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

Optical and Magnetic Measurements of the Photosphere and Low Chromosphere [and Discussion]

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ACTIVE REGIONS

Optical and magnetic measurements of the photosphere and low chromosphere

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[Plates 8–11]

Sequences of photographs at a resolution of 1″ achieved during the past ten years have had a very significant impact upon our understanding of the development, mature structure and decay of active regions. Cinematic studies, especially, have allowed the emergence of new fields and their motions within the active centre to be studied in detail. Cinematic magnetic observations show how sunspots decay through the outward flight of tiny knots of magnetic flux. The newest advances are being made with arrays of photosensitive diodes at the focal planes of high dispersion spectrographs. The diode array at the Sacramento Peak Observatory produces simultaneous photometric observations at many different wavelengths throughout the visible and near infrared spectrum. Quantitative studies of magnetic fields and chromospheric structure are discussed. In particular, the moving magnetic features apparently produce surges in the superpenumbra around large sunspots.

1. Introduction

In the first quarter of this century the spectroheliograph, which produces a solar image at a single wavelength, was the preferred instrument for studying the structure of the chromosphere. Hale's (1929) development of the spectrohelioscope made it possible to view the Sun at many wavelengths in rapid succession, and this instrument was an important research tool for many years, helping to study Doppler shifted (moving) material. Use of the spectrohelioscope was limited, however, because it was impossible to capture on film the many simultaneous impressions that the observer can gain when using the instrument at the telescope. The introduction of the birefringent filter shortened exposure times dramatically and made cinematic studies of motions in the solar atmosphere possible. The most recent developments in ground based instrumentation for chromospheric research are the fully tunable birefringent filter (Beckers, Dickson & Joyce 1975) and arrays of silicon photodiodes (Dunn, Rust & Spence 1974). Both instruments represent attempts to record chromospheric and photospheric features simultaneously at many wavelengths with high time and spatial resolution.

2. Chromospheric fine structure

Most of the observations to be described in this paper were made with an array of 512 diodes mounted in the echelle spectrograph at the Sacramento Peak Observatory. The quantum efficiency of the silicon photodiodes ranged up to 80 % at some wavelengths. The high efficiency made it possible to sample the signal from each diode at a rapid rate (60 times/s) and to build up many spectroheliograms simultaneously. In particular, 64 diodes were queued perpendicular to the direction of dispersion at each of eight wavelengths, and the solar image was slewed rapidly across the spectrograph entrance slit while the diode responses were digitized and recorded with an electronic computer. The highest data collection rate was 30 000 observations/s. The results are best displayed as computer generated photographs. An example is shown in figure 1.

Using the six images in figure 1, it is possible to make detailed comparisons between the photospheric features (sunspots, granules, pores) and chromospheric structures in three of the most important emissions: Ca II (8542 Å), H I (6563 Å) and He I (10 830 Å). By placing diodes in the wings of the Fe I line at 8468 Å, which is formed in the upper photosphere, we were able to obtain magnetograms and tachograms (maps of the line-of-sight velocity) simultaneously with the spectroheliograms. The resolution attained in the best observations, such as those shown in figure 1, was 1″.

The near identity of the Ca II emission network and the distribution of magnetic fields in the photosphere has been known for 15 years, but the Diode Array observations make it clear that the clumps of Ca emission are much larger than the knots of magnetic field underlying them. Many of the magnetic knots are no larger than the resolution limit, but the Ca II emission points are several arc sec in diameter. Since the Ca II emission probably occurs where the chromosphere is heated by shocks or by heat conducted along magnetic field lines, we conclude that the magnetic field as seen as 1″ (or smaller) knots in the photosphere spreads out rapidly when it reaches the chromosphere.

Most of the Ca II emission comes from the network boundaries, where the magnetic field is concentrated. However, on the best quality Ca II spectroheliograms, many 1–3″ bright points appear scattered uniformly within the network cells. There are some knots of magnetic field inside the cells, but careful examination of the diode array data fails to reveal any correlation between cell-centre knots and Ca II faculae. This observation suggests that since bright points on cell boundaries are associated with magnetic knots, and bright points in cell centres are not, different mechanisms may be responsible for causing the brightenings.

The pictures in figure 1† show that chromospheric structure certainly depends upon the wavelength of the light being analysed. If the dark filament running through the centre of the active region in figure 1 is studied with the Ca II line, it shrinks to a few faint traces. In Hα, it is an alleyway. It is a major artery in the rarely used line of He I at 10 830 Å. Quantitative research directed toward establishing the physical conditions in such structures has not yet produced acceptable three-dimensional models, in part because of the unavailability of simultaneous, high-resolution images in many lines.

