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

Optical Observations of Flares

Z. Svestka

Phil. Trans. R. Soc. Lond. A 1976 **281**, 435-441
doi: 10.1098/rsta.1976.0041

Phil. Trans. R. Soc. Lond. A. **281**, 435–441 (1976) [435]
Printed in Great Britain

Optical observations of flares

By Z. Švestka
American Science and Engineering, Inc., Cambridge, Massachusetts, U.S.A.

[Plates 29 and 30]

The lecture describes solar flare effects in the chromosphere and photosphere, particularly emphasizing problems of the energy transfer, and the differences between thermal and non-thermal phases of the flare development. Filamentary and shell models are compared and the depth of the white-light flare emission is discussed. Optical effects possibly associated with other, non-optical flare-associated phenomena are pointed out.

1. Flare spectra

In optical spectral range the flare emission is seen only in individual spectral lines (figure 1, plate 29), and it is most outstanding in those of them which are formed high in the chromosphere. Thus the Balmer series of hydrogen – the Hα line in particular – and the singly ionized calcium H and K lines are most strongly affected by the flare emission. Hence the optical flare is a purely chromospheric phenomenon which only very rarely also affects the photosphere.

Since the Balmer lines of hydrogen are broadened by the Stark effect, we can determine from their width the density of ionized particles in the flare volume, that is, the electron density in the flare (Švestka 1972). The electron density thus found is of the order of $10^{13}\,\mathrm{cm^{-3}}$. From the effect of self-absorption in the high lines of the Balmer series one can estimate the flare optical thickness and then, from the intensity observed, the source-functions in the different lines, which are functions of electron temperature. The electron temperature thus found is always slightly lower than 10000 K.

The kinetic energy density in the flare is proportional to $N_e T_e$ which accounts to the same value in the chromosphere ($10^{13} \times 10^4 = 10^{17}$) and in the corona ($10^{10} \times 10^7 = 10^{17}$). Therefore it is not easy to say where the flare originates, but the prevailing opinion is now that the primary flare instability is located in the low corona or in the transition layer. If the primary flare source were in the chromosphere or even in subphotospheric layers as some authors suggest, one would expect severe disturbances in the chromosphere, this atmospheric layer being then either the seat of the flare instability, or the medium through which the flare energy is transported to the coronal layers. But nothing like that is observed. As figure 1 shows, the metallic lines in the flare spectrum are quite sharp, indicating that there are no significant non-thermal motions in the chromospheric flare region. This, I suppose, is one of the strong arguments for placing the flare origin above the transition layer. In that case the optical flare is a secondary effect due to heat conduction from the corona to the chromosphere, or to streams of energetic particles, flowing from the corona downwards.

When the values of electron density and temperature are known, one can compute the factors $b_2, b_3, \ldots, b_m$, determining the deviations from local thermodynamic equilibrium (De Feiter 1966; Švestka 1972). Then we can determine the density of hydrogen atoms in the second quantum state in the flare, and compare it with the column density deduced from the spectra.

As the result of such a comparison we get extremely small values of the geometrical flare thickness, often only of the order of 10 km.

This result has been interpreted as the consequence of a filamentary structure of flares (Suemoto & Hiei 1959; Švestka 1963, 1972; De Feiter 1966; Polupan & Yakovkin 1966; Kurochka 1970; Semel & Soru-Escaut 1971). Figure 2 shows schematically a cross-section through the atmosphere across the filaments. If all the filaments were put together to form a homogeneous layer, we would get the small effective thickness of the order of 10 km, deduced from observations. However, as soon as the primary source of the flare is placed into the corona, this filamentary model might become superfluous. The heat or particle flow from the corona can actually deposit energy in a fairly thin chromospheric layer, as the analysis of spectra indicates (Canfield & Athay 1974; Canfield 1974; Machado & Rust 1974; Shmeleva & Syrovatsky 1973). It is not yet clear at the present time whether the filamentary model, or the shell model, is the correct one.

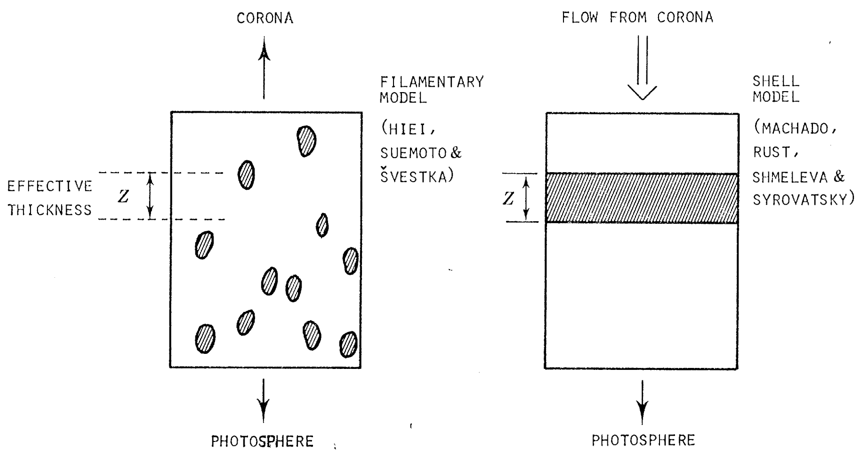


FIGURE 2. Scheme of a vertical section through a chromospheric flare: flaring regions in the chromosphere are hatched. The actual geometrical thickness of the flare is very small. This can be interpreted either by means of a filamentary structure of the flare (left picture) or in the form of a flaring shell (right picture).

2. Hα OBSERVATIONS

In any case we have to realize that in the Hα line, where most chromospheric observations are carried out, we actually see only the 'foot-points' of the high-temperature coronal flare in the chromosphere. Nevertheless, in particular when we combine the very detailed Hα observations with other flare data, the chromospheric observations give us a lot of information on the flare nature, which I shall now try to summarize.

As soon as a bipolar magnetic configuration forms in the solar atmosphere, flares begin to occur. The X-ray observations on Skylab have verified this; flare-like X-ray brightenings occur in loops formed only one day earlier in the solar corona (figure 3, plate 29), and flare-like phenomena are observed even in bright X-ray points which represent tiny bipolar regions on the Sun living only for less than 10 h on an average (figure 4, plate 30).

