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FLARES

Observations of flare-associated magnetic field changes

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[Plates 25–28]

Although it is widely accepted that energy for solar flares must be sought in rapid conversion of magnetic energy, observations of flare-associated magnetic field changes have proven difficult and controversial. Different observers have come to widely varying conclusions about the nature and reality of the reported flare-associated field changes. However, it is possible to reconcile these differences because most of the observations have been made at a level of precision comparable with the maximum field changes that even the largest flares could result from. High resolution filtergrams and magnetograms made within the past five years have made it possible to deduce that flares are associated with the emergence of new flux and with its reconnexion to older fields. Recent observations are reviewed.

1. Pitfalls of the naive approach

What sort of association may we expect to find between the magnetic fields of an active centre and the flares there? At first it was assumed that we might find direct evidence for conversion of magnetic energy into flare energy, since it is widely acknowledged that the only source of energy for flares is in the magnetic fields. All that is necessary is to show that a 0.3 T (3000 G) sunspot field is reduced by 5×10^{-2} T. For a volume 10^4 km on a side, this change will give about 10^{25} J – enough to power a large flare. Typically then, the fields in an active region are examined one day before a large flare, then measured again the next morning with the discovery that the field decreases. The problem with this procedure is that the next observation will usually show a field *increase* after the flare.

The pitfall in this naive approach is that the error in most sunspot field measurements is of the order of 5×10^{-2} T and that the typical daily change for sunspot fields in flaring *and non-flaring* regions is of the same order. These conclusions came from the I.G.Y. study of visual and photographic sunspot magnetic measurements from Mt Wilson, Pulkovo, Crimea and elsewhere. The error in most sunspot field measurements is about 10–20 %. This is enough to mask any energy losses associated with flares, as long as the field observations are made only once per day. Hourly observations may not even be enough to accurately measure any field changes associated with flares. Reports leading to this conclusion are the works by Künzel (1967, 1971) and by Vyal'shin & Krüger (1973). The latter reference is one of a series of papers resulting from an extensive effort to observe rapid field variations in sunspots. Only the largest sunspots were studied and field variations of up to 8×10^{-2} T/day were found, but Baranov, Vyal'shin & Surkov (1972) reported that the field in a fragmenting sunspot decreased at the rate of 8×10^{-2} T/h. More frequently, observations separated by 1 or 2 h indicated field changes of 2×10^{-2} T, and it is conceded that these variations were probably not real (Künzel 1971). The field variations were compared with

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

flare activity and no association was found. However, no attempt was made to concentrate on the spots over which the flares occurred: the only criterion was that the spots and the flares were in the same active centre.

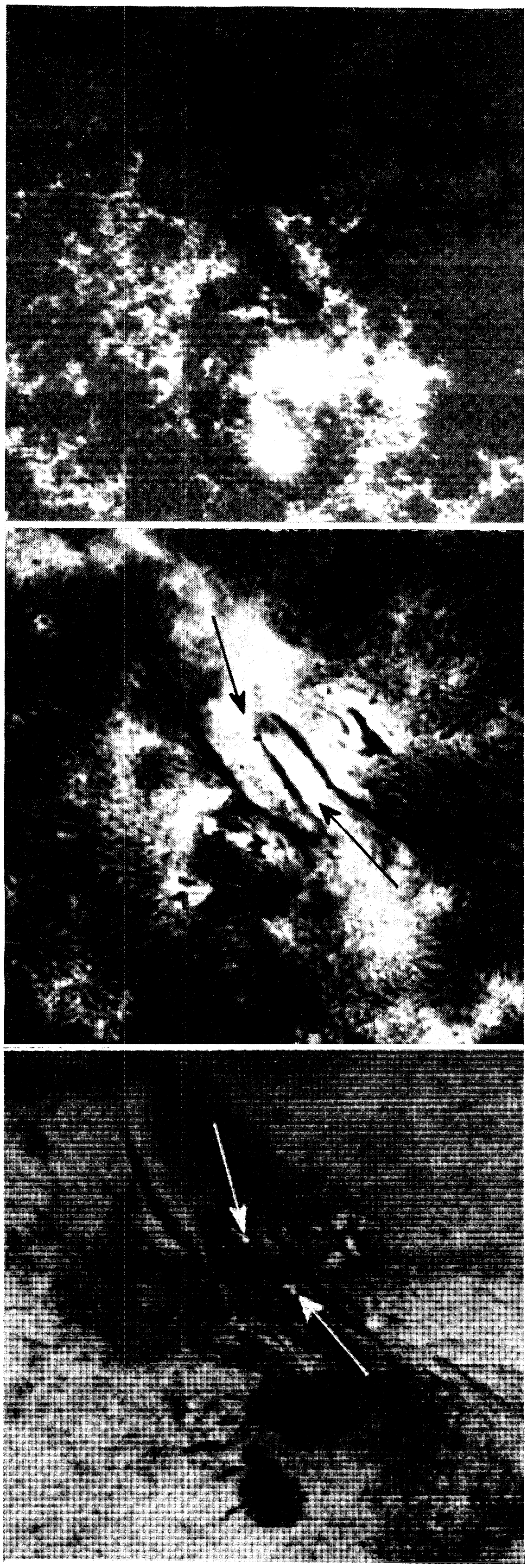
To establish the proper baseline for the study of flare-assciated field changes, we must know how fields usually vary. Cowling (1946) deduced that value from the Mt Wilson observations many years ago. He found that the rate of increase of field in spots is about 5 mT/h, and the rate of flux increase is about 1.5×10^8 Wb/s. The normal rate of decay is about 0.5×10^8 Wb/s. This rate may be compared with the flare-associated changes found by Severnyi and his co-workers (Severnyi 1963, 1969*a*, *b*; Zvereva & Severnyi 1970). They find that major flares are accompanied by flux changes of $3\text{–}10 \times 10^8$ Wb/s. The fields in the region that produced the proton flare of 7 August 1972 decreased at the rate of 6×10^8 Wb/s in an hour and a half period following flare onset (Rust 1973*b*), and Livingston (1974) observed a drop in field strength following the 4 July 1974 proton flare of a similar magnitude and over a similar time interval (several hours). On the other hand, these rates are somewhat larger than the rates of change usually found with magnetograph observations (Rust 1968, 1972; Ribes 1969) made during minor flares. These observations give rates of $10^7\text{–}10^8$ Wb/s in small spots underlying flare kernels. Thus, *except possibly in those rare cases of the largest proton flares, the rates of change in sunspot fields do not differ from normal growth or decay rates.*

There are many reports in the literature to indicate that photospheric fields do not change when flares occur (Wiehr 1972; Harvey, Livingstone, Harvey & Slaughter 1971; Howard & Babcock 1960), but these reports should be viewed in the same light as the positive reports. The observations have suffered from insufficient sensitivity (e.g. Harvey *et al.* and Howard & Babcock) or from insufficient time resolution (e.g. Wiehr).

2. Flares and evolving magnetic fields

Improvements in resolution in the past five years have made possible a better understanding of how flares are related to photospheric magnetic fields. The emphasis has moved from attempts to show that the magnetic fields weaken in flares to attempts to find whether the photospheric fields have any relationship to flare occurrence at all. In a thorough study of spectrograms from an evolving active region, Ribes (1969) found that flares occur when the magnetic flux in one pole of an evolving magnetic feature is decreasing while the flux in the opposite pole is increasing. Excellent flare sequences have been obtained at the Lockheed, Sacramento Peak and Big Bear solar observatories, and these observations have confirmed the early results of Ogir & Shaposhnikova (1965), Martres, Michard & Soru-Iscovici (1966) and of Martres, Michard, Soru-Iscovici & Tsap (1968). Flares tend to occur in regions of growing pores, and surges associated with small flares occur near growing pores on the boundaries of large spots (Ogir 1971; Koval & Stepanyan 1972). Roy (1973) has studied these events most thoroughly, and Roy & Michalitsanos (1974) have described a case of apparent collision between a moving satellite sunspot and older network fields. When the two patches of field approached each other, there was continual flare and surge activity. This ceased when the fields there weakened.