The He I line should prove especially useful for delineating chromospheric structure because nearly 20 eV are required to excite its upper level: the line is purely chromospheric. Few observations have been made at 10 830 Å because of the poor quantum efficiency of photographic materials at that wavelength. But, the diodes are near their peak efficiency there, so low noise spectroheliograms at the highest resolution can be made in this line for the first time. Figure 2 shows a subtraction of two spectroheliograms made in the wings of the He line. The subtraction reveals moving chromospheric structures (sunspots and granules) that show through the thin helium blanket. Spicules appear as white and black dots, reflecting motions towards and away from the observer, respectively. The dots occur in broad (10″) chains overlying network cell boundaries. Many individual dots are only 1″ wide. The spicules also appear as bushes of white (upward) streaks stretching across the solar surface from the network vertices. Typical velocities are 20–40 km/s. Figure 2 shows that there is helium structure everywhere, not just along the cell

† Figures 1–5 appear on plates 8–11.

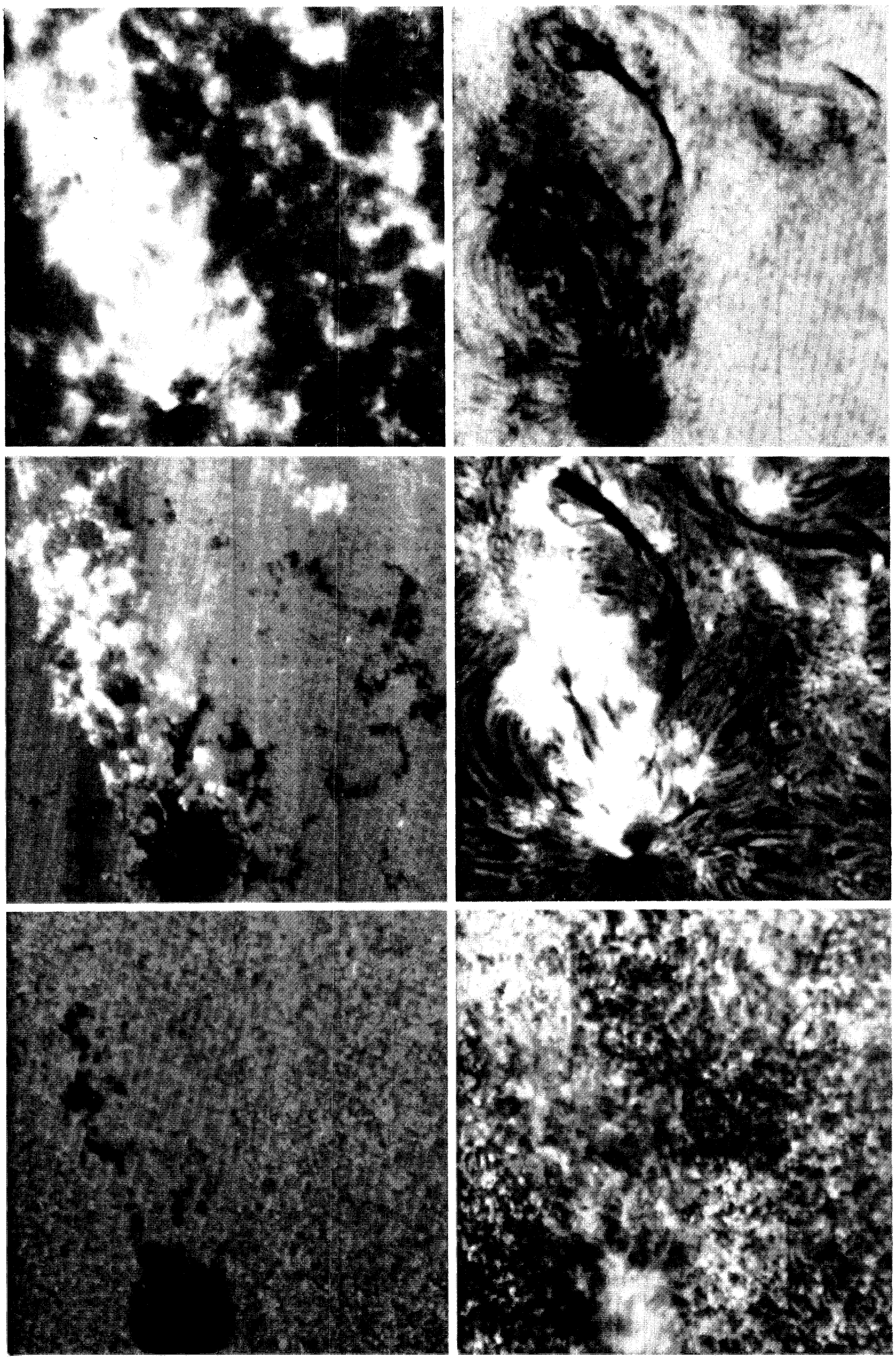

FIGURE 1. Simultaneous observations from the diode array at 6521 Å (continuum), 8468 Å (magnetic fields and velocities), 8542 Å (Ca II), 6563 Å (Hα), and 10830 Å (He I). Each photograph shows an area 240″ × 240″ on the Sun. The resolution is 1″.

