PASJ: Publ. Astron. Soc. Japan **44**, L7–L13 (1992)

White-Light Flares of 1991 June in the NOAA Region 6659

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(Received 1991 October 2; accepted 1991 October 19)

Abstract

We report on observations of flare activities in an active region NOAA 6659, which appeared on the sun in 1991 June. Among six X-class flares in this region, we observed three flares (June 4, 9, and 11), all of which were white-light flares. A detailed discussion is given concerning a particularly interesting white-light flare which occurred on June 11.

Key words: Sun: Flares — Sun: Activity — Sun: Sunspots — White-light flares — Moreton waves

1. Introduction

NOAA region 6659, an active region which appeared on the sun in 1991 June, showed unprecedented flare activities (Preliminary Report and Forecast of Solar Geophysical Data, NOAA-SESC PRF 823 and 824, 1991). At the National Astronomical Observatory of Japan, a newly built instrument (the Solar Flare Telescope) which is equipped with CCD cameras and a video disk recording system observed the region in Hα and at a continuum wavelength of 4300 Å. Three major flares in this active region were successfully observed: flares of June 4 (X-ray class X12, Hα importance 3B, maximum time 0339 UT), June 9 (X10/3B, max. 0140 UT), and June 11 (X12/3B, max. 0206 UT), respectively. All of these flares were white-light flares. Unfortunately, the magnetic and velocity measurement systems of the Solar Flare Telescope had not been completed at the time of this flare activity. (A description of the instruments and scientific aims of the Solar Flare Telescope will be given elsewhere.) In addition, photographic and video observations as well as the usual Hα full-disk flare patrol observations were made using other telescopes.

Among other major flares in this region, an X12/4B flare on June 6 (max. 0112 UT) and an X12/3B flare at the west limb on June 15 (max. 0831 UT) were not observed due to cloudy weather in Tokyo. An M4/3B flare on June 7 (max. 0134 UT) was observed through thin clouds. An X12/1F flare at the east limb on June 1 (max. 1529 UT) occurred at night in Japan.

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2. The Flare of June 4

2.1. Hα Observation: Moreton Wave

This flare (X-ray class X12, Hα importance 3B, maximum time 0339 UT) took place near the east limb. Using the Solar Flare Telescope we observed this flare from the beginning to the later phase with a spectacular loop prominence system (figure 1a). The Hα images were recorded on a video disk at the rate of one frame per 10 s. The flare started as a bright point in the southern large umbra. With ejection of material toward the north, the Hα emission explosively expanded in the north-south direction, and a twisted, low-lying loop appeared above the Hα flare ribbons. Then, tall loop prominences formed, first in the northern part and subsequently in the southern part above the flare ribbons. The loop prominence system gradually increased its height, reaching a height of about 65,000 km, when the observation was interrupted by sunset. A point in the western flare ribbon remained particularly bright for a considerable period of the loop prominence phase. This point could be a footpoint that was connected to a localized energy liberation site; it was situated close to (but not exactly at) the location of the initial Hα bright point.

A full-disk Hα patrol recording shows the propagation of a Moreton wave along the solar limb in the direction of the north pole (figure 1b). The wave swept the solar surface over 45° in heliocentric angle. The speed of propagation was around 2500 km s^{-1} when the wave was initiated, and increased to 4000 km s^{-1} when the wave approached the north polar region during the later phase. These values are at the largest end of the range of Moreton wave speeds ever observed (Smith and Harvey 1971).

According to the standard model (Uchida 1968), a Moreton wave is a disturbance caused by a magnetohydrodynamic (MHD) shock wave emitted from the flare site into the corona. The shock wave is refracted in the corona and re-enters the chromosphere, where the impinging wave is visible in Hα as a Moreton wave. The speed of the Moreton wave reflects the speed of the MHD shock wave in the corona. For weak shock waves (Mach number close to unity), the propagation speed is the MHD fast-mode speed, which is virtually equal to the Alfvén speed ($V_{\rm A}$) in the case of the solar corona. For strong shock waves, for example when the compression ratio is 2, the propagation speed is $1.5V_{\rm A}$ (Priest, 1982). The acceleration of the wave speed found in the present event is presumably due to reduced density in the polar coronal hole region; a density reduction of factor 2.5 explains the observed change in the propagation speed.

