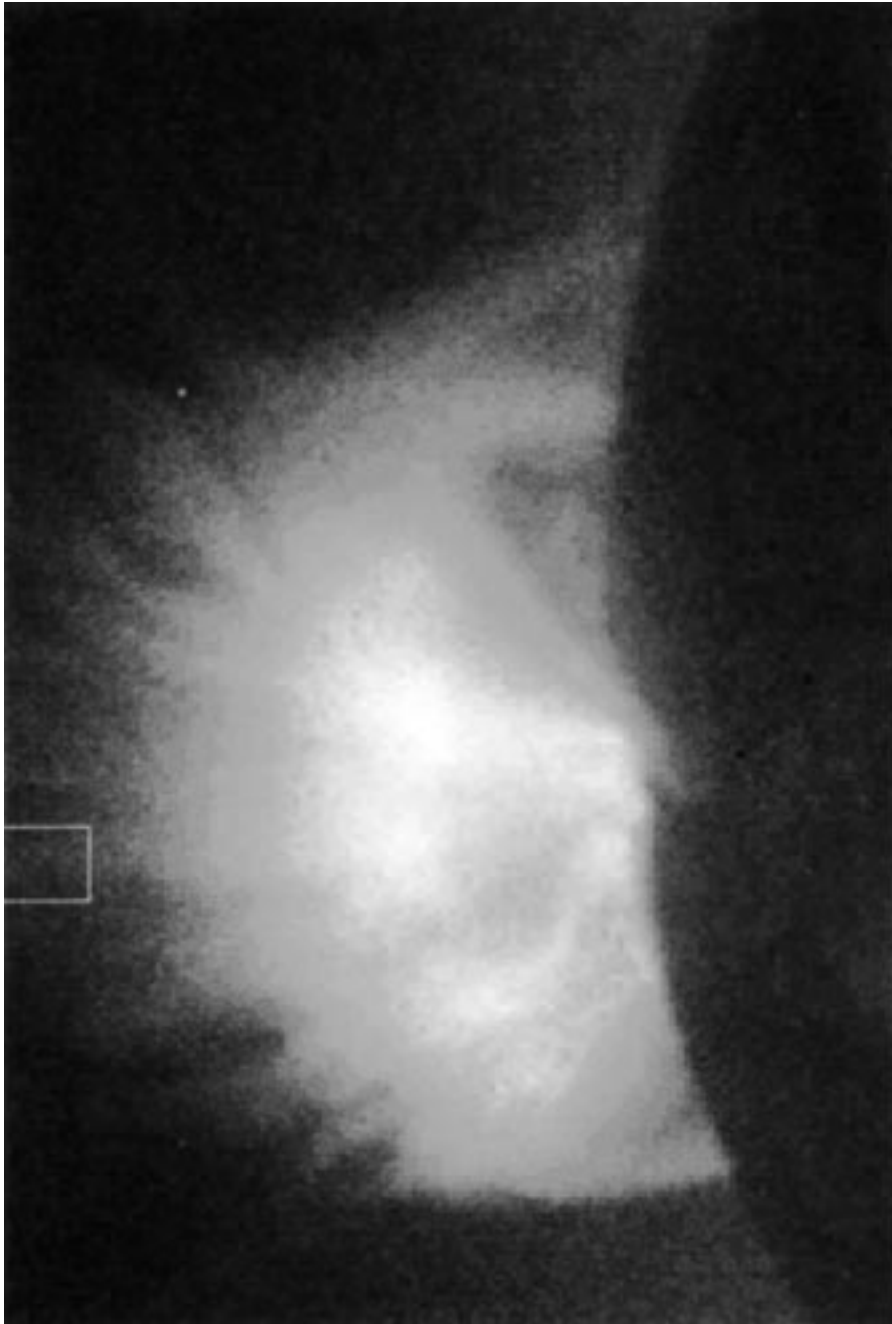


Figure 7. Image of the flare loops embedded in a fan-like coronal structure at 02:43:50 UT on 29 August. (AlMg filter, 2668 ms exposure, 4.9 arc sec resolution.) A rectangle marks the area, in which the measurements of the 'fan' data in Figure 8 were made.