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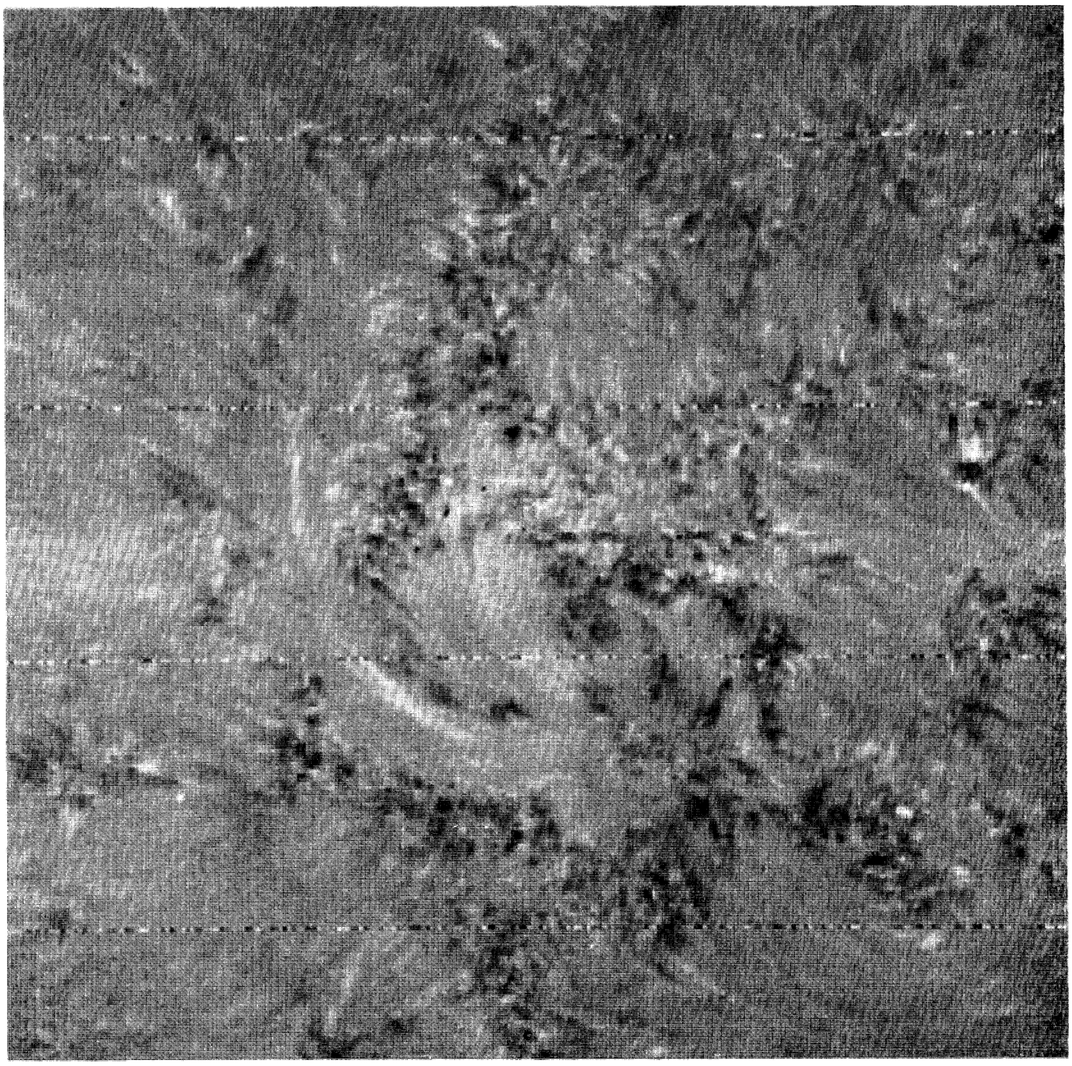

FIGURE 2. A computer-produced subtraction of spectroheliograms in the wings of the He I line at 10830 Å. This image of McMath region 12694 on 15 January 1974 shows, by their motions, the bushes of spicules along the boundaries of the chromospheric network.