However, all the flares which are observed in purely bipolar magnetic fields, are relatively uncomplicated phenomena, that can be explained, in all their effects, as simply due to increase in temperature in the solar corona and subsequent cooling (Švestka 1973). The Hα observations reveal that the first chromospheric flare brightenings always occur near the zero line of the

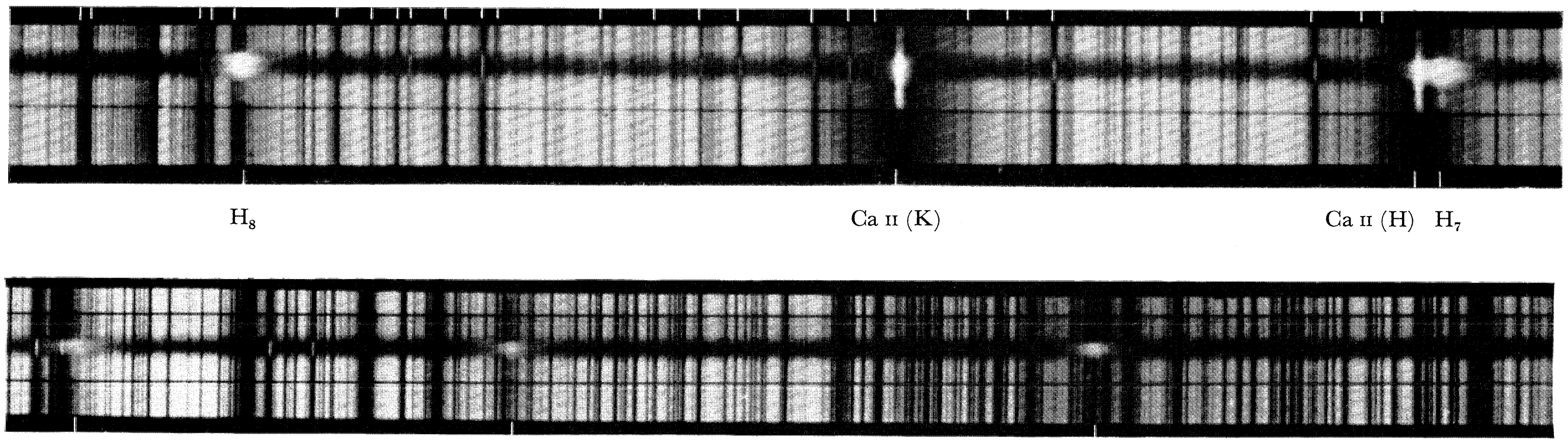


FIGURE 1. Example of the spectrum of a major solar flare (photographed at the Astronomical Institute of the Czechoslovak Academy of Sciences at Ondřejov on 12 July 1961). The upper part shows the spectrum between $\lambda 3873$ and $\lambda 3988$ Å, with the H and K lines of the singly ionized calcium, $H\epsilon$ and $H\zeta$ lines of the Balmer series of hydrogen and many metallic lines (e.g. No. 11 is Si I, 13 is Ti II, 22 and 23 are Al I, most of the others are Fe I lines). The lower part shows the spectrum between $\lambda 3747$ and $\lambda 3825$ Å, including three higher members of the Balmer series. (After Švestka 1972.)