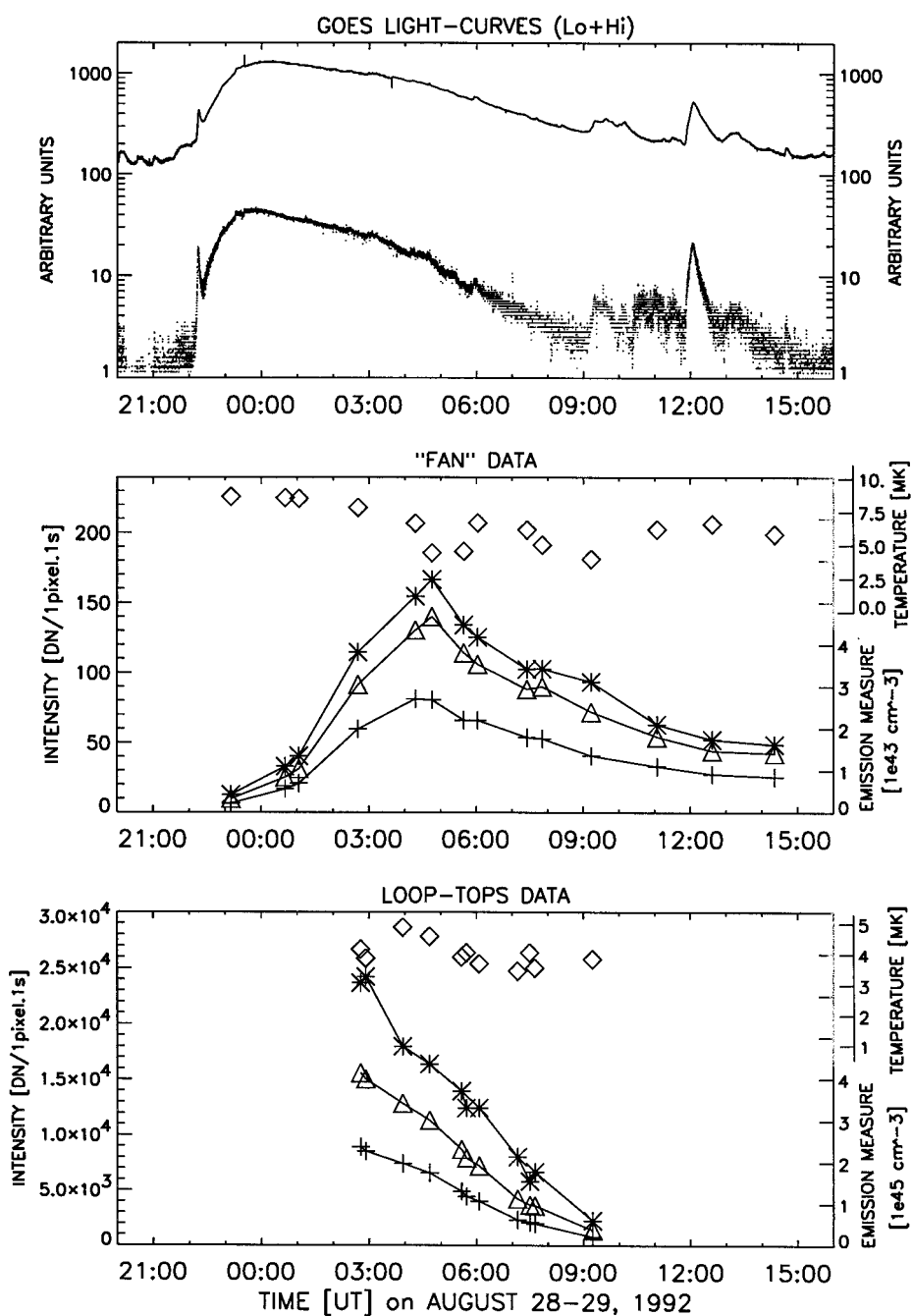


Figure 8. Upper part: GOES record of the event in $1-8 \text{ \AA}$ and $0.5-4.0 \text{ \AA}$. Middle part: the brightness variation in *Yohkoh* SXT Al.1 filter (triangles), AlMg filter (crosses), the temperature (diamonds), and emission measure (asterisks) in the area of coronal rays marked by the rectangle in Figure 7. Temperature and emission measure were determined from intensity ratios in filters Al.1 and AlMg. Lower part: Same measurements in an area at the top of the flare loops.