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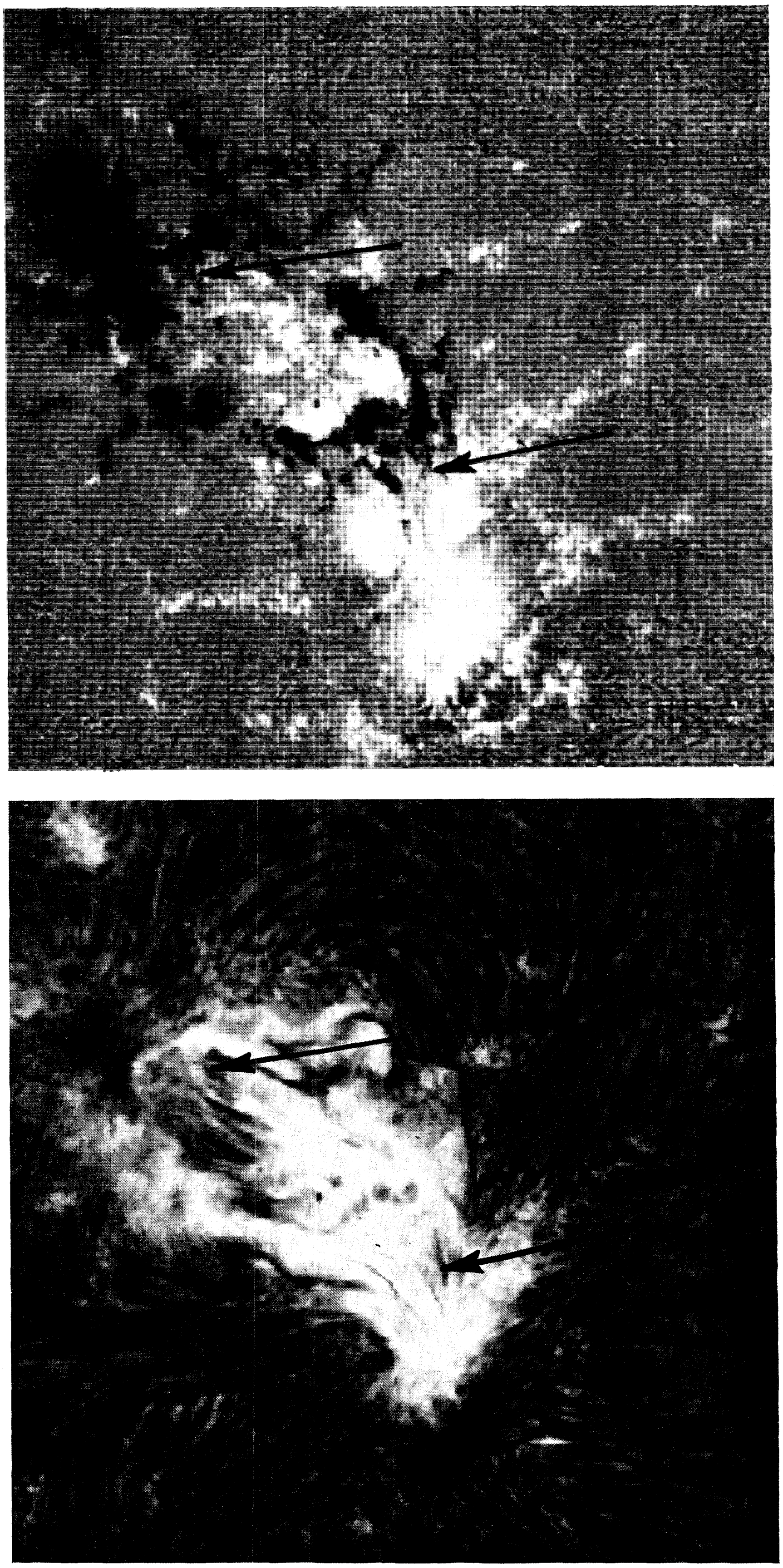

Figure 3. Hα (left) and magnetic fields (right) in McMath region 12848 on 12 April 1974. Positive fields are white, negative fields black. The arrows show where new fields are emerging.

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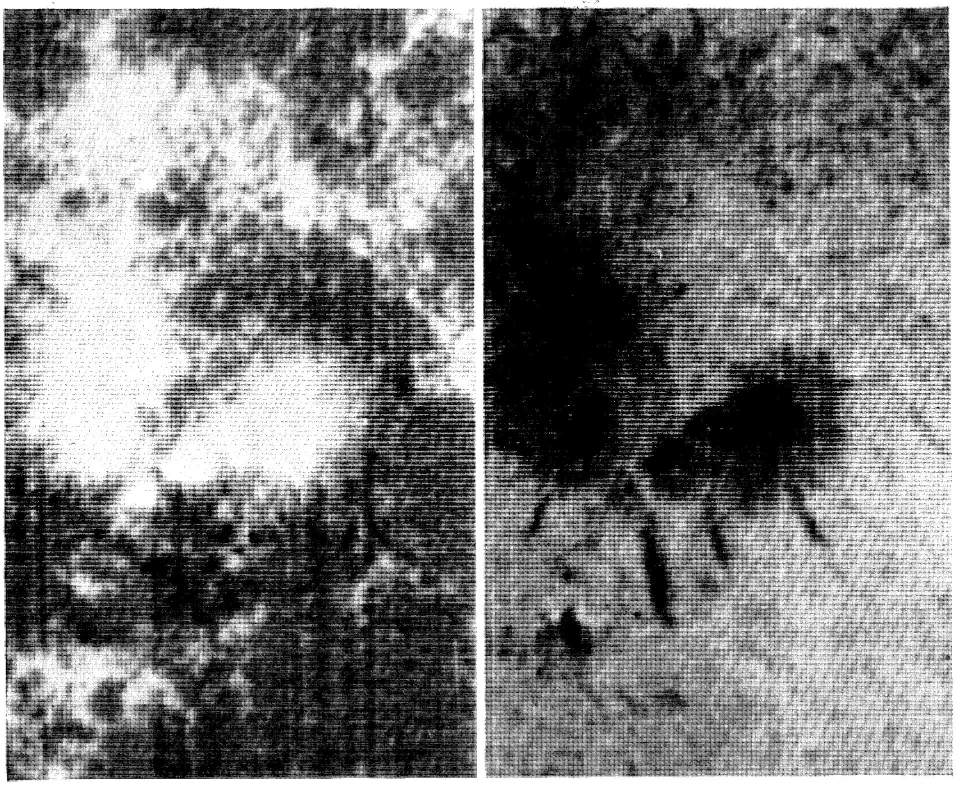