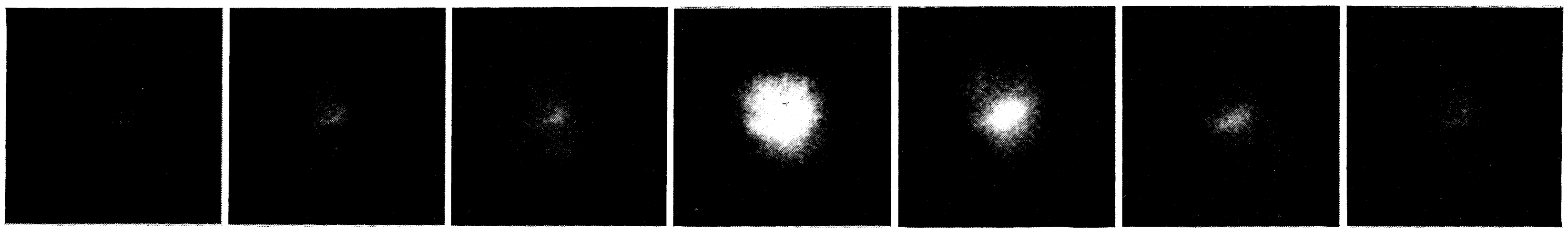
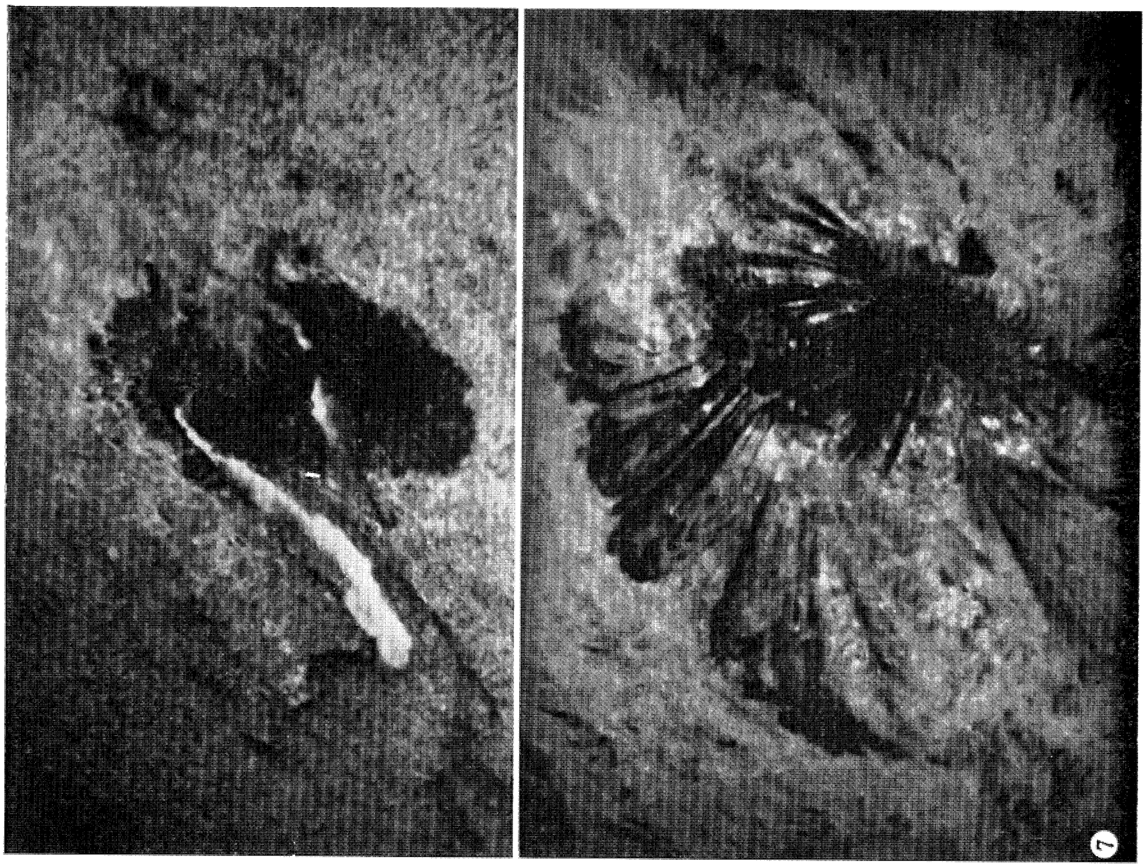
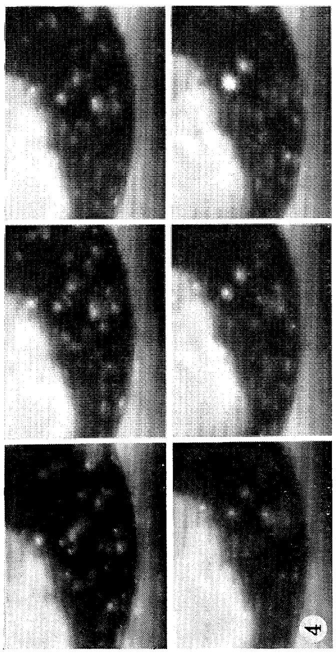
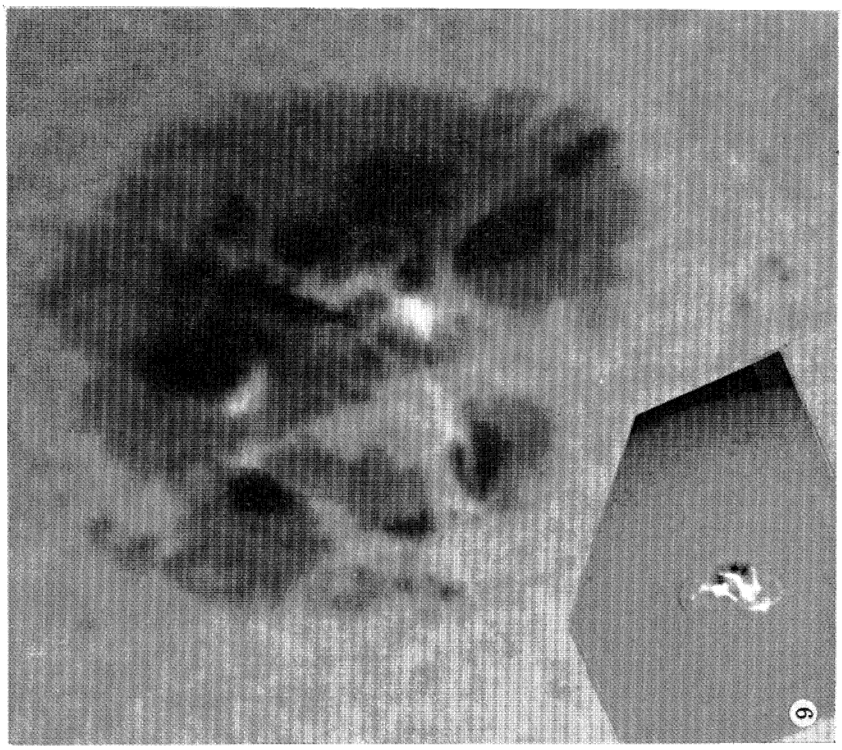


FIGURE 3. A flare-like brightening occurred on 1 September 1973 in one of the three loops which formed the active region McM 12511, born only one day before. (American Science and Engineering A.t.m. experiment on Skylab, courtesy R. Petrasso.)

(*Facing p.* 436)







FIGURES 4, 7 AND 9. For description see opposite.

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

longitudinal magnetic field, on both sides of it (Martres, Michard & Soru-Iscovici 1966; Moreton & Severny 1968), so that the flare can be interpreted as a loop, or system of loops, rooted in the chromosphere and extending into the corona (figure 5). Along this loop the heat from the coronal flare is conducted downwards into the chromosphere where it produces the Hα brightenings observed.

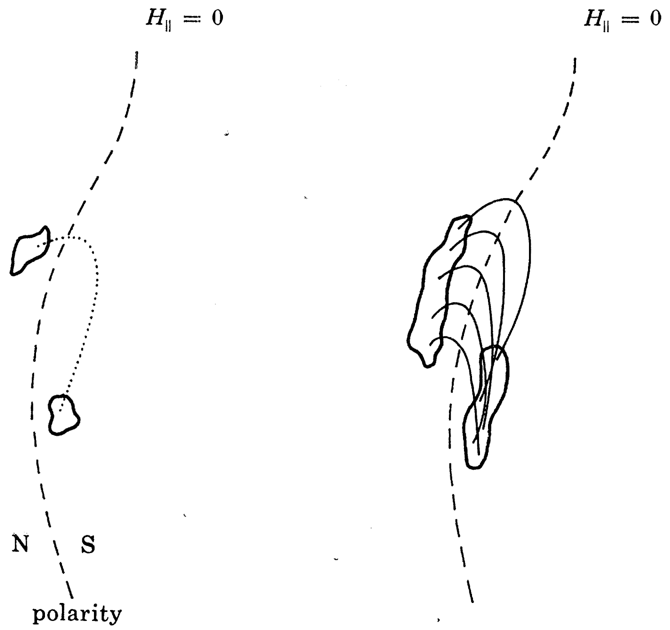


FIGURE 5. Schematic drawing of the location of the first bright flare patches in the chromosphere, representing foot-points of a coronal loop (left part). ———, $H_{\parallel} = 0$ represents the zero line of the longitudinal magnetic field. Larger flares then extend along this zero line forming two bright ribbons in the chromosphere (right part).