Ramsey & Martin (1974) studied flares in the D_3 line of helium I and showed that the kernels, which are especially clear at that wavelength, occur near changing pores. Recent observations with the diode array at Sacramento Peak confirm their results. Rust & Bridges (1975) studied 12 sub-flares that occurred in McMath 12848 and 12849 on 10–14 April 1974, and in McMath



magnetic fields

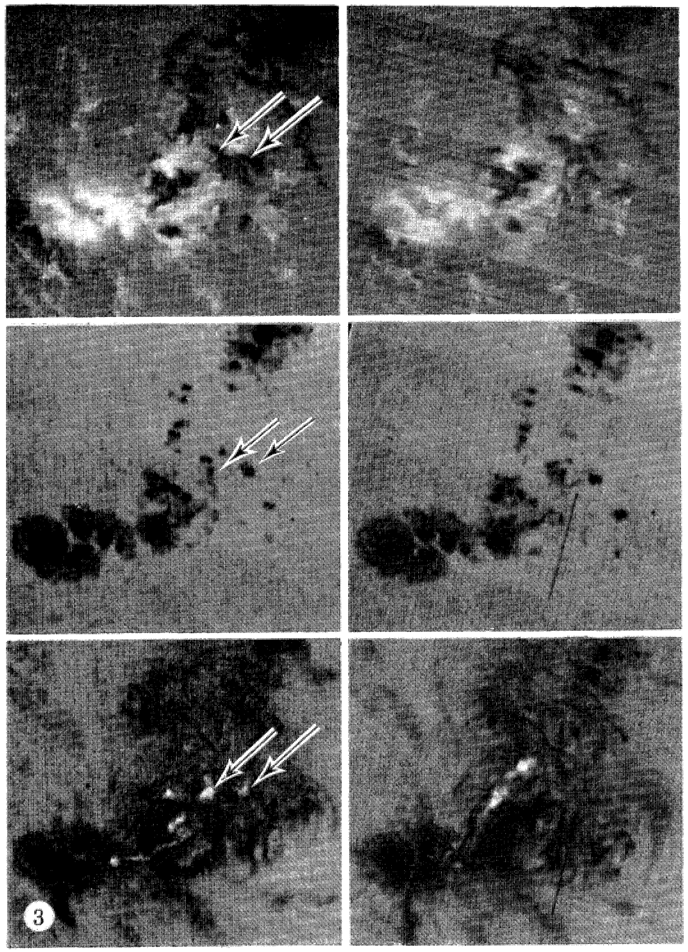
Hα

He 10830 Å

FIGURE 1. Three simultaneous views from the diode array showing a small two-ribbon flare near disk centre on 7 May 1974 at 15h 20 U.T. The area shown is about 240″ square. Arrows point to the flare patches.

(*Facing p.* 428)

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES



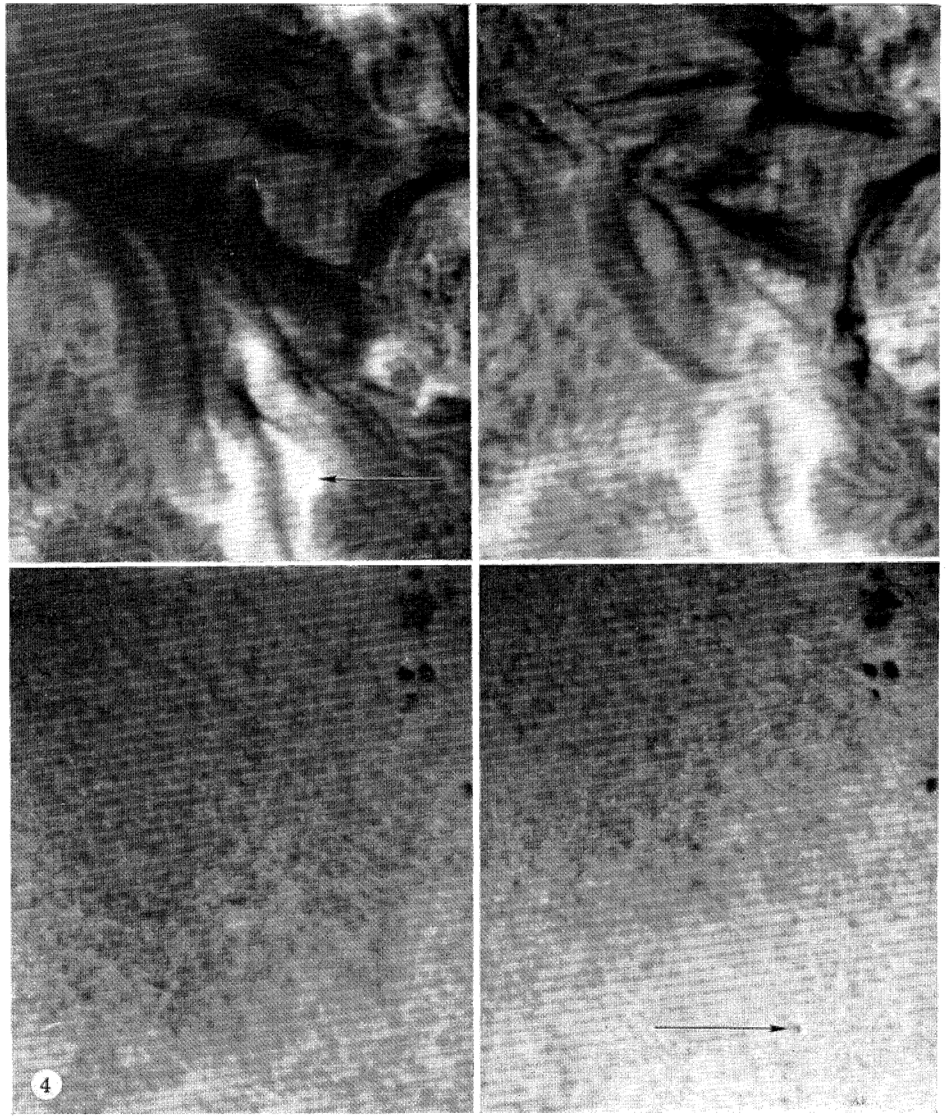


FIGURE 3. Flare kernels (bottom), growing pores (middle) and magnetic fields (top) in McMath region 12848 at S 12° W 34° on 13 April 1974. North is down in this picture and west is to the left. Arrows indicate flare kernels and growing pores for the subflare at 15h 50 U.T. (left column). Right column is 18h 07 U.T.

FIGURE 4. Hα (top) and continuum (bottom) pictures of a subflare on 23 June 1972. Dark material at 22h 30 U.T. (left column) is an erupting filament. The arrows show one of the bright knots of the flare (at 22h 30 U.T.) and the emergence of a pore in the underlying photosphere at 22h 55 U.T. (right column).

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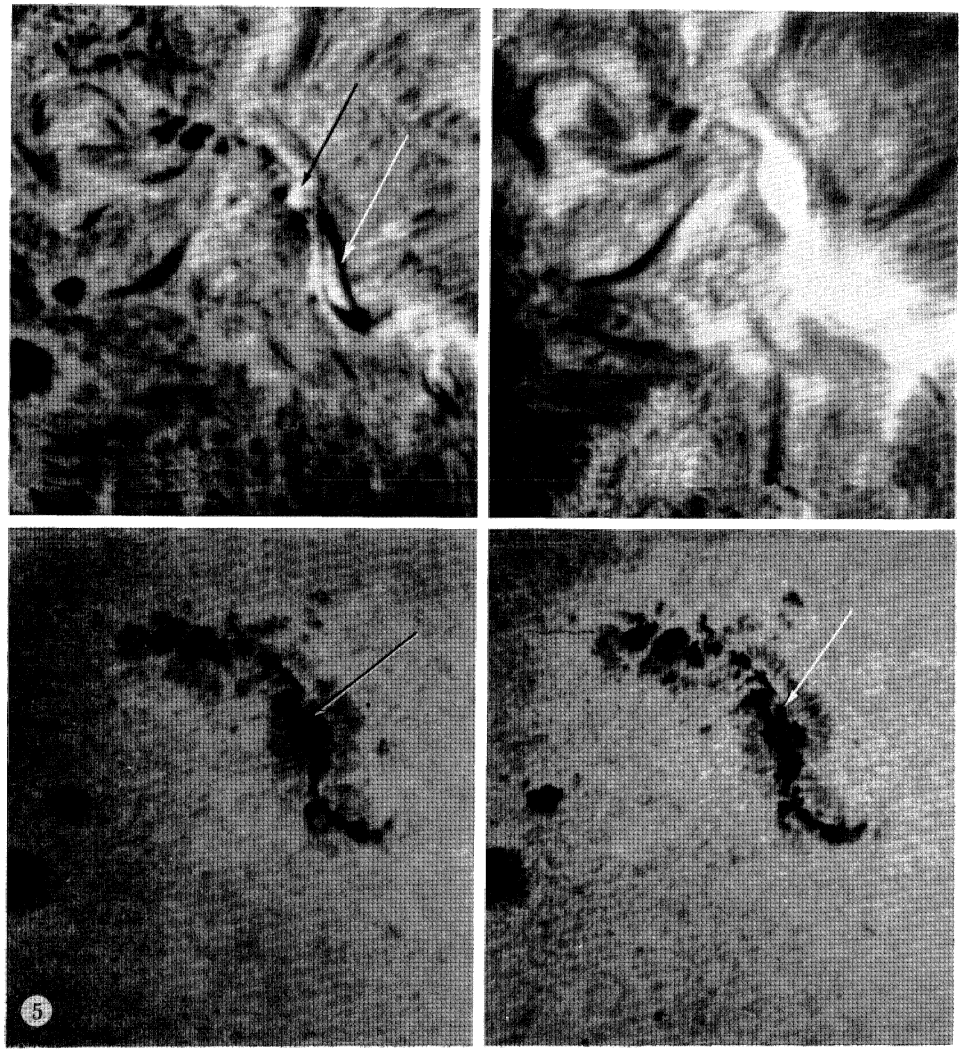