FIGURE 5. Surges and m.m.fs in McMath region 12906 on 7 May 1974. M.m.fs drifted outward from the spot shown here for many days, always accompanied by many surges (dark streaks in the He 10830 picture).

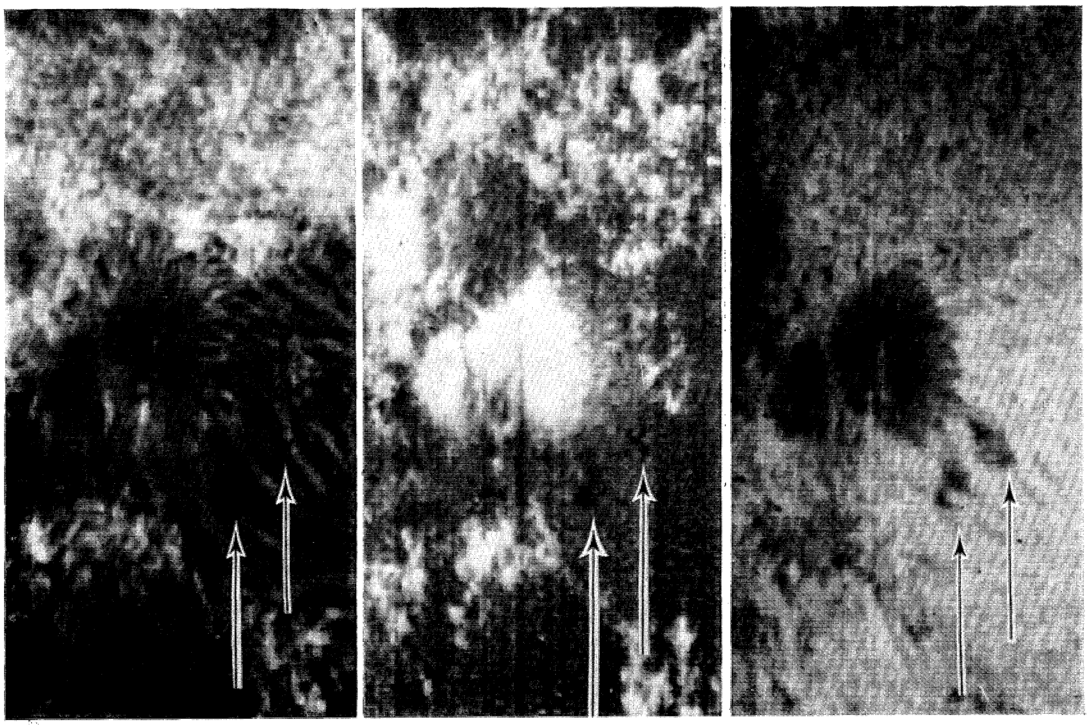

FIGURE 4. Surges and m.m.f's in McMath region 12906 on 4 May, 1974. The surges (indicated by arrows in the He 10830 image) are dark, but they start in bright flare points that lie immediately over m.m.fs.

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boundaries or in active regions, and comparison with the Hα spectroheliogram taken simultaneously shows that fibril patterns seen in the two lines are similar.

So far, only morphological studies of the helium spectroheliograms have been carried out, but the diodes produce photometric data that is ready for quantitative analysis. The uncertainties, difficulties and delays associated with photographic photometry need no longer stand in the way of quantitative chromospheric research.

3. Moving magnetic features and evolving sunspot groups

The most interesting questions that can be investigated with multi-channel observations are those concerning the effect of photospheric events upon the chromosphere and the related questions of what the magnetic field in the photosphere looks like as it bubbles up from below and how active regions age and decay. Vrabec (1975) has written an excellent and comprehensive review of this field, and so only the highlights and a few new points based upon the diode array observations will be presented here.

Sequences of magnetograms, especially those made by Vrabec (1971) and by Harvey & Harvey (1973) have shown that sunspots decay as tiny knots of flux stream radially away toward the network cell boundaries. Further, Vrabec (1975) has shown how, on one active region, most of the smaller sunspots participated in a streaming motion leading to the largest leader and follower spots. The pores with negative fields swam toward the largest negative spot, while the positive pores converged on a large positive spot. Vrabec's example illustrates an empirical rule that appears to govern the behaviour of magnetic fields in active regions: 'Like fields attract'. That is, as magnetic fields emerge at the photosphere, they are usually very complex – frequently resolvable on the best magnetograms as a fine mosaic of positive and negative field elements only 1″ or less in diameter. Then, with time, the pattern becomes bipolar on a large scale, mostly due to proper motions of the field elements and *in situ* growth by the largest spots. Observations with the diode array showed this pattern clearly in emerging flux regions, which may be identified readily in Hα filtergrams by their arch filament systems (Frazier 1972). Two such regions are shown in figure 3.