In large flares these Hα patches then extend along the zero line, finally forming the typical bright flare ribbons (figure 5). These ribbons separate from each other and depart from the zero line (Dodson & Hedeman 1960; Valníček 1961; Švestka 1962; Malville & Moreton 1963). As long as the magnetic field is weak, the separation proceeds, with speeds of a few kilometres per second, until the flare decays. Obviously, the flare loops are expanding, or successively higher loops are affected by the radiation so that the loop foot-points steadily move from the zero line

---

DESCRIPTION OF PLATE 30

FIGURE 4. A flare-like brightening of an X-ray bright point which can be identified with a tiny bipolar structure in the photospheric magnetograms, but lives only for about 10 h. Time sequence starts in the left upper corner (where the bright point that later flared cannot yet be seen) and the subsequent pictures follow approximately in two-hour time intervals. Some 8 h after its birth the bright point flared (right lower corner). (American Science and Engineering A.t.m. experiment on Skylab, courtesy L. Golub.)

FIGURE 7. An example of two bright ribbons anchored within big sunspots. (Flare of 10 September 1974; upper picture in the helium D_3, lower one at the wing (+0.9 Å) of the hydrogen Hα line.) The lower picture makes visible the loops connecting the two bright ribbons. Such 'visible loops' are seen in some flares in which particles were accelerated to high energies; a tentative explanation is that some particles are captured in the loops, are thermalized, and while cooling they become visible in the Hα light. (Courtesy J. M. Beckers, Sacramento Peak Observatory.)

FIGURE 9. The white-light flare of 7 August 1972. The insert shows the bright Hα ribbons of the flare at one-twelfth the scale. Note that only a very small part of the flare became visible in white light. (Courtesy D. M. Rust, Sacramento Peak Observatory.)

outward. In strong magnetic fields, however, the situation is different. As soon as the moving ribbon hits strong longitudinal field, it slows down and eventually stops (figure 6); thus, in a group of big sunspots the flare is finally embedded within the spots and the ribbons do not move any more (figure 7, plate 30).

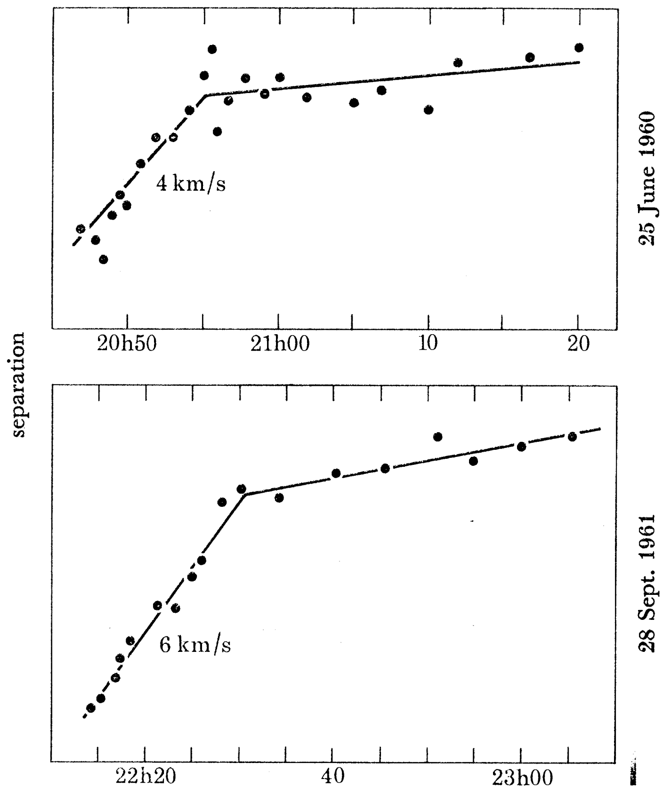


FIGURE 6. Measured velocities of separation of the flare bright ribbons in two flares (after Malville & Moreton 1963). The motion slows down when the ribbons encounter large spots.

This leads us to another category of flares which occur in more complicated, complex magnetic configurations, originating as a combination of two or more bipolar fields emerging in the close vicinity. Flares that occur in such magnetically complex situations cannot be interpreted any more as purely thermal phenomena (see, for example, Švestka & Simon 1969). Hard X-ray bursts, impulsive microwave bursts and type III radio bursts show that elementary particles have been accelerated to suprathermal energies in these flares and often these particles also are directly recorded in space. Since this acceleration process always occurs during the initial phase of the flare development, prior to the flare maximum brightness in the Hα light, many authors have suggested that particle acceleration is the primary instability giving rise to the whole flare phenomenon (see, for example, Elliot 1969; Brown 1971; Kandel, Papagiannis & Strauss 1971; Cheng 1972; Syrovatsky & Shmeleva 1972). But this is obviously not true. First, as I mentioned before, there are many flares in which there is no evidence for the existence of suprathermal particles at all. We observe soft X-rays and Hα emission, sometimes gradual e.u.v. and microwave burst, but no impulsive hard X-ray burst; and in the cases where an impulsive burst is recorded (as is the case shown in figure 8) then on many occasions it does not appear at the very beginning of the flare, but a few minutes later, when the soft X-ray and Hα flare already rise to their maximum (Kane & Anderson 1970; Kahler & Kreplin 1970; Švestka 1973).

Hence one has to conclude that the primary effect, common to all flares, is increase in temperature, still preserving Maxwellian distribution of velocities. Only in some flares, and as far as we know these are predominantly or explicitly flares in magnetically complex active regions, an additional non-thermal process is accomplished, which accelerates electrons and possibly protons to suprathermal energies.