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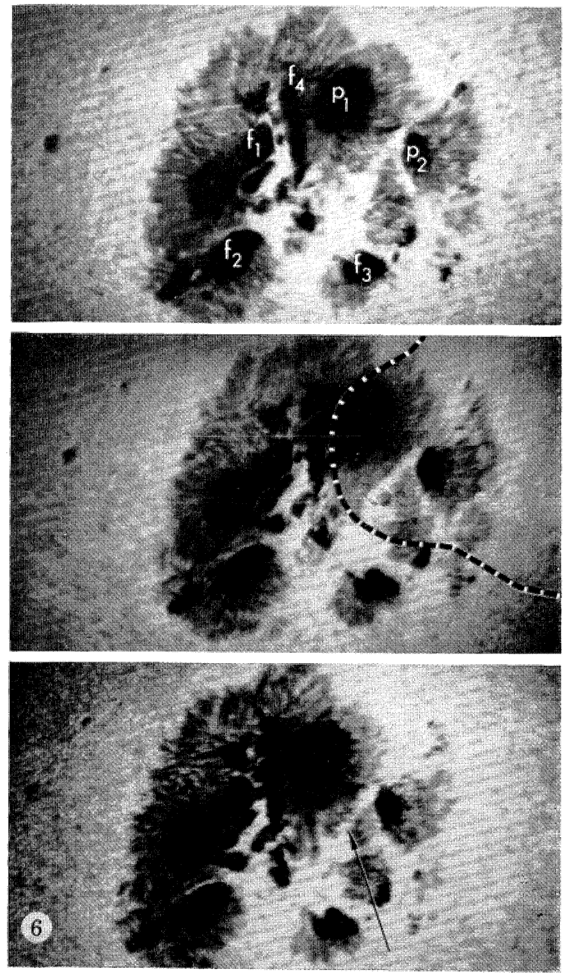
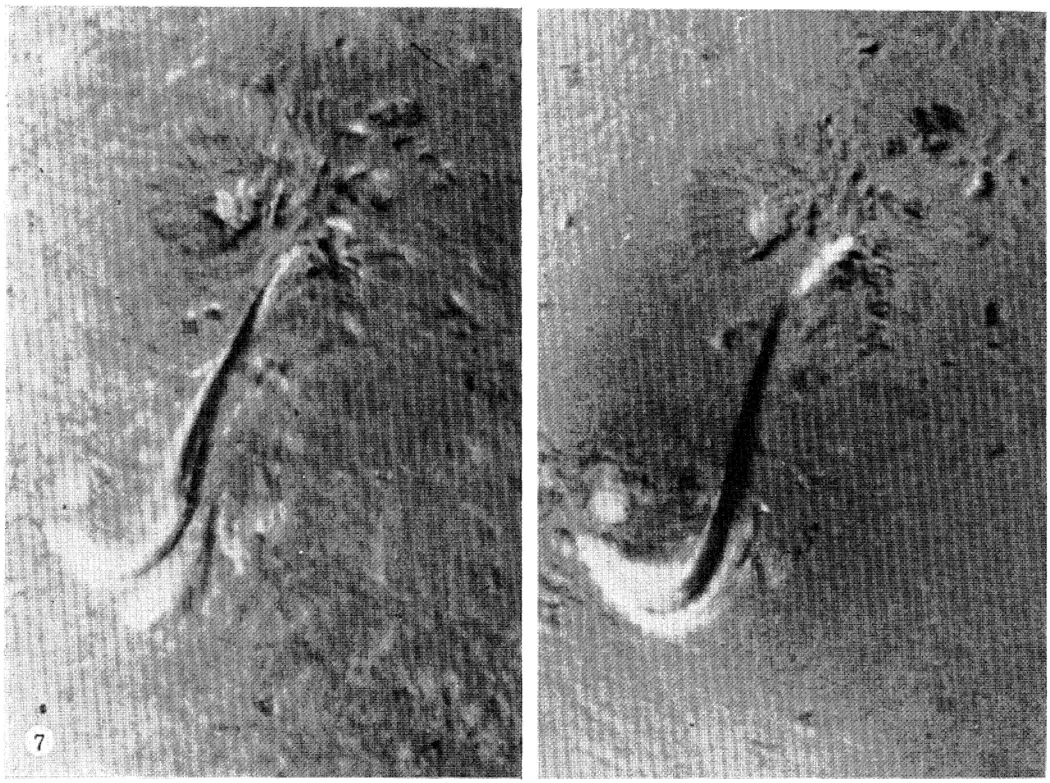
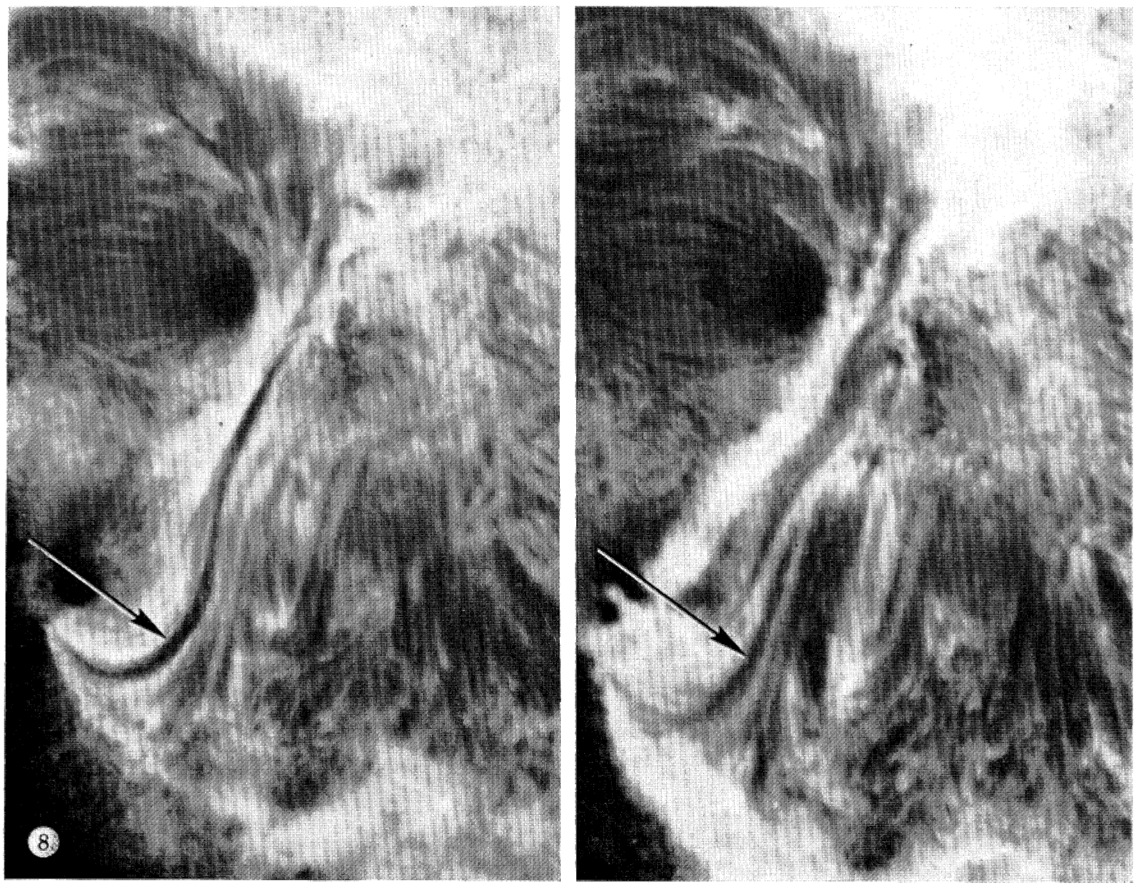


FIGURE 5. Hα (top) and continuum (bottom) pictures of a subflare on 24 June 1972. Universal Time and offset (Å) from Hα (6563 Å) are indicated above or below each frame. At 19h 13 U.T. the filament (white arrow) erupted from over the neutral line as the first flare kernels (black arrow) appeared. Flare maximum occurred at 19h 18 U.T. The pictures 19h 22 and 20h 17 U.T. show two stages in the growth and elongation of a small spot (indicated by arrows) that lay under the crescent-shaped flare kernels and first appeared during the hour preceding flare onset at 19h 05 U.T.