The figure illustrates most of the phases in the magnetic evolution of an active centre. The black arrows point to the two arch filament systems where new fields were emerging. Positive and negative fields there mingled on a scale of a few arcseconds. (A similar region can be discerned just to the right of the large negative (black) polarity spot in figure 1.) Sequences of such magnetograms viewed as movies show that, even over short (2 h) intervals one may see considerable consolidation of the elementary 1″ magnetic knots into larger clumps of 5–10″ diameter.

In the centre of the magnetic region in figure 3, there is a steep boundary where positive (white) fields have clustered against a barrier of negative (black) fields. By the next day, this boundary had broken and the patch of positive fields in the centre of figure 3 was contiguous with the large positive area around the leader spot (left in the figure). As the region aged, like fields consolidated and coalesced further, and the activity in the chromosphere that is associated with complex fields gradually ceased.

Finally, figure 3 shows that the leader (lower left) and follower (upper right) spots were already beginning to decay even while new flux was crowding into the centre of the spot group. Both leader and follower were surrounded by telltale decay products – shreds of positive and negative fields being swept like flotsam and jetsam to the surrounding plages.

4. Surges and moving magnetic features

The emergence of magnetic flux at the photosphere is always accompanied by chromospheric activity. Ellerman bombs and small surges are found at the feet of arch filament systems (Weart & Zirin 1969). Also, it is well known that many large sunspots are surrounded by a 'super-penumbra' that, upon cinematic examination, is found to consist of a continual outpouring of large and small surges. Until the advent of multi-channel detectors, this activity was usually studied separately from the photospheric magnetic fields. However, Rust (1968) showed that the surges are associated with 'satellite sunspots', that is, with 5–10″ magnetic poles near the outer

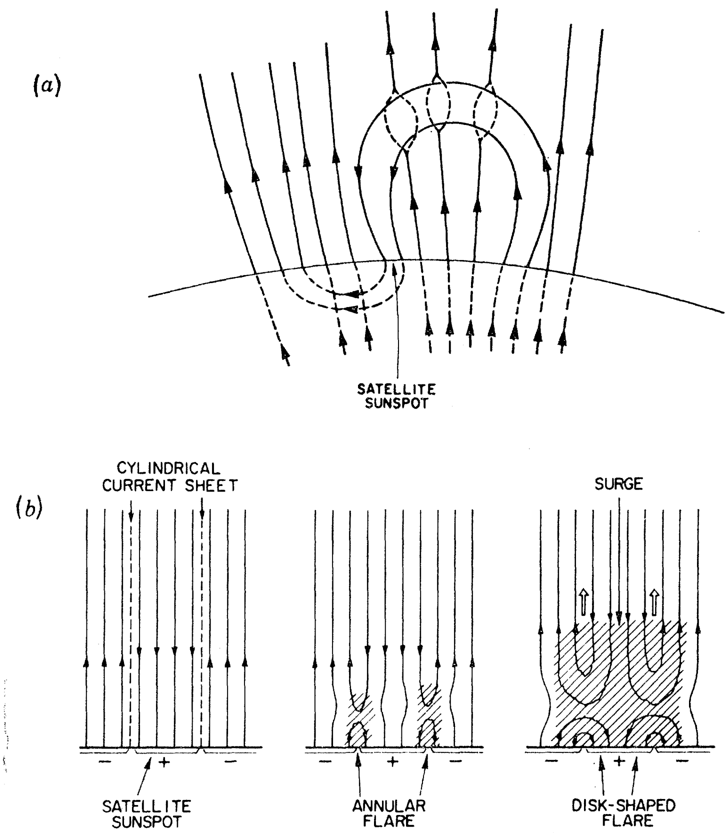

Figure 6. (*a*) Schematic drawing of how a tube of flux may thread the photosphere three times to produce a 'satellite sunspot'. (*b*) Idealization of the field-line reconnection around a satellite sunspot that may cause a small flare and a surge.

boundary of large spots' penumbrae. The fields at these poles had a sign opposite that of the parent spot. Some were visible in white light, but most were not. They appeared only as depressions on contour maps of the magnetic fields surrounding large spots. The moving magnetic features (m.m.fs) studied by Vrabec and the Harveys were not thought to be associated with such chromospheric activity.