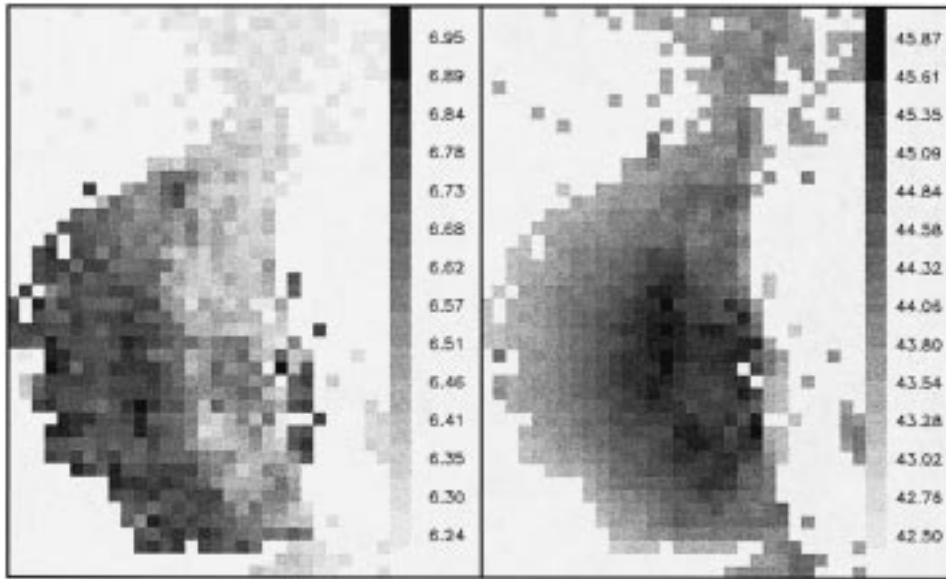


Figure 9. Temperature (*left*) and emission measure (*right*) maps of the limb event composed of Al I and Al Mg images made between 02:42 and 03:01 UT on 29 August. Both scales are logarithmic, the EM values are given per pixel. Spatial resolution on these maps is 20 arc sec. Color reproductions of these two maps are in Enclosure 5 on the accompanying CD-ROM.

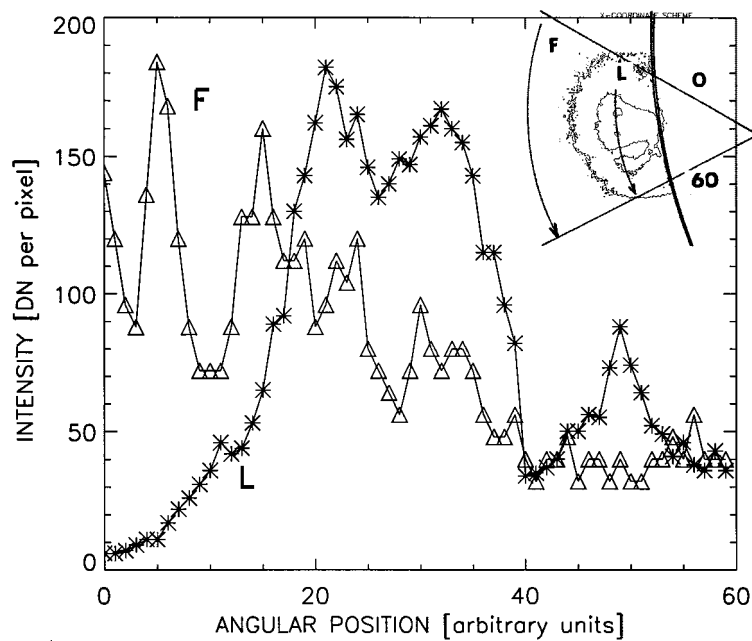


Figure 10. Photometric scans along circles running through the tops of the flare loops (L) and the higher region of the fan of rays (F). Vertical scale gives the count number per pixel, multiplied by 8 in the fan.

in the east-west direction. However, we have found other similar events in *Yohkoh* SXT images (cf., Section 8) and it is unlikely that such an orientation would be repeated in all cases. Thus the fan elements rather seem to be rays extending from the active region high into the corona, either some sort of a set of ministreamers, or extensions similar to polar plumes in quiet parts of the Sun (coronal holes).

7. Mass Flow from the Flaring Active Region

Hick *et al.* (1995) used interplanetary scintillation (IPS) measurements of the disturbance factor, g (Woan, 1992), which is related to density in the solar wind (Houminer and Hewish, 1974; Tappin, 1986), to construct synoptic Carrington maps of the structure of the quiet solar wind. When extrapolating these data to the solar surface, assuming a solar wind speed of 400 km s^{-1} and comparing them with X-ray Carrington maps from *Yohkoh*, the enhanced g -values tended to match active regions on the Sun. Thus the authors concluded that active regions play a role in feeding mass into the quiet solar wind.