FIGURE 6. Rapid changes in sunspots on 7 August 1972. The times of the pictures (top to bottom) are 12h 05, 14h 40, and 15h 40 U.T.; a 3B proton flare occurred at 15h 10 U.T. The heavy dashed line in the middle picture indicates the location of the neutral line in the longitudinal magnetic fields. The arrow shows a region with changing penumbral structure where magnetograph measurements indicated a sharp field decrease following the flare.

16h 19 16h 36 U.T.





before after

FIGURE 7. Two Doppler subtractions showing motions of a filament on 19 January 1972. Left to right: subtraction of Hα ± 0.875 Å photographs 15 min before flare onset; subtraction of Hα ± 1.375 Å photographs 2 min after flare onset. Grey indicates no line-of-sight motion, white shows falling material, and black shows rising material.

FIGURE 8. Two Hα pictures of the region that flared on 19 January 1972. The arrows pointing to the lower end of the eruptive filament before (16h 19 U.T.) and just after (17h 27 U.T.) the flare show how the dark feature curving upward from the spot changes from being part of the filament before (left) to being part of an emerging arch filament system (right).

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

12906 on 4–8 May 1974. *In every case* the flares were marked by one or more kernels with emission above the continuum level at 10830 Å. Figure 1, plate 25, shows a typical example of the flares studied by Rust & Bridges (1975). The only transient events in the 10830 line were brief (15 min) brightenings of small (10″) patches and fluctuations in the position and contrast of the dark filaments. Notice that the flare ribbons are much more extensive in the Hα spectroheliogram and that the 10830 plage near the flare kernels and within the perimeters of the Hα flare ribbons was unaffected by the flare. The advantages of flare observations in the helium 10830 line are obvious from study of this figure. The flare kernels, believed most directly connected to the invisible point of flare origin in the upper chromosphere, are seen in sharp relief. Sunspots are easier to see at 10830 than at Hα. This facilitates comparisons of flare morphology with the photospheric magnetic fields.

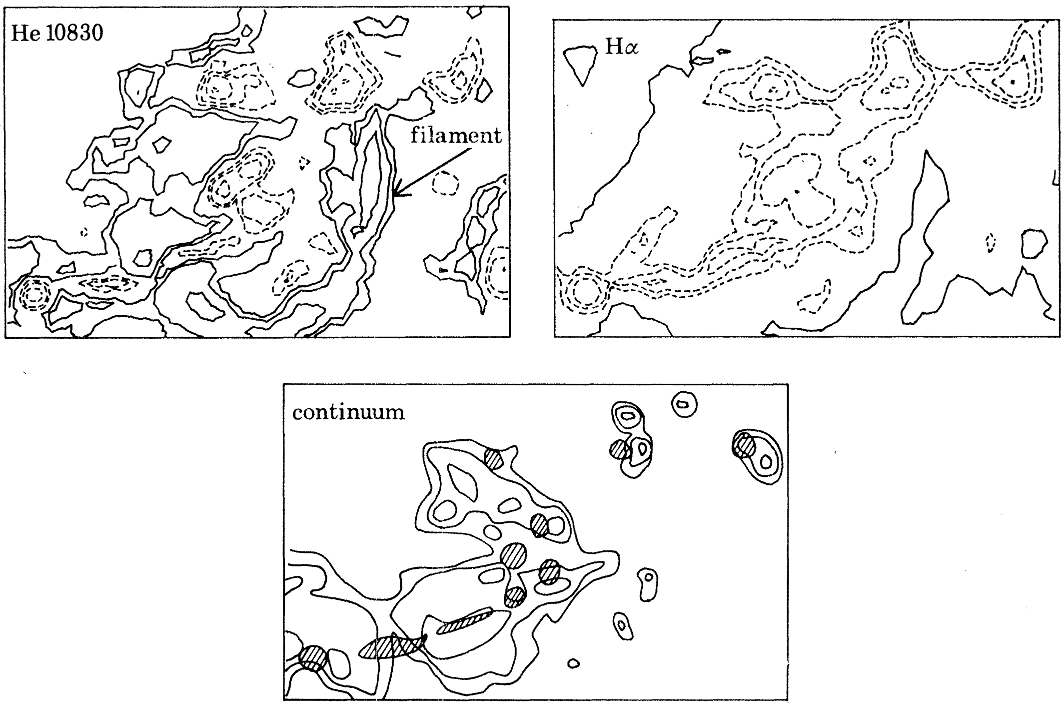


FIGURE 2. Contours of relative brightness in the chromosphere and photosphere at the peak of the subflare shown in the next figure. Solid contours enclose dark areas (such as the filament) and dashed contours enclose the bright flare patches. In the bottom frame the hatched areas represent the He 10830 emission kernels.

In all of the studies of flares with the diode array, magnetograms and sunspot images with 1–2″ resolution were obtained simultaneously with the flare observations. This makes possible the sort of comparison shown in figure 2, where it may be seen that the helium knots have a 1 : 1 correspondence with the well studied (Moreton & Severny 1968) Hα kernels. Of greater interest is the fact that each flare kernel lies just off the centre of a sunspot umbra. Careful study of long sequences of spectroheliograms revealed that many of the umbrae 'kissed' by flare kernels were growing or changing shape rapidly.

In 8 cases out of 12 studied by Rust & Bridges (1975), at least one of the flare kernels brightened within 3–5″ of a clearly identifiable knot of emerging magnetic field. The emerging fields revealed their presence in two ways: as 5″ knots on the magnetograms and as darkening pores in the photosphere. For example, figure 3, plate 26, shows the behaviour of the magnetic field, the sunspots and the He 10830 chromosphere in the subflare at 15h 50 U.T. on 13 April 1974. The pattern of 10830 emission shown in the figure was followed by many of the other flares, but the intimate association between the emergent fields and the bright kernels is clearest in the 13 April data. Two of the emergent poles are marked by white arrows in figure 3.

Usually at least one kernel appeared over one of the older spots of the region. Only on 12 April did we detect changes in an older spot during the flare period (from an hour before to an hour after the flare), but subtle changes in large spots are difficult to detect because the magnetograph saturates at 1.4×10^{-1} T and the perimeters of large spots are ragged and difficult to follow in poor visibility.

In 3 of the 4 cases where we could not establish an unambiguous association between the 10830 kernels and emerging fields the observations lasted for less than an hour or the flaring region was near the limb. Even in these cases, however, it was clear that the flare occurred over a 'peculiar' magnetic field – a complex region where magnetic poles 5″ or smaller were closely packed in a 'salt and pepper' pattern. The diode array data revealed that all of the flares occurred over such complex regions.

There is another class of flare, those occurring with filament eruptions over 'spotless' regions, and Rust & Roy (1974) studied one of these. As figure 4, plate 26, shows, we found that the flare was associated with the emergence of a tiny pore. Magnetograms obtained just before the flare showed that a bipolar feature was emerging through the photosphere below the erupting filament. One of the poles of the magnetic feature appeared as a pore 25 min after the flare. The brightest knots of the flare were centred on the two new poles. So, again we have the same result: the flare is intimately associated with emergent fields.

Rust & Roy (1974) also studied quite a different kind of flare (figure 5, plate 27) with surprisingly similar results. In this case, the flare occurred when a thin, dark filament erupted from a narrow channel between two rows of sunspots. The upper left panel in figure 5 shows how the brightest part of the flare started as a crescent wrapped around a spot that emerged between the two rows of spots. Small spots are always coming and going in active centres, but on the basis of careful examination of high resolution observations of many flares, I find that the earliest and brightest kernels almost always occur within a few arc seconds of the emergent field. Furthermore, the flux emergence occurs within 10″ of a neutral line, in agreement with Moreton & Severnyi's (1968) results.