In April and May 1974, several sequences of eight-wavelength observations with excellent image clarity were obtained at the diode array. Movies made from these observations clearly showed that surges, which stand in particularly sharp relief on He 10 830 spectroheliograms, originated at bright, flare-like points just over m.m.fs. Figures 4 and 5 show examples of this phenomenon. From the 1″ diode array data and the earlier, low resolution studies with point scanning magnetographs, it is evident that 'satellite sunspots' of any size and description between 1″ m.m.fs and 10″ pores will lie at the root of an almost continuous sequence of surges. However, the relationships between chromospheric activity and the behaviour of m.m.fs must be studied much more carefully. Although Rust (1968) and Roy (1973) showed that the field in satellite sunspots apparently weakens as the surges occur and that surges do not occur unless an isolated magnetic pole is present, quantitative measurements at the highest resolution are not available. The field configuration and the mechanism for generating surges remain unknown, although Sturrock (1972) has proposed a plausible model. He suggests that a tube of magnetic flux may become 'hooked' through the photosphere to form an apparent field reversal (see figure 6*a*). The fact that m.m.fs are frequently seen in pairs of positive and negative fields seems to support this view. To give rise to chromospheric activity, Sturrock proposes that field-line reconnexion occurs at a cylindrical current sheet surrounding the errant flux tube (figure 6*b*). Heating in the current sheet or particles accelerated there would cause an annular brightening at the base of the surge. The crescent shape of many flare kernels found near satellites lends further support to this model. Finally, the surge will be seen as material is ejected by magnetic stresses from the field-line reconnection site.

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Discussion

Dr N. O. Weiss

Meyer *et al.* (*Mon. Not. R. astr. Soc.* October 1974) have recently produced a model of the decay of a sunspot in which moving magnetic features correspond to kinks in a flux rope transported outwards by a large scale convective motion. The kinks are generated by granules and may travel with the Alfvén speed relative to the outward flowing gas. Could your surges be excited by granules or, more probably, by the travelling Alfvén wave?

Dr D. M. Rust

The surges are associated with magnetic features of polarity opposite that of the central spot, but no surges are detected where the spot and the moving magnetic features have the same polarity. This fact must say something basic about the mechanism, so I do not believe that granule motions alone excite surges.

Dr H. U. Schmidt

Do you see in your film of moving magnetic features and subsequent surges both signs of magnetic field in the sequence of moving magnetic features?

Dr D. M. Rust

Yes, and considering the limited resolution, the magnetic field may be even more mixed than it sometimes appears.

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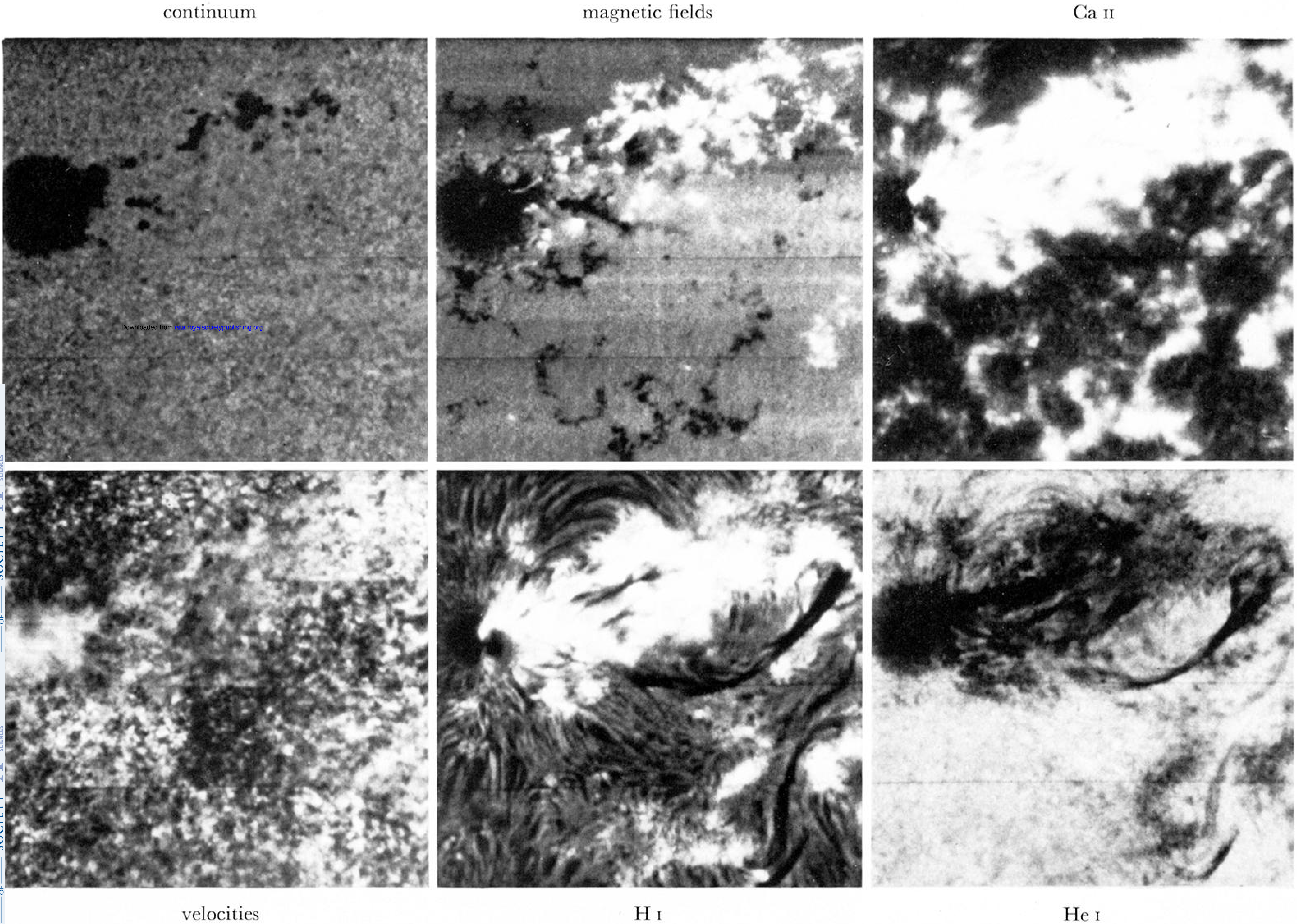