2.2. White-Light Observation

The white-light flare was observed with a 20 cm refractor through a green colored-glass filter, and was recorded on video tape. The recording speed was one frame per second. Since the field of view was nearly full disk, the spatial resolution in the video recording was not very high. Nevertheless, an interesting development of the white-light flare was observed (figure 2a, b).

The first brightening in white light was seen at a southern portion in the active region, at 0337 UT (figure 2b, the first frame). The point at which the brightening started in Hα was displaced 30$''$ toward the north from this white-light brightening. Along with the rapid expansion of the Hα flare ribbons toward north, successive brightenings of white-light patches were observed in the northern part of the region. At 0339 UT three patches were seen (figure 2b, the second frame), and at 0340 UT five patches were seen (figure 2b, the third frame) in addition to the first bright patch in the south. Among them, one patch was located in the northern umbra; the others were inside, or at the periphery, of the penumbra. At around 0342 UT the initial southern patch faded away. The other bright patches also disappeared one after another, and the last patch near the northern edge of the penumbra of this region (figure 2b, the fourth frame) faded away at about 0346 UT. Therefore, the lifetime of some of the patches was as long as 6 minutes, though they generally formed and decayed with the time scale of about 1 min. Brightness fluctuations with time scales shorter than 20 s were observed.

The patches were 2–3$''$ in size and were aligned along the magnetic neutral line. A comparison with Hα images shows that they all correspond to the brightest portion of the Hα ribbons (Hα kernels). It is difficult to determine on which side the individual patches were located, and whether two patches made a pair as two footpoints of a single loop. Within the resolution of the observations, individual patches did not show any detectable motion.

3. The Flare of June 9

This flare (X-ray class X10, Hα importance 3B, maximum time 0140 UT) showed a development similar to the flare of June 4. The Hα images through the Solar Flare Telescope at first showed a pair of sheared Hα ribbons that formed above the sunspots. Subsequently, a distant region to the west of the sunspot region brightened and became additional flare ribbons (figure 3). In a later phase, loop prominences (which were still sheared) appeared, connecting the two Hα ribbons. This loop prominence system was diffuse and only existed for about one hour.

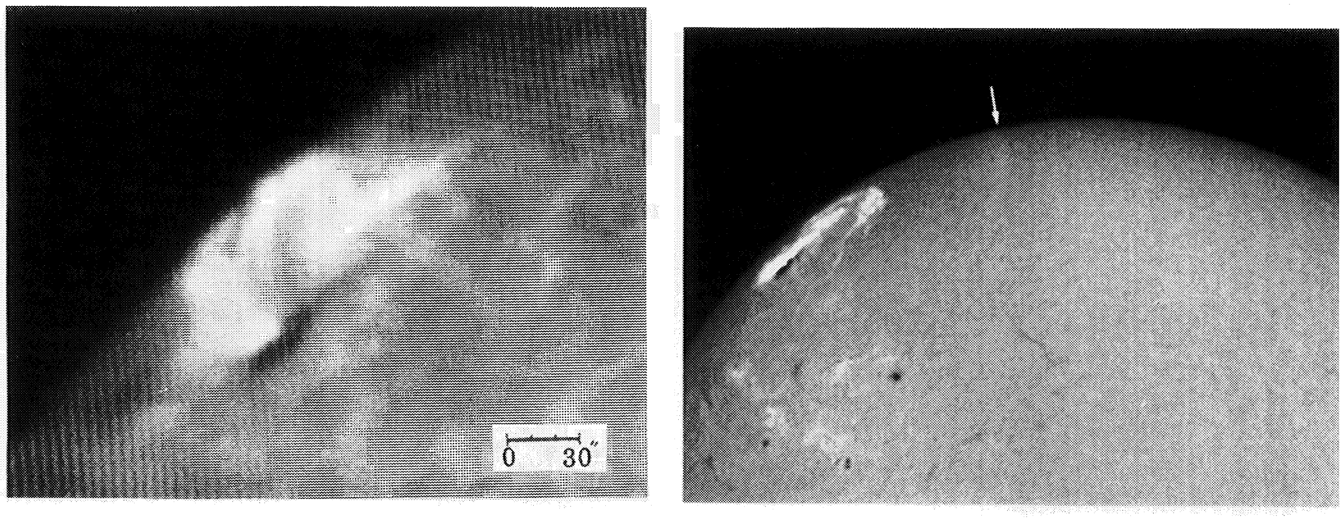
The Solar Flare Telescope also observed this flare with a continuum wavelength at 4300 Å, the so-called g-band of CN. An interference filter with a passband of 20 Å was used. Only one white-light patch was observed in this flare (figure 4). The patch was first seen at 0137 UT near the northern border of an umbra (which corresponds to the umbra A of June 11 in figure 6b). This location corresponds to the brightest part of the northern flare ribbon, and the patch was elongated (the size is $5'' \times 15''$) along the flare ribbon. The white-light patch was observed to move or expand toward the center of the umbra at 0139 UT, and then receded to the edge of the umbra. This behavior corresponds to the time development of the Hα ribbons. Since the patch was seen until 0143 UT, its lifetime was about 6 min. The brightness distribution within the patch was observed to fluctuate, and it may well be that the patch actually comprised several smaller patches that varied over shorter time scales.