3. Proton flares and steep magnetic field gradients

We may now graduate from discussion of small flares to the great proton flares and ask whether the same pattern of change at the neutral† line has been detected there. Figure 6, plate 27, shows a sequence of sunspot photographs before, during and after the proton flare of 7 August 1972. This flare was one of the largest in the past 25 years. By examination of the sunspot pictures, one may see that the elongated spot f_4 became larger and darker and that the two small pores attached to it (between f_4 and f_1 in the figure) became larger. Observations of the fields in the two hour period following flare onset showed that, indeed, the field at f_4 was increasing. The magnetograph

† As used in this paper, 'neutral line' is shorthand for the boundary between patches of positive and negative fields as detected with a magnetograph measuring the longitudinal component of the photospheric field. It is a serious error to confuse such a boundary with a line where $|H| = 0$.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

also showed that the fields in spots f_3 and p_2 decreased at the rate of about 6×10^8 Wb/s, so these observations tend to confirm two features of the sunspot fields associated with large flares reproted by Severnyi (1969*b*) and by Gopasyuk, Ogir, Severnyi & Shaposhnikova (1963). They concluded that proton flares occur when there is a steepening gradient at the neutral line and that the spot fields weaken after the flare. Severnyi inferred from his magnetograph observations of the 7 July 1966 proton flare, in particular, that the gradient steepened before the flare. McIntosh (1969) noticed darkening penumbra along the neutral line just before the 7 July 1966 flare, and the same behaviour has been reported in association with numerous other giant flares. We may conclude that new flux is emerging at a neutral line with very steep field gradients, just as Severnyi reported long ago. A word of caution is in order, however: we do not know the magnitude of the field gradients involved. The reported values all depend upon the aperture of the instrument and on the visibility. Severnyi associates proton flares with gradients larger than 10^{-5} T/km. In the case of the 7 August 1972 flare, Rust (1973*b*) measured a gradient of 8×10^{-4} T/km between spots f_4 and p_1, but the resolution was better than 1″. Title & Andelin (1971) observed a gradient of 1.6×10^{-3} T/km in a stable sunspot. They used high resolution spectra from Kitt Peak. These results show that we cannot place much weight upon the actual numbers reported for the gradients and that we cannot associate large flares with *unchanging* steep gradients.

It is wrong, however, to conclude that we have no reliable data on the magnetic fields associated with proton flares. Besides the well-observed darkening along the neutral line, it is clear the magnetic field is not zero at the $H_\parallel = 0$ line at all, because $H_\perp \neq 0$. $H_\parallel$ and $H_\perp$ refer to the components of the magnetic field (usually measured in regions near disk centre) that are parallel and transverse, respectively, to the line of sight. From observations made by Severnyi, Harvey *et al.* (1971), and Rust (1973*b*), we may conclude that large flares, if not all flares, are associated with the development of a strong transverse field *parallel to a neutral line* that is flanked by flare ribbons. The presence of this transverse component has been inferred also from vector magnetograms and from high resolution photographs of penumbral fibrils (McIntosh 1969).

4. Inferences from morphology

With mention of penumbral fibrils, we have entered upon the subject of inferences of magnetic field changes from morphology rather than from measurements of the Zeeman effect. Zirin (1974) has given several examples of sequences of Hα pictures that seem to show fieldline reconnection. The underlying assumption in his work and in the work I am about to describe is that chromospheric fibrils and filaments outline magnetic field structures. Thus, when high resolution filtergrams of the chromosphere are combined with sunspot pictures and magnetograms, we may infer something of the 3 dimensional structure of the magnetic field.

Rust *et al.* (1975) detail observations of a class I flare that occurred near disk centre on 19 January 1972. We used a flare prediction scheme (Rust 1973*a*) to select a region for intensive observation with the spectroheliograms on OSO-7 and with the Doppler–Zeeman Analyzer (DZA) and the Tower Telescope at Sacramento Peak. We obtained filtergrams with a 0.25 Å Zeiss filter at the rate of eight frames each 20 s, and each eight-frame sequence included observations from Hα − 2 Å to Hα + 1.4 Å. The seeing was excellent, and we were able to follow sunspot developments as well as off-band filament activation throughout the flare.

When the 19 January filtergrams are viewed as a movie, it is clear that a long dark filament over the neutral line erupted just before the first flare brightenings in the chromosphere. Figure 7, plate 28, shows two views of the Doppler motions in his filament at 15 min before flare onset and 2 min after flare onset. The Doppler motions are obtained by subtracting filtergrams at Hα +0.875 Å from those at Hα −0.875 Å. Material moving upward is dark in these photographs and downward moving material is light. The light and dark areas show line-of-sight velocities of ± (40–80) km s^{-1} in the filament. Careful examination of the velocity picture at 16 h 19 reveals that the black band of material (moving toward the observer) curved from one side of the filament to the other once in the filament's length. The white band of falling material appeared to cross under the rising material a little north of the mid-point. The second picture (at 16 h 36 U.T.) shows the filament material uniformly rising at the centre (black streak) and falling at the ends (white streaks). Rising and falling material were not intertwined at 16 h 36 as they were at 16 h 19. Figure 7 may be interpreted as showing an untwisting filament before the flare. The photograph at 16 h 36 U.T. indicates that the twist has disappeared and the filament with the magnetic field that runs lengthwise through it is erupting at the centre (dark strand) and draining into the chromosphere at both ends (white patches).

It is not at all unusual to observe twisting motions in a filament just before a flare. Zirin & Tanaka (1973) show a similar photographic subtraction revealing twist in the filament that lay over the neutral line of the 7 August 1972 proton flare region. And many flare-associated eruptive prominences seen at the solar limb show a pronounced spiral structure. The point of discussing these observations in the present context is that *erupting, untwisting prominences are unambiguous evidence for restructuring of the field associated with flares*. The ionized material in filaments is constrained to move with the magnetic field lines of force, and so it becomes a 'tracer' as the fields change. The changes in filaments lying over flares are obvious, and the fact that a filament may reappear after ejection at the onset of a flare does not mean that the magnetic field was uninvolved in the flare process. Quite the contrary, the intimate association between filament activation and flares probably provides an important clue to understanding that process.

Frequently, the chromosphere surrounding the flare region is subtly changed, but with low resolution observations it was impossible to infer whether any change in the magnetic fields had taken place. However, Zirin's (1974) work and the before–after pair of Hα pictures shown in figure 8, plate 28, are inferential evidence for a rearrangement of the chromospheric field in association with flares. Rust *et al.* (1975) interpret the observations shown here in figures 7 and 8 to indicate that the lines of force linking emergent sunspots somehow disturbed the equilibrium of the fields supporting the filament. We go on to conclude that a reconnexion took place linking the fields in the filament with the fields rooted in the emergent poles. The calculated reduction in available magnetic energy that would result from such a reconnexion was about 10^{24} J.

5. Summary and conclusions

We have learned that the association between magnetic field changes in the photosphere and flares is not one of a catastrophic energy drain. No sunspots vanish or fly apart, nor is there any evidence in most cases for any weakening of the photospheric fields. However, we certainly need more observations of the behaviour of the fields when a major proton flare occurs. There is evidence for a decrease in fields in the wake of one of these flares, and it is certain that there is a marked change in the fields along the neutral line before flare onset.

We have a much clearer picture of the magnetic field developments associated with small flares, which are much easier to observe and build statistics with. If there is any field weakening associated with small flares, then we have not detected it. We have learned, however, that small flares take place where new spots are appearing; the kernels of flares usually occur within a few arc seconds of an emerging spot. Perhaps we should consider the emergent spots as a trigger which sets off the release of magnetic energy stored in the upper chromosphere. Perhaps the stressed magnetic fields threading filaments there provide energy for the flares. The magnetic energy in filaments is easily enough to fuel flares. It is not necessary to seek the magnetic energy in the photosphere.

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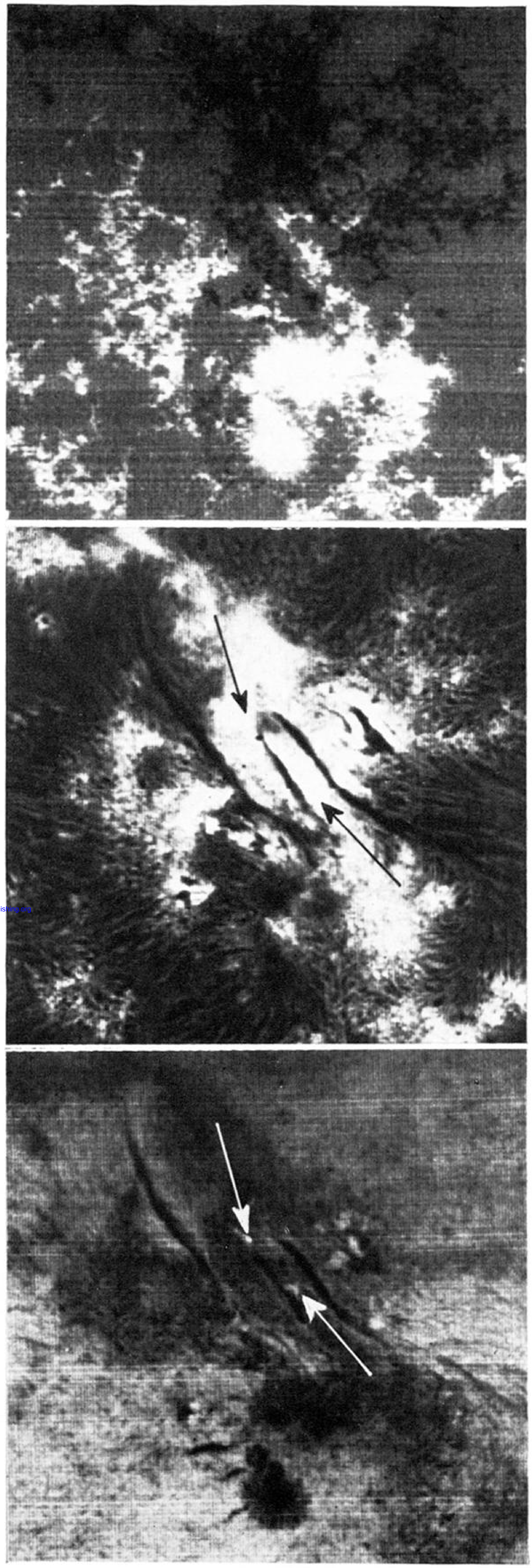
PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES



magnetic fields

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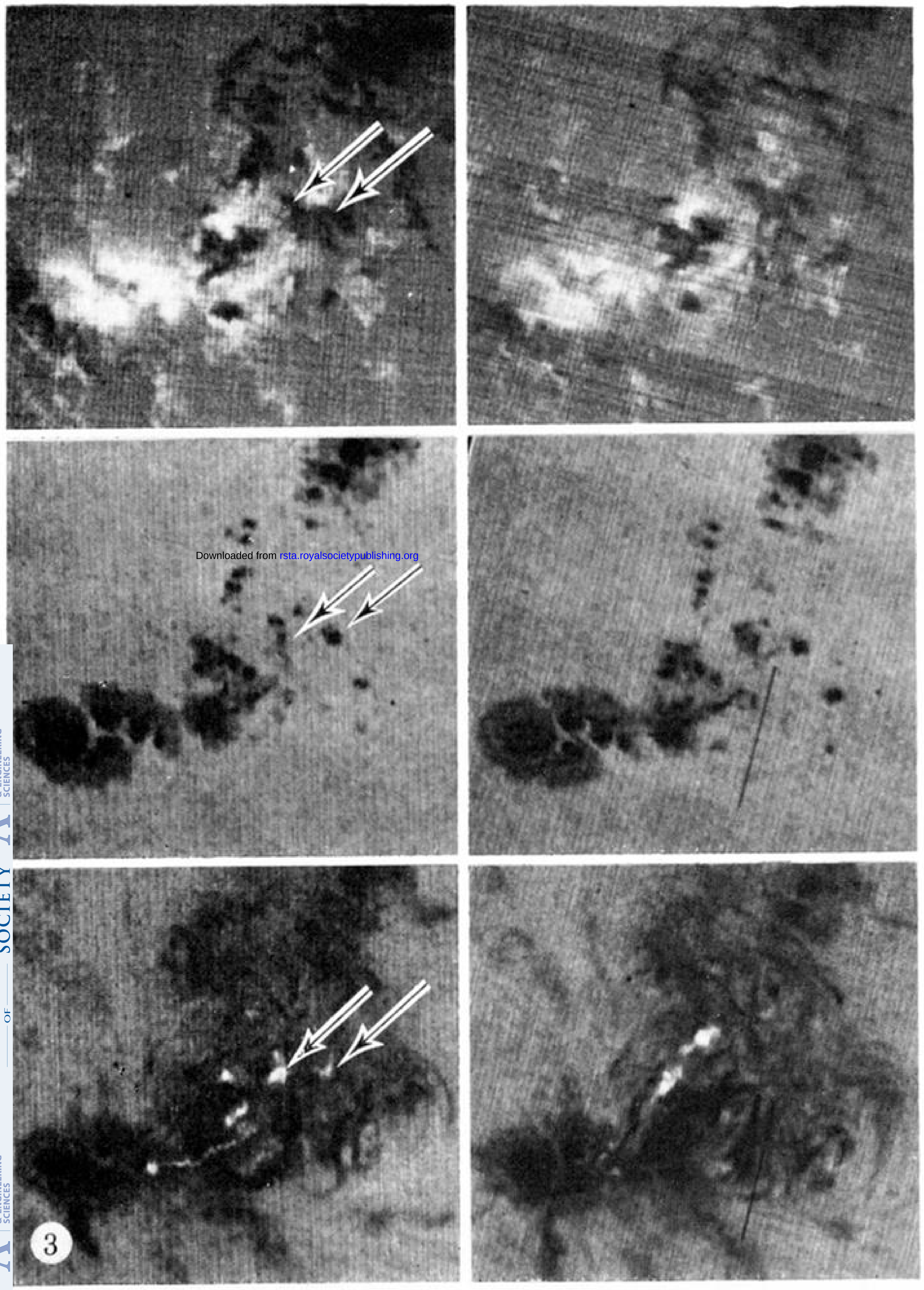


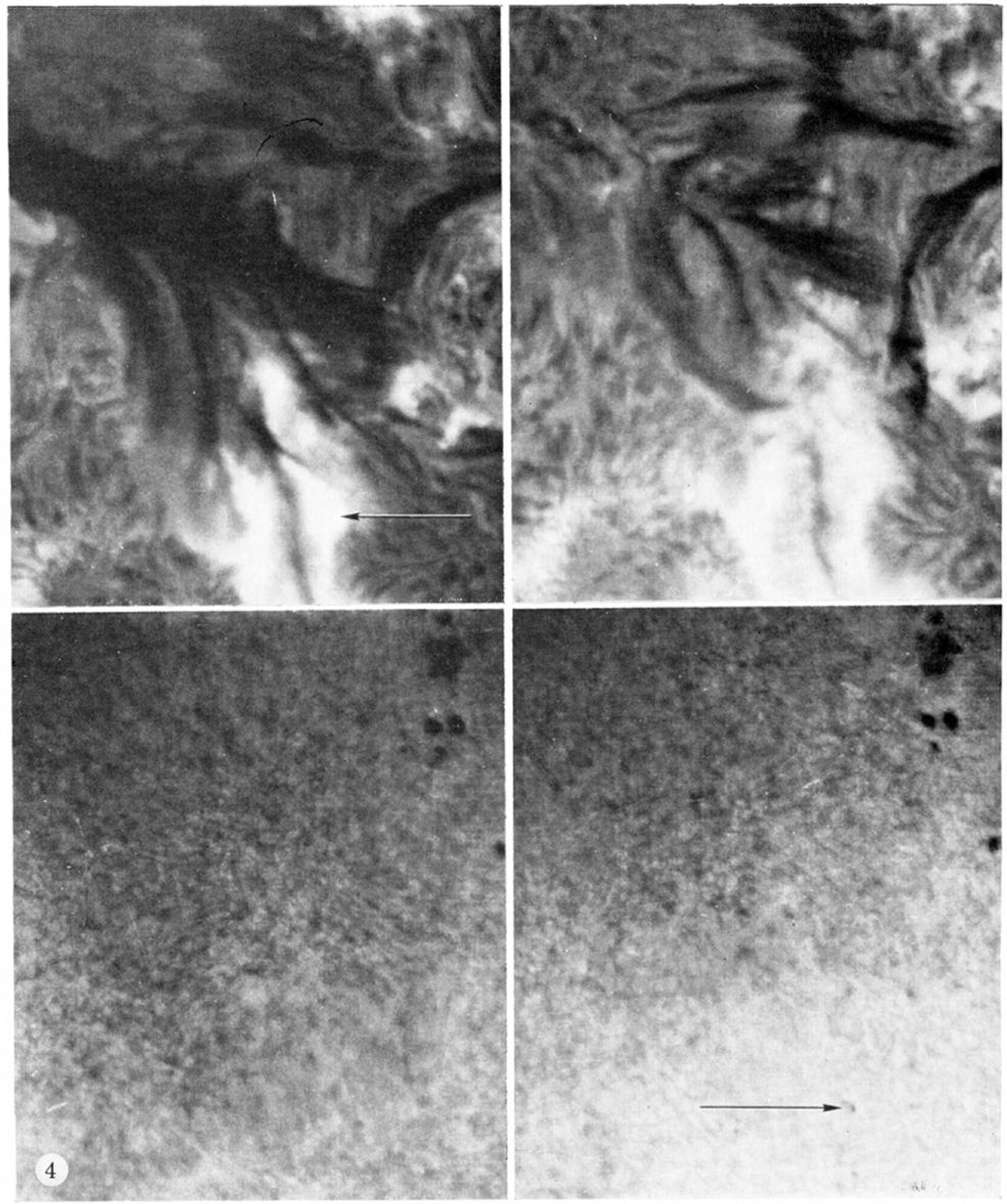
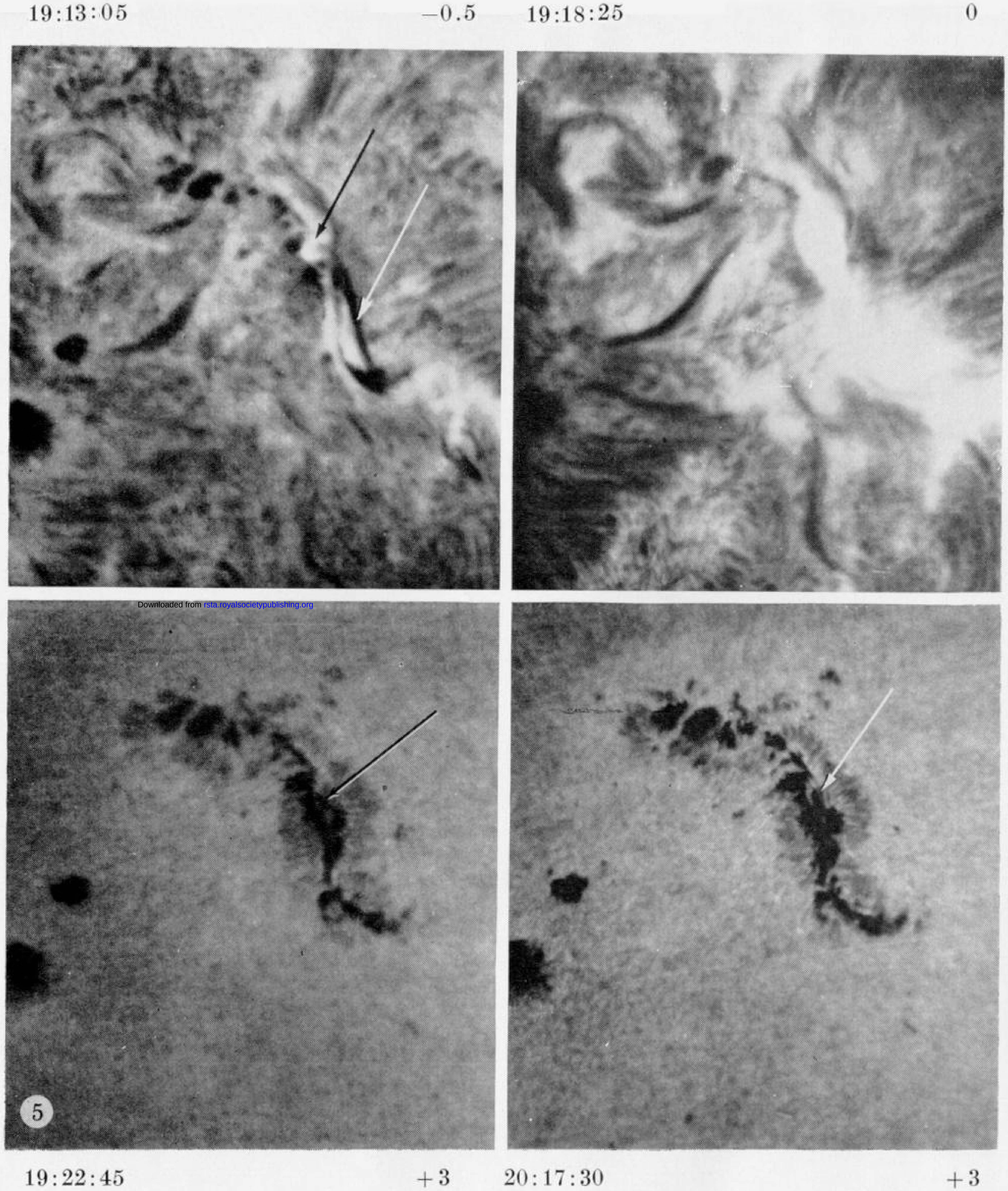