Based on the results of Hick *et al.* we suggest that the observed fan of rays reflects material streaming from the active region into the solar wind. If this suggestion is true, then it indicates that active regions may not be permanent sources of solar wind, but become temporary sources of mass fed into the wind during and after some large flares, when field lines open and — for some time at least — only partially reconnect. Recently several authors (Klimchuk, 1996; Sterling and Hudson, 1998; Hudson *et al.*, 1998) have found indications that the reconnection process following initial field-line opening associated with a CME can be inhibited, so that it remains incomplete, or at least slows down.

We suppose mass outflow along the rays in the fan structure. If one assumes Klimchuk's (1996) configuration (his Figure 6) for sheared magnetic field lines, some field lines reconnect low in the atmosphere, but the reconnection process cannot proceed upwards, as it is assumed in the Kopp and Pneuman model. Thus configurations reminiscent of miniature streamers can be formed, with closed minihelms below and extended rays of open field lines above them. Such ministreamers can be sources of plasma flowing out of the active region: recently, Sheeley *et al.* (1997) identified solar wind streams with extensions above cusps of helmet streamers. The reconnection at the tops of the minihelms could heat these ministreamers so that they become temporarily visible in soft X-rays, like streamers seen after flares in some active regions, a phenomenon that we discussed in Paper III (Švestka *et al.*, 1997).

In such a situation, one might expect in Figure 10 an anticorrelation of the positions of open fields in the rays and close fields in the flare loops. However, one should not forget that we see here, and can correlate, only a two-dimensional projection of the three-dimensional configuration of the corona above the active

region: open and closed fields can alternate as well in the lateral direction (checked in Figure 10) as along the line of sight.

Another possibility is that we observe here structures similar to polar plumes. While ministreamers presuppose a bipolar configuration, plume-like structures would be unipolar. Recent SOHO observations (DeForest *et al.*, 1997; Hassler *et al.*, 1997) indicate that the polar plumes are cool relative to the inter-plume regions and that the likely source of the solar wind is not polar plumes, but the inter-plume lanes associated with open magnetic field regions. Thus it is possible that the mass flow occurs in between the ‘rays’. Unfortunately, the count statistics in our data is not good enough to make it clear (in Figure 9 and CD-ROM Enclosure 5) whether the whole structure, or only the rays forming the fan, or only the space between them, were hot. Hopefully, SOHO observations of similar events might clarify this problem.

8. Synoptic IPS Maps

In order to test this hypothesis of solar-wind flow from active regions, we have constructed a synoptic IPS map for the Carrington rotation in which AR 7270 appeared (Figure 11(a)). An arrow points to an enhancement which — within the limits of spatial resolution of this method — corresponds to the position of AR 7270. We then constructed the synoptic map once again, omitting a period of 5 days that followed the event observed. The result (Figure 11(b)) shows that the g -factor enhancement at the position corresponding to AR 7270 disappeared. This indicates that the mass emission was temporary.

We have seen other similar events in *Yohkoh* SXT images, although not all as conspicuous as the 28/29 August event. In particular, for three active regions we saw growing flare loop systems embedded in hot extensive coronal structures both when the regions crossed the eastern and western solar limb: AR 7345 in November 1992 (CM passage on 22 November, latitude 20° – 26° S), AR 7440 in March 1993 (CM passage 7–9.5 March, corresponding to Carrington longitude 85° – 120° , latitude 4° – 8° S), and AR 7448 in March 1993 (CM 15–17 March, corresponding to Carrington longitude 350° – 10° , latitude 14° – 18° N). We could not construct any IPS synoptic map for November 1992, because the active region was too far south on the southern hemisphere where IPS coverage is insufficient. However, we have constructed IPS maps for the period when the March 1993 active regions crossed the solar disk, and we again found remarkable enhancements of the g -factor intensity at the positions corresponding both to AR 7440 and AR 7448 (Figure 11(c)).