4. The Flare of June 11

4.1. Hα Observation: Winking Filaments

This flare (X-ray class X12, Hα importance 3B, maximum time 0206 UT) showed a slower development, compared with the other two flares, and the flare brightenings had a tendency to expand toward the east rather than toward the north-west. Weak flare activities had been seen in this region about one hour prior to this flare, and dark filaments to the east of this region showed continuous changes.

The Hα flare started as a sheared pair of bright ribbons, one in the north above the umbra (marked as A in figure 6b) and the other to the south of the umbra (figure 5a). Then, the northern ribbon expanded toward the east, and the southern ribbon expanded toward the west. In a later phase a loop prominence system running north-south appeared, which showed a relaxed structure



(a) (b)

Fig. 1. (a) An Hα image of the flare of June 4 in the phase of a loop prominence system (0432 UT). North is up and west is to the right in this and in all the following figures. (b) An Hα image of the Moreton wave (pointed by the arrow) seen in the flare of June 4 (0341 UT).

(a)

(b)

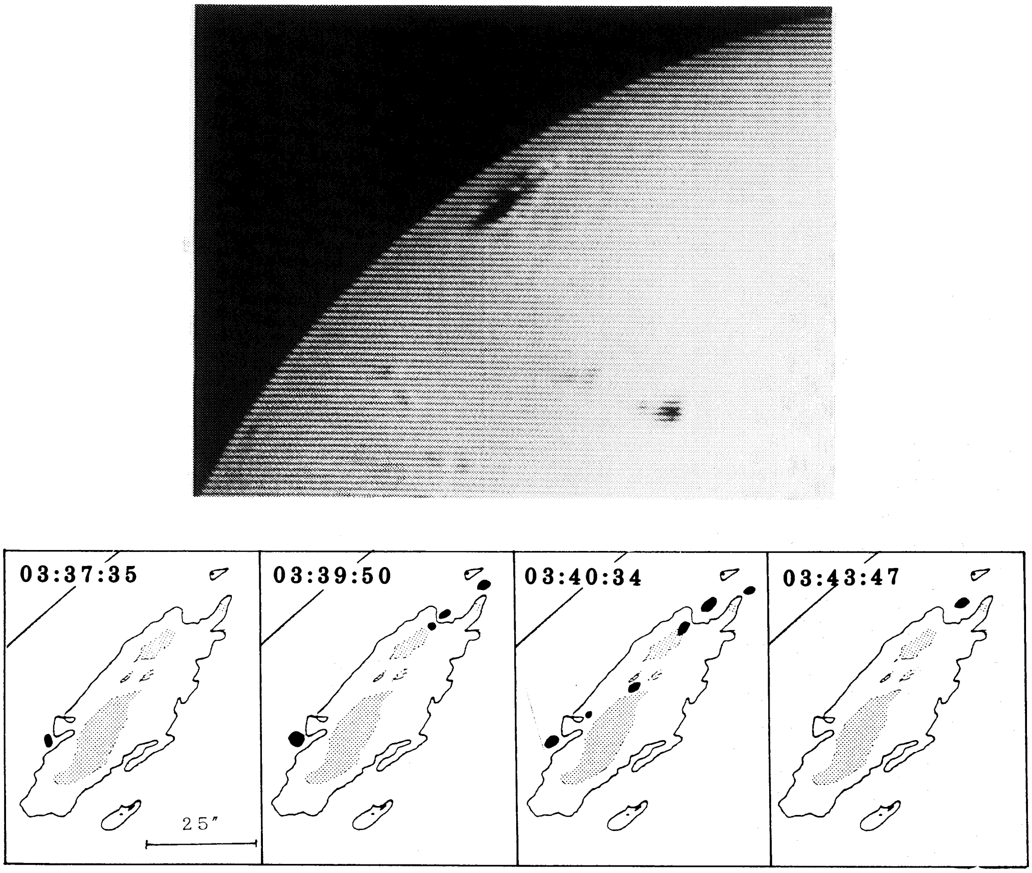


Fig. 2. (a) White-light image of the flare of June 4 (0340 UT). (b) A series of sketches indicating the time development of the white-light flare patches (shown by dark dots). The shaded areas indicate the sunspot umbrae. The third frame corresponds to the photograph (a).

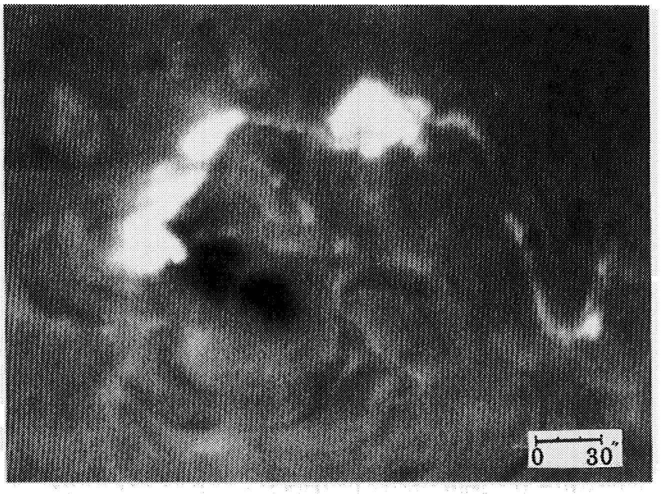


Fig. 3. Hα image of the flare of June 9 in its initial phase (0139 UT).

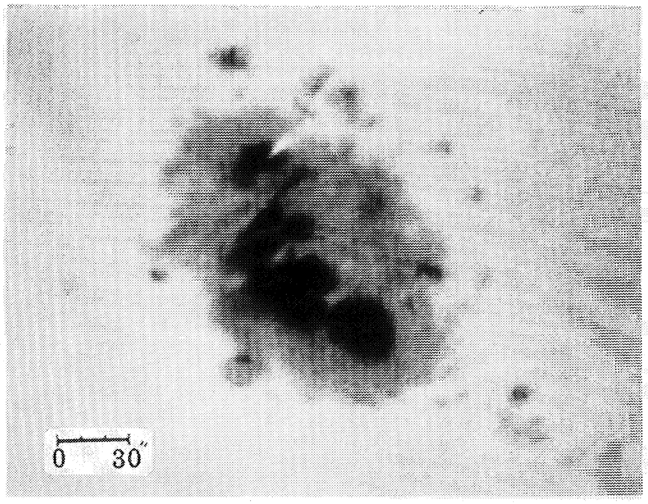
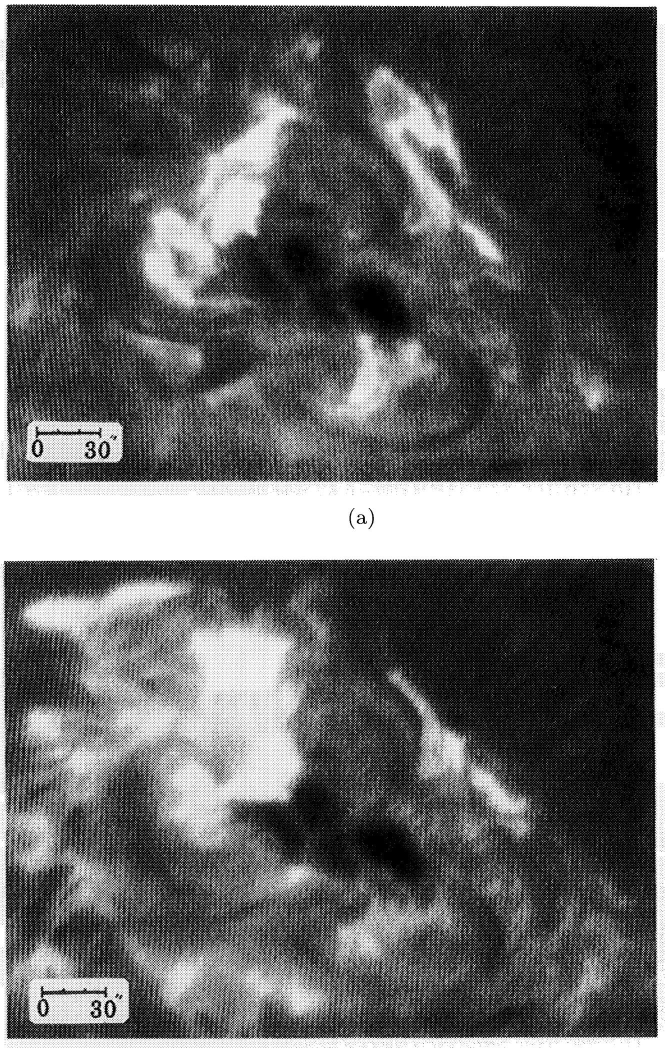