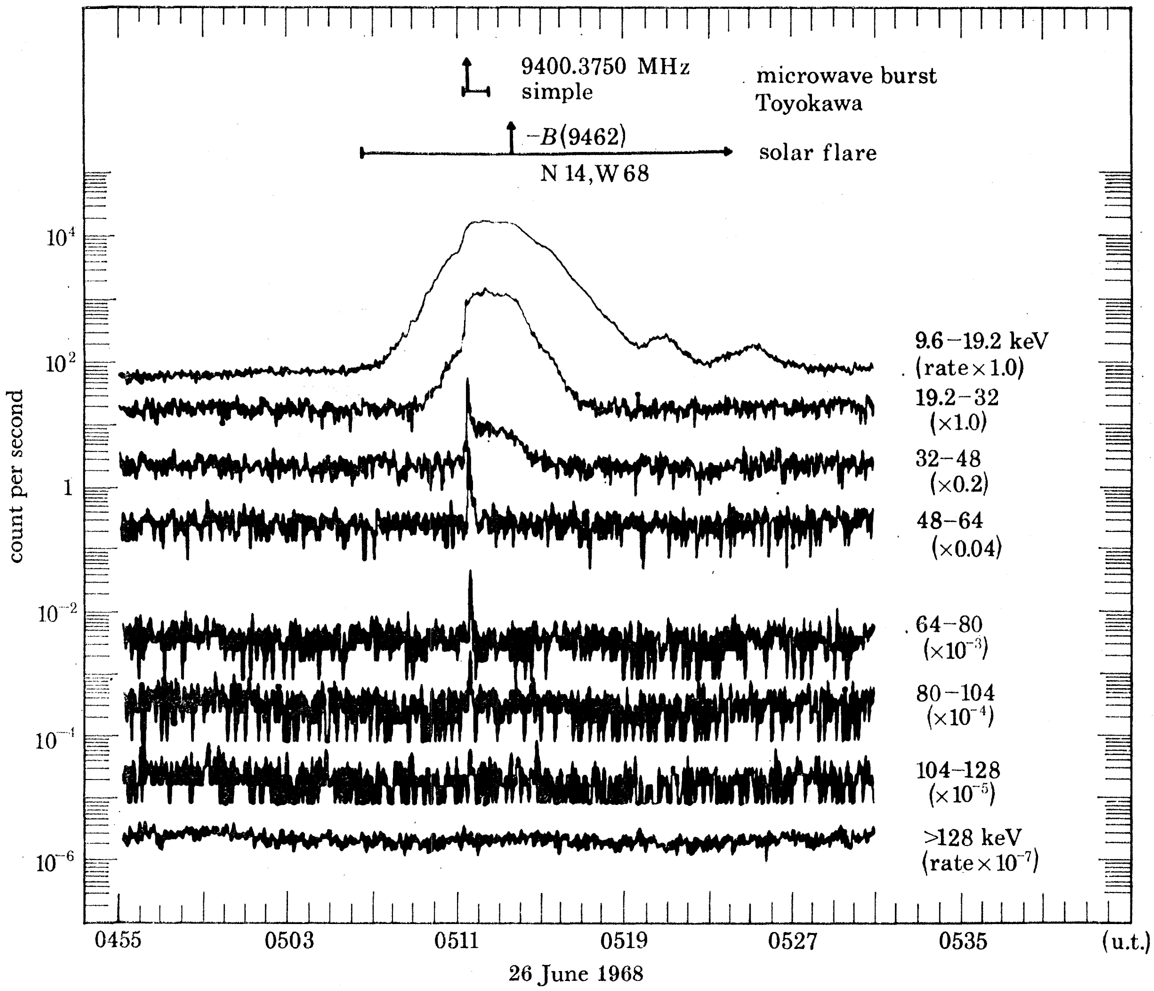


FIGURE 8. Example of an X-ray burst with an impulsive hard X-ray component (after Kane 1969). Note that the soft X-ray flare started some 4 min before the impulsive burst.

3. The impulsive phase

It has been mentioned above that the Hα emission of the thermal flares is probably due to heat conduction from the corona downwards to the chromosphere (Švestka 1973). During the impulsive, non-thermal phase, the chromosphere is additionally heated by streams of particles (Brown 1973; Shmeleva & Syrovatsky 1973; Somov & Syrovatsky 1974). It is not easy to see the short-lived Hα brightenings associated with these streams, but several such cases were clearly observed by De Jager (1967), Vorpahl & Zirin (1970), Zirin, Pruss & Vorpahl (1971), Vorpahl (1972), and others. The Hα brightenings show that the non-thermal acceleration has been accomplished only in a restricted volume of the flare, significantly smaller than the total extension of the basic thermal flare. Obviously the acceleration process is accomplished only in some of the loops, of which the thermal flare is composed.

In most of these flares, in which the non-thermal acceleration process is accomplished, the particles deposit their energy fully in the chromosphere. There are some outstanding flare events, however, where the brightening extends down to the photosphere, for a short time making the flare visible in white light (figure 9, plate 30). There is no doubt that the white-light emission is produced by energetic particles, since it coincides in time with the other non-thermal phenomena (Švestka 1970). Opinions, however, differ on the nature of these energetic particles. Some authors (Hudson 1972; Machado & Rust 1974) have tried to explain the emission as originating in the low chromosphere, where it is produced by a large number of relatively low-energy electrons. Objection to it is that all particle streams recorded from white-light flares in space, have abnormally hard energy spectra, with characteristic rigidity about 200 MV for protons (Najita & Orrall 1970). This is evidence that the acceleration process in these flares produces large numbers of relativistic electrons and protons in the energy range of 10–100 MeV. As computations show, particles of this energy can penetrate into the photosphere (Schatzman 1965; Švestka 1970; Najita & Orrall 1970). Since the white-light emission always occurs on the border of large penumbrae (cf. figure 9 as an example), the magnetic field near the white-light patches must be very strong. This leads to heavy synchotron losses in the streams of relativistic electrons. However, there is no hindrance for the protons as they penetrate downwards, and it has been shown, at least for one white-light flare, that the energy the protons carry is sufficient for producing the white-light brightening observed (Švestka 1970; Najita & Orrall 1970). Therefore, proton streams still remain the most probable explanation for the white-light flares.

To end up, I would like to emphasize that the 'old fashioned' Hα observations of flares should not be underestimated by the space scientists, as often is the case. We have observed solar flares in the Hα light for some 50 years, and during 5 solar cycles, and on the basis of this long experience we know something about the flare properties in the chromosphere. Any more sophisticated observations obtained on Skylab or other satellites should be related to this our basic source of information about the flare phenomenon. Without doing that, the ground-based solar physicists and space scientists might very soon speak two different languages, without being able to understand each other.