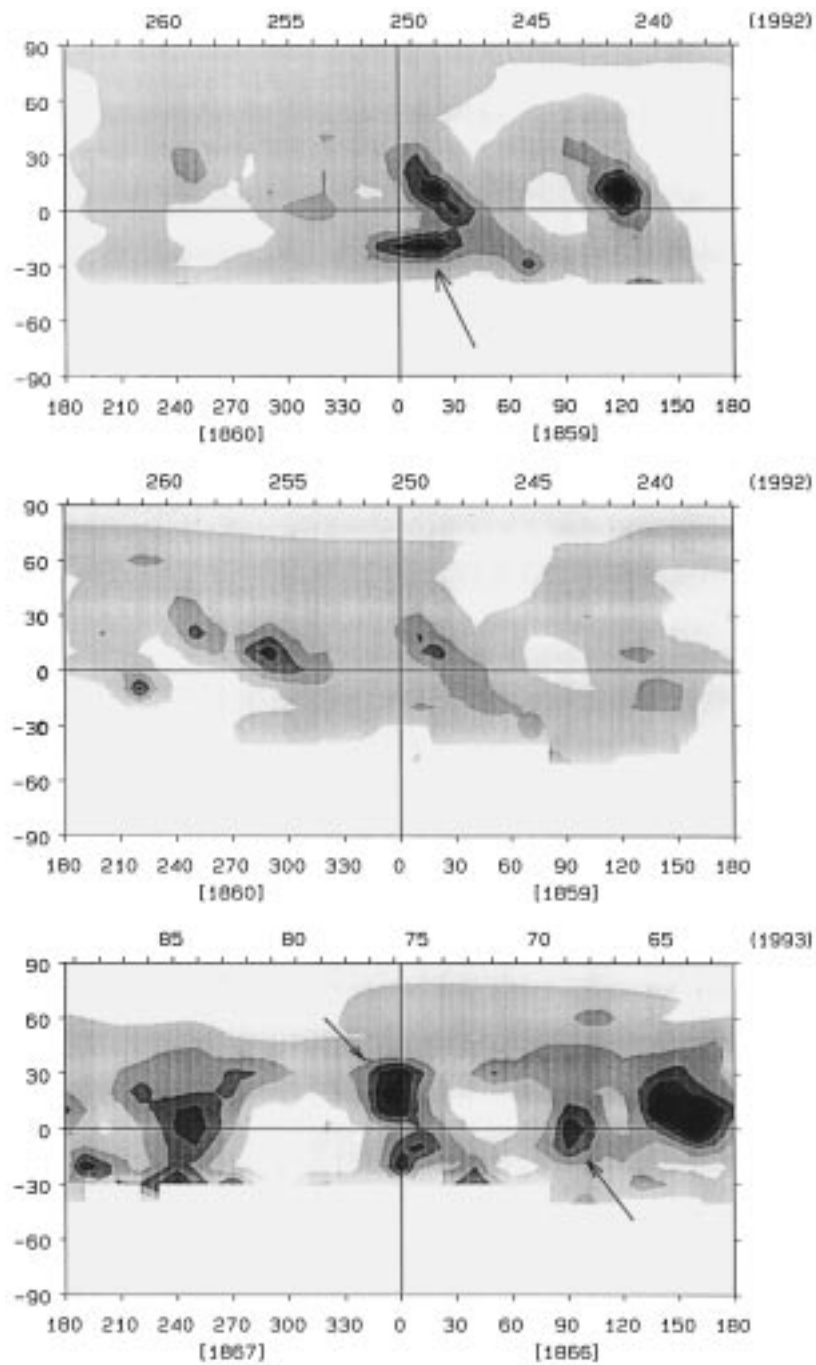


Figure 11. (a) IPS synoptic map for Carrington rotation 1859/1860 showing enhancements of the g factor (density) in the solar wind. An arrow points to the enhancement that coincides with AR 7270. (b) The same map after omitting 5 days following the fan-like structure observed; the enhancement corresponding to AR 7270 disappeared. (c) IPS synoptic map for Carrington rotations 1866/1867 showing enhancements of the g factor at the positions of AR 7440 and AR 7448 (arrows).

9. Conclusion

Thus the suggestion that the fans of rays observed by *Yohkoh* represent mass emission from active regions is strongly supported by IPS data. As this coronal ray structure above active regions can be distinguished only when it is formed in events close to the solar limb, and we have seen several of them in *Yohkoh* SXT data in 1992 and 1993, there must be quite a number of active regions on the Sun which feed mass into the solar wind, in agreement with the supposition made by Hick *et al.* (1995). However, whereas Hick *et al.* assumed a permanent emission of mass from some active regions, our observations rather indicate that the emission is temporary, or strongly variable, dependent on the occurrence of events (CMEs) which open the magnetic field which thereafter stays partially open for tens of hours or – in some cases – perhaps for many days.

Acknowledgements

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