FIGURE 3. Flare kernels (bottom), growing pores (middle) and magnetic fields (top) in McMath region 12848 at S 12° W 34° on 13 April 1974. North is down in this picture and west is to the left. Arrows indicate flare kernels and growing pores for the subflare at 15h 50 U.T. (left column). Right column is 18h 07 U.T.

FIGURE 4. Hα (top) and continuum (bottom) pictures of a subflare on 23 June 1972. Dark material at 22h 30 U.T. (left column) is an erupting filament. The arrows show one of the bright knots of the flare (at 22h 30 U.T.) and the emergence of a pore in the underlying photosphere at 22h 55 U.T. (right column).



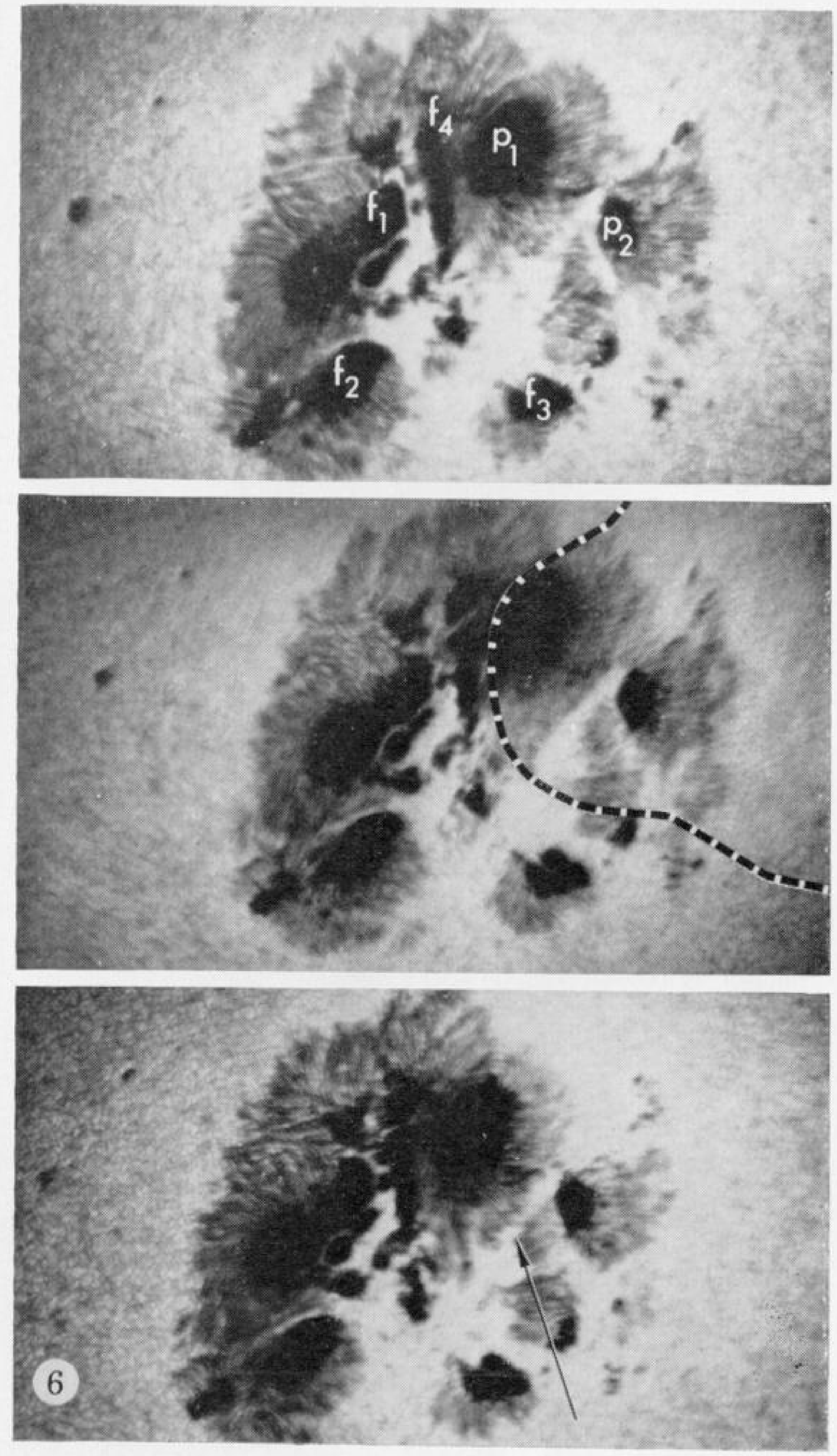
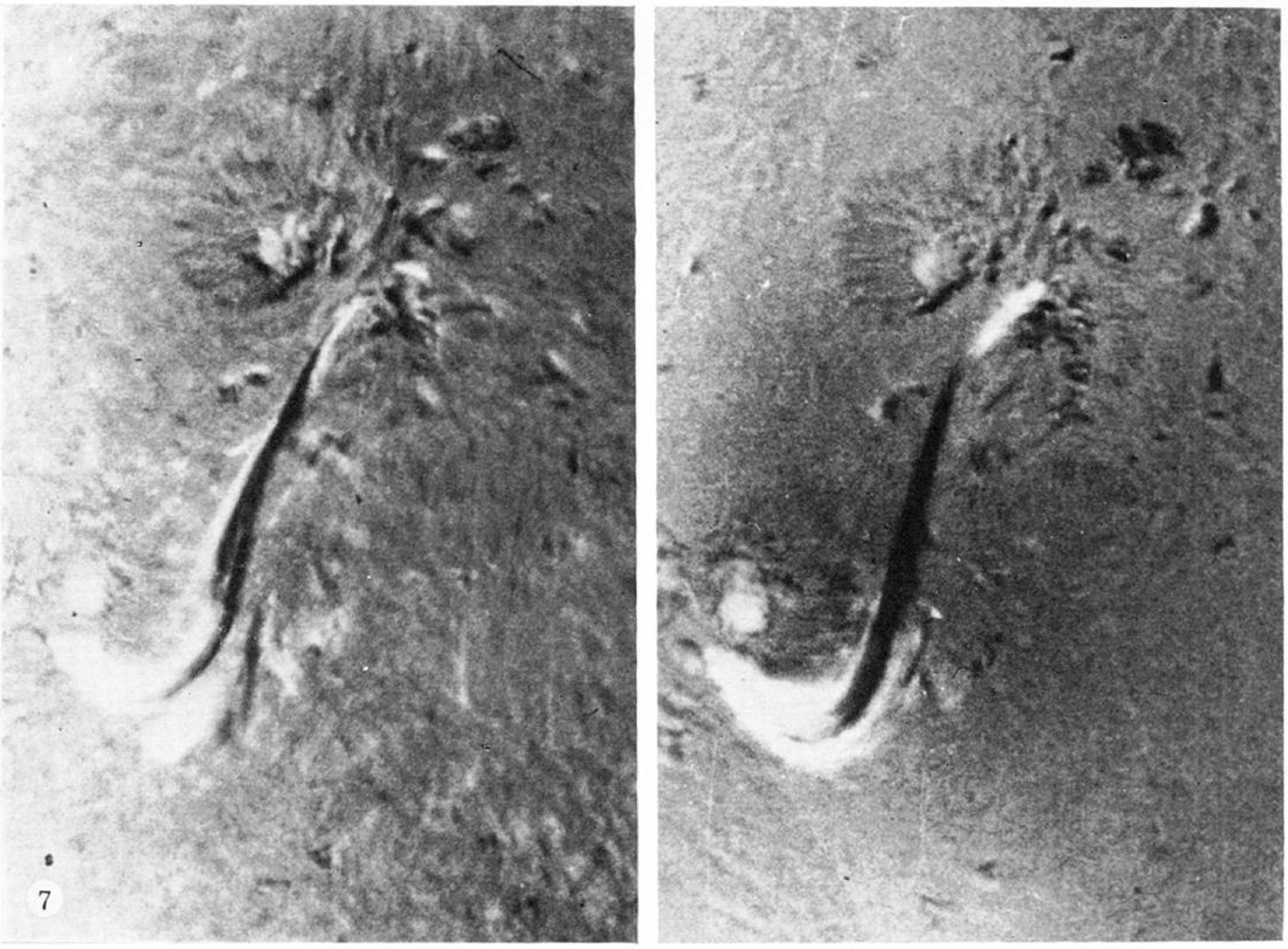
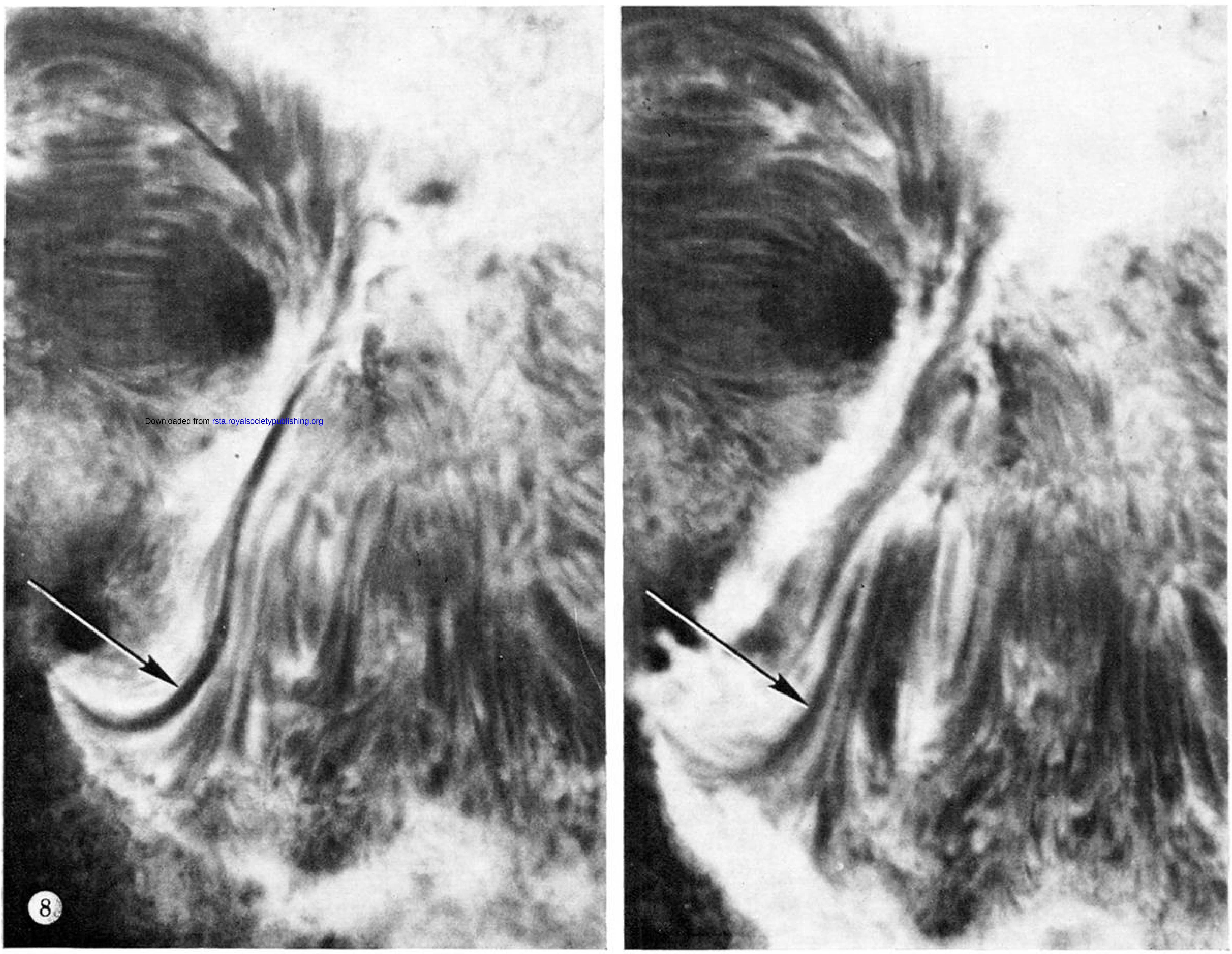


FIGURE 5. Hα (top) and continuum (bottom) pictures of a subflare on 24 June 1972. Universal Time and offset (Å) from Hα (6563 Å) are indicated above or below each frame. At 19h 13 U.T. the filament (white arrow) erupted from over the neutral line as the first flare kernels (black arrow) appeared. Flare maximum occurred at 19h 18 U.T. The pictures 19h 22 and 20h 17 U.T. show two stages in the growth and elongation of a small spot (indicated by arrows) that lay under the crescent-shaped flare kernels and first appeared during the hour preceding flare onset at 19h 05 U.T.

FIGURE 6. Rapid changes in sunspots on 7 August 1972. The times of the pictures (top to bottom) are 12h 05, 14h 40, and 15h 40 U.T.; a 3B proton flare occurred at 15h 10 U.T. The heavy dashed line in the middle picture indicates the location of the neutral line in the longitudinal magnetic fields. The arrow shows a region with changing penumbral structure where magnetograph measurements indicated a sharp field decrease following the flare.

16h 19 16h 36 U.T.





before after

FIGURE 7. Two Doppler subtractions showing motions of a filament on 19 January 1972. Left to right: subtraction of H$\alpha \pm 0.875$ Å photographs 15 min before flare onset; subtraction of H$\alpha \pm 1.375$ Å photographs 2 min after flare onset. Grey indicates no line-of-sight motion, white shows falling material, and black shows rising material.

FIGURE 8. Two Hα pictures of the region that flared on 19 January 1972. The arrows pointing to the lower end of the eruptive filament before (16h 19 U.T.) and just after (17h 27 U.T.) the flare show how the dark feature curving upward from the spot changes from being part of the filament before (left) to being part of an emerging arch filament system (right).