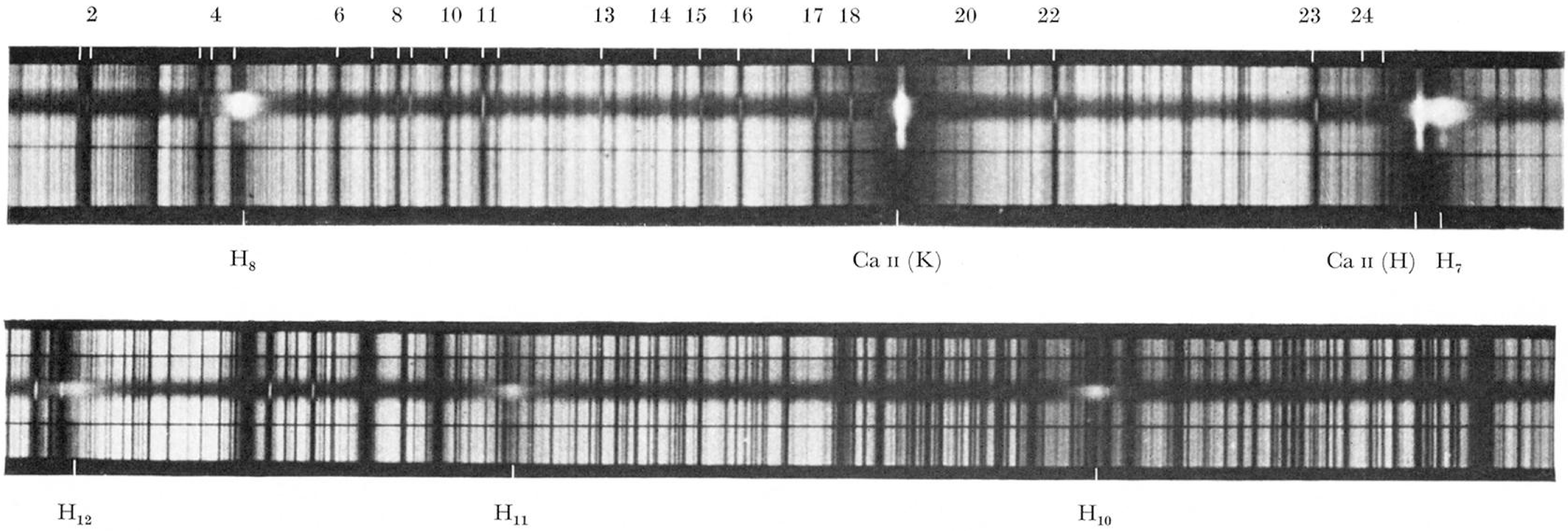
References (Švestka)

Brown, J. C. 1971 *Solar Phys.* **18**, 489.
Brown, J. C. 1973 *Solar Phys.* **31**, 143.
Canfield, R. C. 1974 *Solar Phys.* **34**, 339.
Canfield, R. C. & Athay, R. G. 1974 *Solar Phys.* **34**, 193.
Cheng, Chung-Chieh 1972 *Solar Phys.* **22**, 178.
De Feiter, L. D. 1966 *Rech. Astron. Observ. Utrecht* No. 18 (2).
De Jager, C. 1967 *Solar Phys.* **2**, 327.
Dodson, H. D. & Hedeman, E. R. 1960 *Astron. J.* **65**, 51.
Elliot, H. 1969 In *Solar flares and space research* (ed. C. de Jager & Z. Švestka), p. 356. COSPAR Symp.
Hudson, H. S. 1972 *Solar Phys.* **24**, 414.
Kahler, S. W. & Kreplin, R. W. 1970 *Solar Phys.* **14**, 372.
Kandel, R. S., Papagiannis, M. D. & Strauss, F. M. 1971 *Solar Phys.* **21**, 176.
Kane, S. R. 1969 *Astrophys. J.* **157**, L139.
Kane, S. R. & Anderson, K. A. 1970 *Astrophys. J.* **162**, 1003.
Kurochka, L. N. 1970 *Astron. Zh.* **47**, 111.

Machado, M. E. & Rust, D. M. 1974 *Solar Phys.* **38**, 499.
Malville, J. M. & Moreton, G. E. 1963 *Publ. Astron. Soc. Pacific* **75**, 176.
Martres, M. J., Michard, R. & Soru Iscovici, T. 1966 *Annls. Astrophys.* **29**, 249.
Moreton, G. E. & Severny, A. B. 1968 *Solar Phys.* **3**, 282.
Najita, K. & Orrall, F. Q. 1970 *Solar Phys.* **15**, 176.
Polupan, P. N. & Yakovkin, N. A. 1966 *Astron. Zh.* **42**, 764.
Schatzman, E. 1965 In *The solar spectrum* (ed. C. de Jager), p. 313. Dordrecht, Holland: Reidel.
Semel, M. & Soru-Escaut, T. 1971 *Astron. Astrophys.* **12**, 340.
Shmeleva, O. P. & Syrovatsky, S. I. 1973 *Solar Phys.* **33**, 341.
Somov, B. V. & Syrovatsky, S. I. 1974 *Solar Phys.* **39**, 415.
Suemoto, Z. & Hiei, E. 1959 *Publ. Astron. Soc. Jap.* **13**, 152.
Švestka, Z. 1962 *Bull. Astron. Inst. Czech.* **13**, 190.
Švestka, Z. 1963 *Bull. Astron. Inst. Czech.* **14**, 234.
Švestka, Z. 1970 *Solar Phys.* **13**, 471.
Švestka, Z. 1972 *A. Rev. Astron. Astrophys.* **10**, 1.
Švestka, Z. 1973 *Solar Phys.* **31**, 389.
Švestka, Z. & Simon, P. 1969 *Solar Phys.* **10**, 3.
Syrovatsky, S. I. & Shmeleva, O. P. 1972 *Astron. Zh.* **49**, 334.
Valníček, B. 1961 *Bull. Astron. Inst. Czech.* **12**, 237.
Vorpahl, J. 1972 *Solar Phys.* **26**, 397.
Vorpahl, J. & Zirin, H. 1970 *Solar Phys.* **11**, 285.
Zirin, H., Pruss, G. & Vorpahl, J. 1971 *Solar Phys.* **19**, 463.

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

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



IGURE 1. Example of the spectrum of a major solar flare (photographed at the Astronomical Institute of the Czechoslovak Academy of Sciences at Ondřejov on 12 July 1961). The upper part shows the spectrum between λ3873 and λ3988 Å, with the H and K lines of the singly ionized calcium, Hε and Hζ lines of the Balmer series of hydrogen and many metallic lines (e.g. No. 11 is Si I, 13 is Ti II, 22 and 23 are Al I, most of the others are Fe I lines). The lower part shows the spectrum between λ3747 and λ3825 Å, including three higher members of the Balmer series. (After Švestka 1972.)