Fig. 4. White-light patch of the flare of June 9, taken through a g-band filter (0139 UT).



(a)

(b)

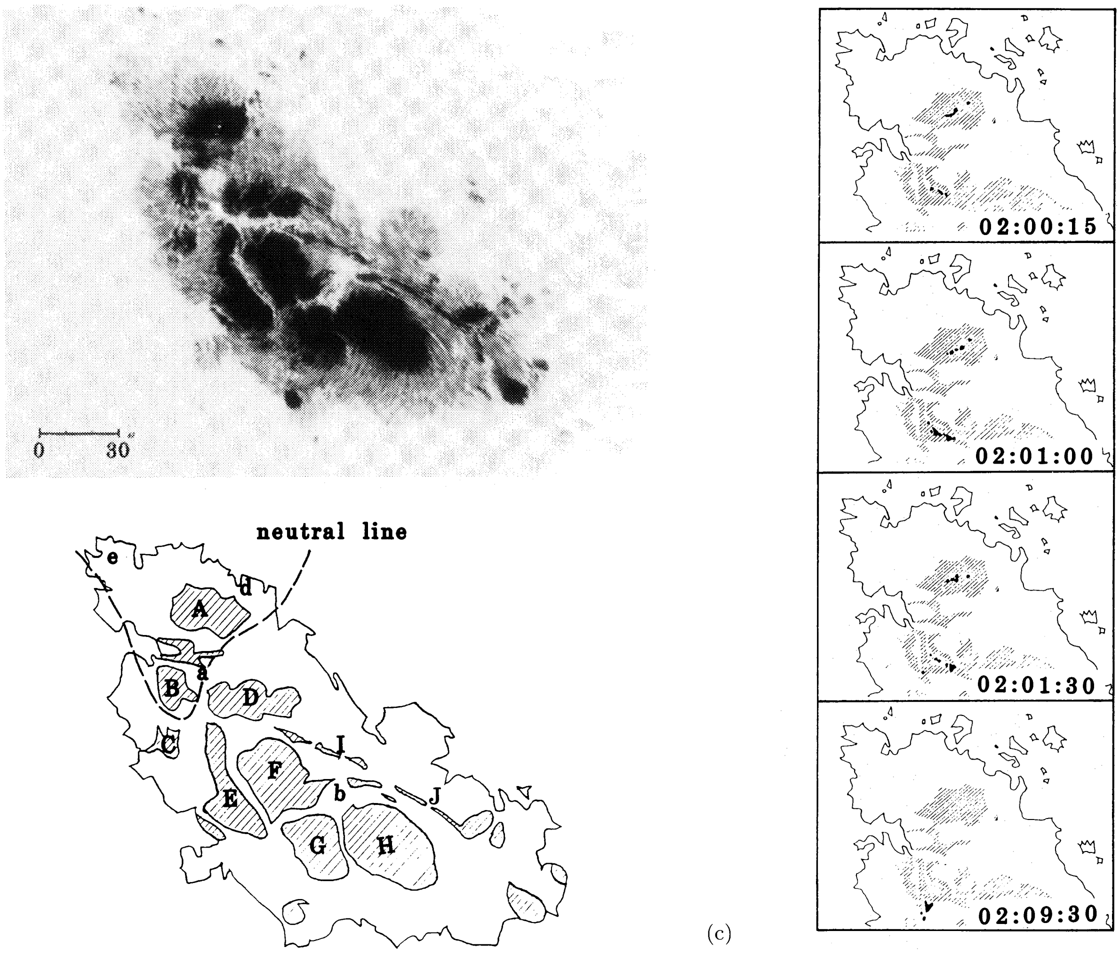
Fig. 5. Hα images of the flare of June 11 in the initial phase (a, 0202 UT) and in the late phase with a loop prominence system (b, 0227 UT).