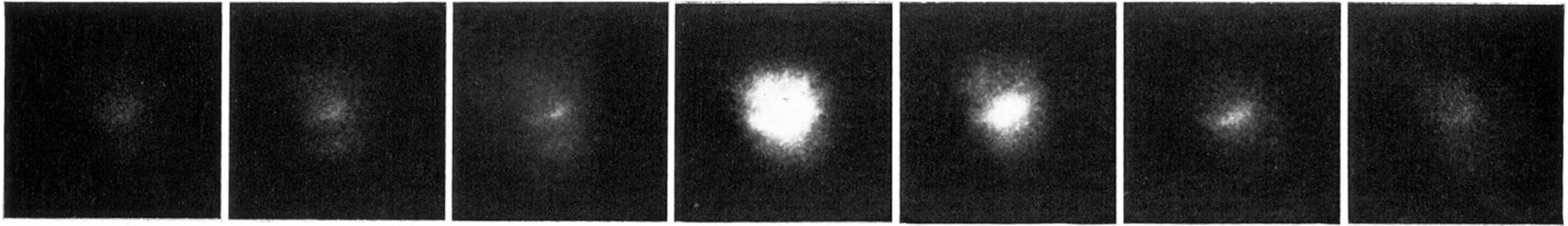
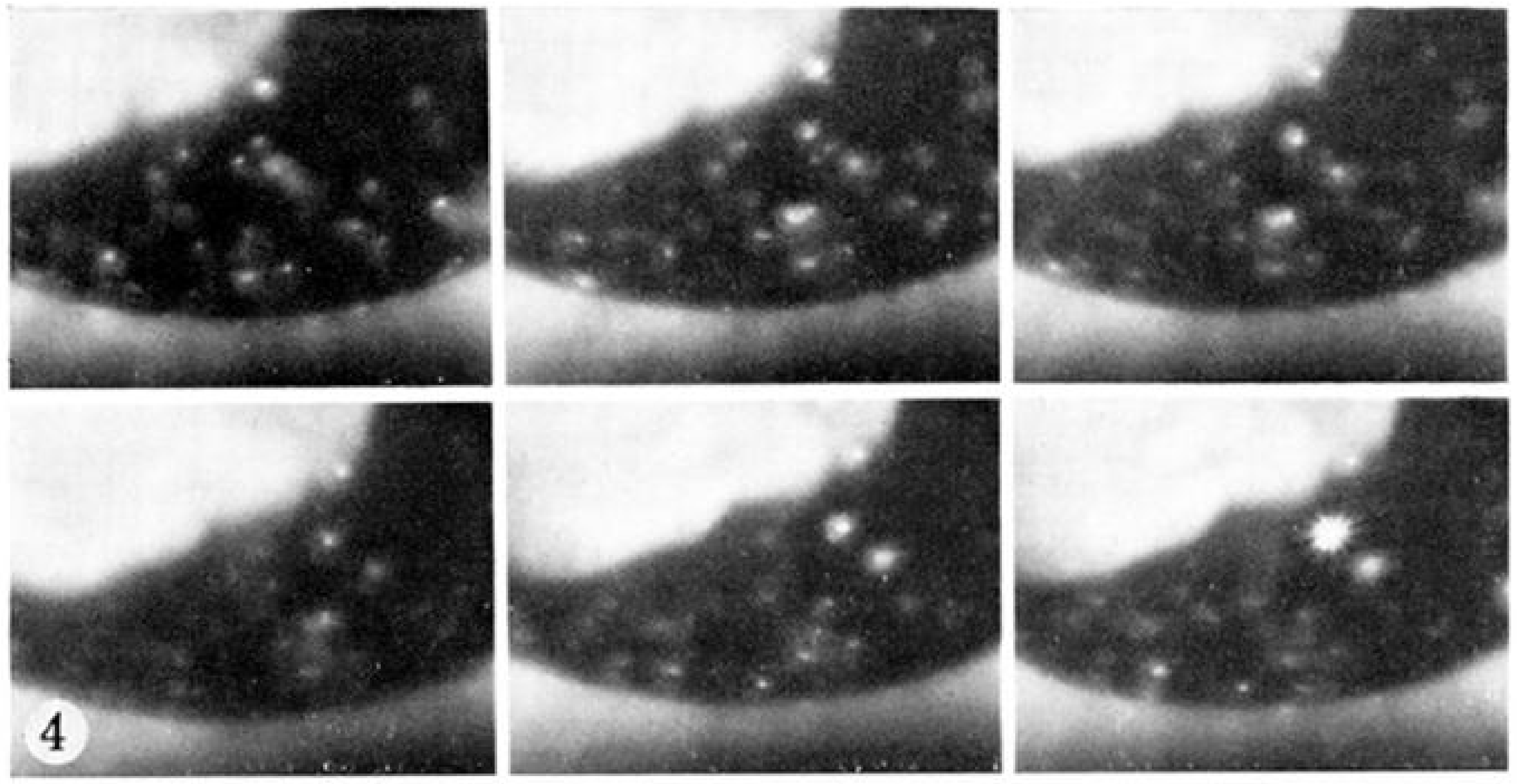
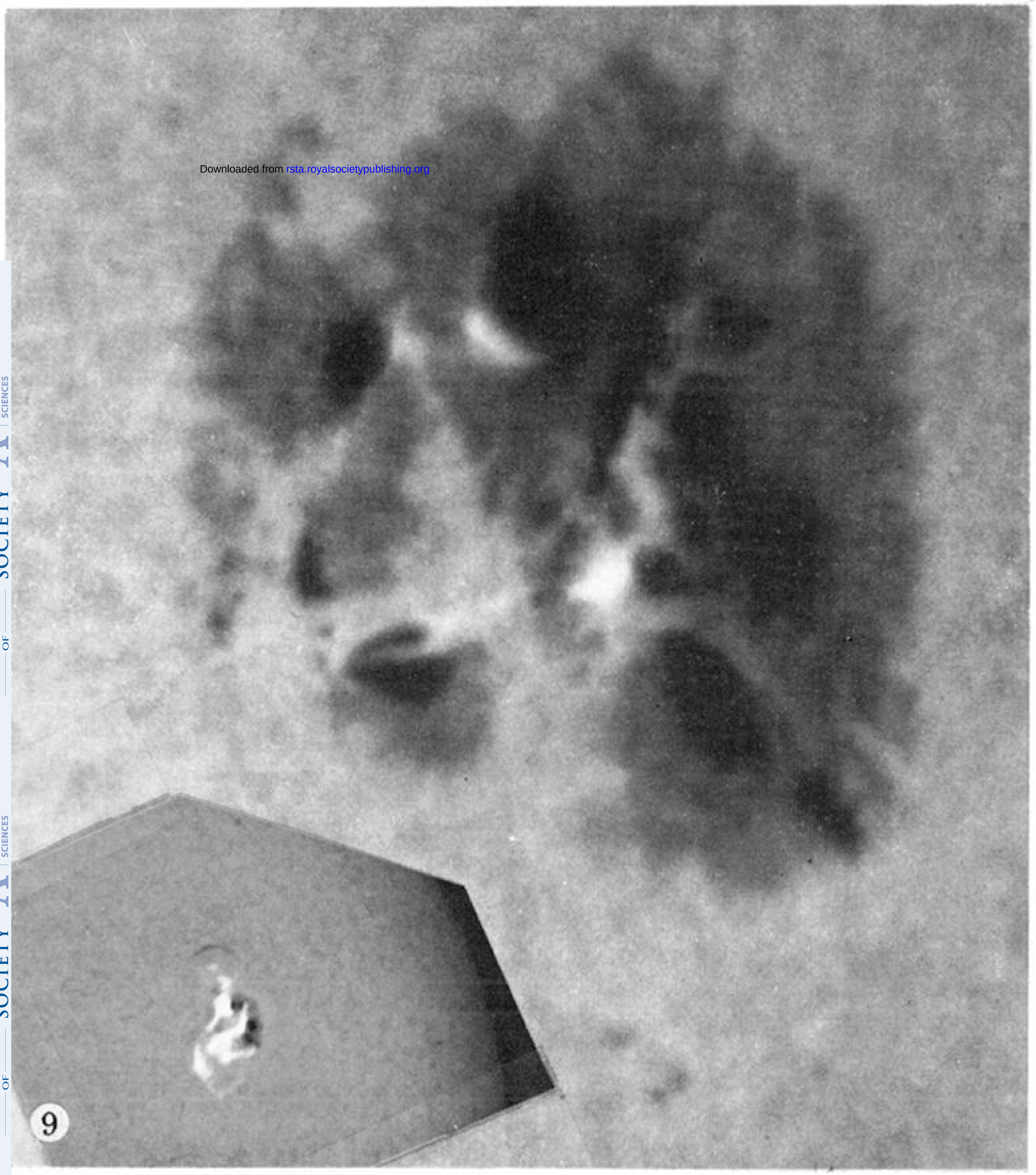
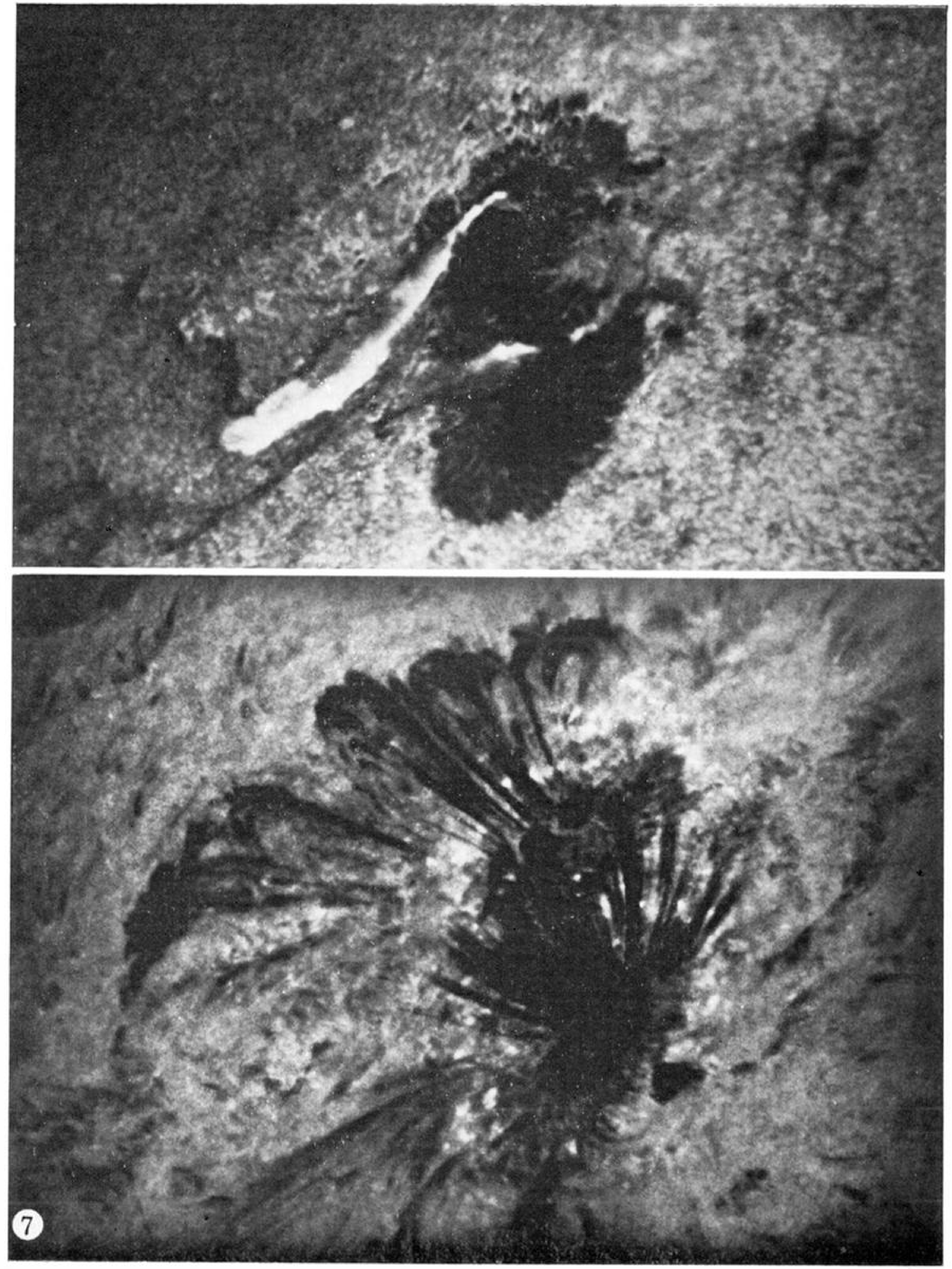


FIGURE 3. A flare-like brightening occurred on 1 September 1973 in one of the three loops which formed the active region McM 12511, born only one day before. (American Science and Engineering A.t.m. experiment on Skylab, courtesy R. Petrasso.)







FIGURES 4, 7 AND 9. For description see opposite.