of the magnetic field lines (figure 5b).

A full-disk Hα patrol recording shows the so-called winking filaments (Bruzek 1969) associated with this flare. After initiation of the flare, several dark filaments far to the east of this active region (more than 30° away in heliocentric angle) were disturbed, indicating propagation of a disturbance from the flare. The speed of the disturbance is estimated to be around 800 km s^{-1}. Also, the so-called remote brightening phenomenon (Smith and Harvey 1971) was observed in the same area. No indication of a Moreton wave was found in our data, however.

4.2. White-Light Observation

The Solar Flare Telescope observed this flare through a g-band filter. The photographic observation was also made with a 20-cm refractor with a green colored-glass filter. The photographs were taken roughly every 15 s during the maximum phase of the flare; figure 6a is an example of the photographs taken at the time of the flare. The sunspots and other notable structures are labeled as in figure 6b. The two magnetic polarities aligned almost north-south, and the umbrae were surrounded by a common penumbra (the δ-configuration). The penumbral region showed a very fine structure: bright channels running through the penumbra were most notable.

(a)
(b)


(c)

Fig. 6. (a) White-light image of the flare of June 11 (0201 UT). (b) Schematic drawing of the active region NOAA 6659 on June 11. (c) A series of sketches depicting the time evolution of white-light patches (shown by dark dots). The shaded areas indicate the umbrae. The third frame corresponds to the photograph (a).

Regions a and b in figure 6b were as bright as the surrounding quiet photosphere, and granular structures were seen there. The direction of penumbral threads, particularly to the west of umbra H, indicated a highly sheared magnetic field. According to the vector magnetograms taken at Mees Solar Observatory, University of Hawaii (R. C. Canfield, private communication), the location of the magnetic neutral line is inferred, as is reproduced in figure 6b. A high degree of shear in the transverse magnetic field was also seen in the magnetograms.

The long chains of umbrae I and J were very peculiar. They comprised several elongated umbrae which were aligned along the penumbral filaments. This structure was seen to gradually develop from the penumbral filaments in three days (June 9–11). We may conjecture that these chains of umbrae were formed from penumbral filaments as their field strengths increased. The chain structure may reflect a wiggle in nearly horizontal magnetic field lines.

The white-light patches were seen in umbra A (fig 6a) and in the region surrounded by umbrae B, C, and E. These two areas are where the brightest part the Hα flare ribbons were located. The time evolut of the white-light flare patches is illustrated in figure Figure 6a corresponds to the third frame of figure 6c

The patches in umbra A first appeared at 0200 U the center of the umbra. The sizes of the patches w 1–2″. Although individual patches showed continu changes in shape with a time scale of 15 s or so, a group they delineated east-west, along the northern ribbon. From 0203 UT the bright patches shifted in sition toward the eastern edge of umbra A. This refl an expansion of the northern Hα ribbon toward the e The patches were visible until 0208 UT.

The other group of white-light patches appeare 0201 UT between umbrae B and D. The patches peared in pairs, one in the east and the other in the west of the magnetic neutral line. The sizes of these patches were larger than those in umbra A, namely 5–10″. As the flare proceeded, a pair of patches moved toward the south. At 0206 UT the patches reached between umbra C and the northern edge of umbra E, and faded away. This behavior also reflects the development of the southern Hα ribbon.

The area marked d in figure 6b is the place where Hα flare brightening initially started at 0156 UT. Although in white-light images this region also showed an enhancement in brightness from the onset of the flare, its brightness contrast was much lower compared with the other white-light patches mentioned above.

There were several reported cases in which a sunspot penumbra disappeared after a flare (e.g., Zirin and Tanaka 1973; Hiei et al. 1987). In the present case, part of the penumbra (marked e in figure 6b) disappeared several hours after the flare. The bright channel in umbra B increased its width and umbra B, itself, shrank. The bright channel at the northern periphery of umbra B disappeared. Flare-related magnetic-field changes like these examples were studied in detail by Tanaka (1978, 1991).

5. Discussion

Regarding the present observations, although no spectroscopic data were collected, a very complete coverage of filtergrams made it possible to study the detailed time development of the white-light flares in this active region.

It has been known that white-light flare brightenings fall into several classes (Rust and Hegwer 1975; Zirin and Tanaka 1973; Hiei 1986). In one class of brightenings, several small (1–3″) patches with lifetimes of a few tens of seconds ("impulsive white-light patches") appear, which vary in correlation with the hard X-ray intensity. Kurokawa et al. (1988) found that point-like brightenings in Hα, which had time scales of seconds, are correlated with hard X-ray spikes. These facts suggest that hard X-ray bursts, impulsive white-light flare patches, and Hα brightenings might be due to a beam of high-energy electrons impinging onto the lower atmosphere. In the second class of white-light brightenings, the bright patches have longer lifetimes and resemble the shape of the Hα flare ribbons. These can be called "gradual white-light patches." The third class of white-light brightenings is called "white-light flare waves" (Rust and Hegwer 1975) or "diffuse white-light brightenings" (Hiei 1986). They move toghether with the Hα flare ribbons.

In the present observations:

(a) The flare of June 4 showed several white-light patches, some being impulsive and some having longer lifetimes. Both the impulsive and the long-lived patches did not show any apparent motion, but the flare location was not favorable to observe such motion, even if the patches might have followed the separating motion of the two ribbons.

(b) The flare of June 9 only showed a long-lived white-light flare patch, which showed a motion or expansion in responding to the development of the Hα flare ribbons. There is an indication that the patch comprises several smaller patches with impulsive variations.

(c) In the flare of June 11, the white-light flare patches in the umbra showed impulsive variations in the initial phase; they later turned into a long-lived brightening and showed a motion that followed the Hα ribbon. The white-light patches in the penumbral region were long-lived and showed a motion following the development of the Hα ribbons.

In summarizing, we observed two kinds of white-light brightenings: impulsive patches with a time scale of several tens of seconds, and the more stable patches that move together with the Hα ribbons. The latter had sizes no larger than 15″, and are classified as "gradual white-light brightenings" rather than "diffuse brightenings" or "flare waves."

All of the patches that we observed correspond to the Hα bright points (kernels), in agreement with previous reports (e.g., McIntosh and Donnelly 1972; Slonim and Korobova 1975). However, in the flare of June 4, the brightest Hα kernel did not show white-light emission, while the other less bright kernels were detected in white light.

The usual rule that the white-light patches are found near the border of penumbrae (McIntosh and Donnelly 1972; Slonim and Korobova 1975) applies only to some of the white-light flare patches that we observed. The other white-light patches were located at the middle of the umbra. It is expected that the strong and rapidly converging magnetic field in a sunspot umbra would tend to hinder the penetration of particle beams or heat flow. Therefore, the present case gives a new restriction in considering the models of flare energy release.

We are grateful to Dr. R. C. Canfield for providing us with the magnetograms of the region studied here. The Solar Flare Telescope Project was financially supported by a Grant-in-Aid from the Ministry of Education, Science and Culture (No. 63065001). The Project had initially been led by the late Prof. Katsuo Tanaka, who died on January 2, 1990.

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