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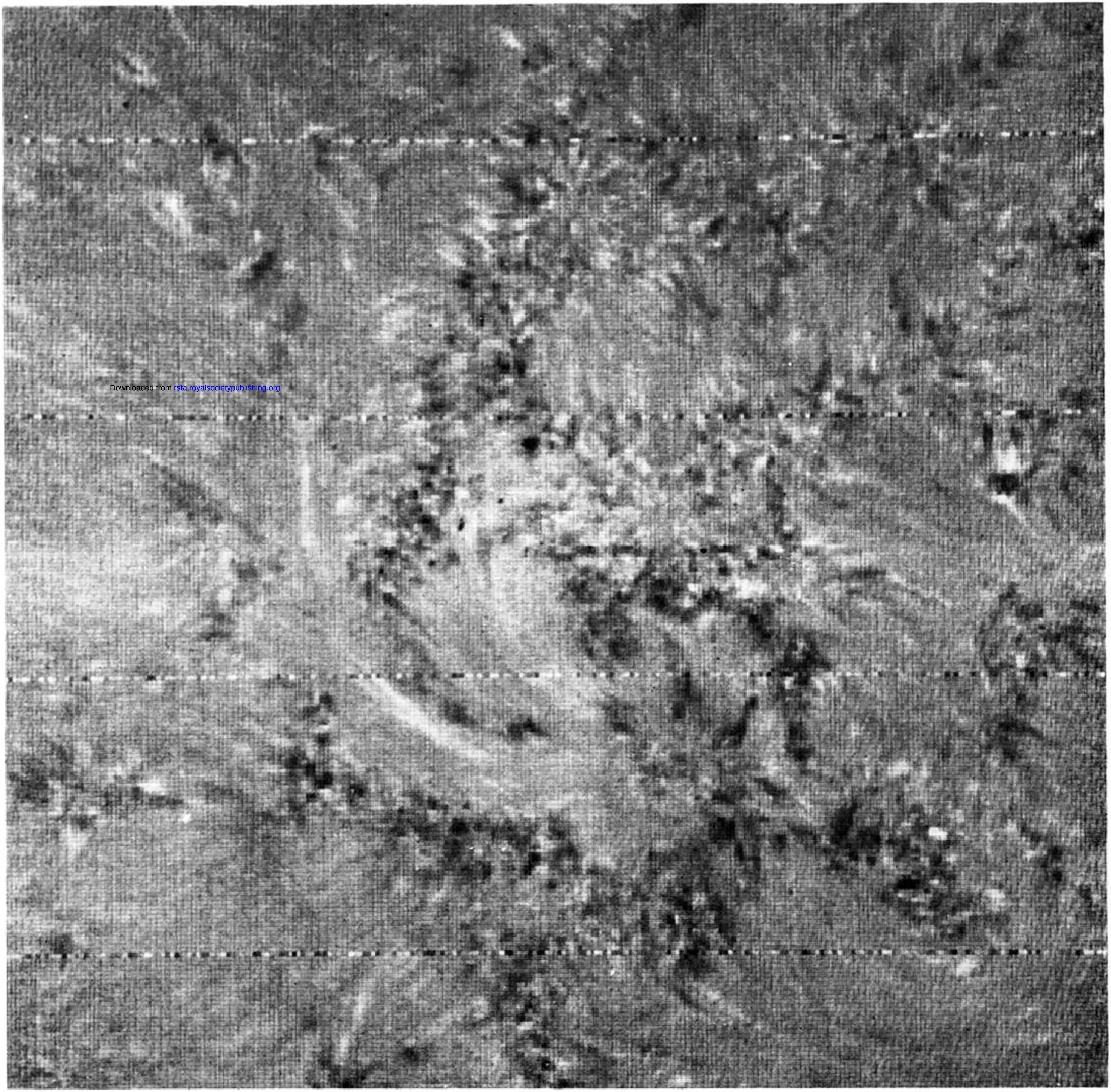

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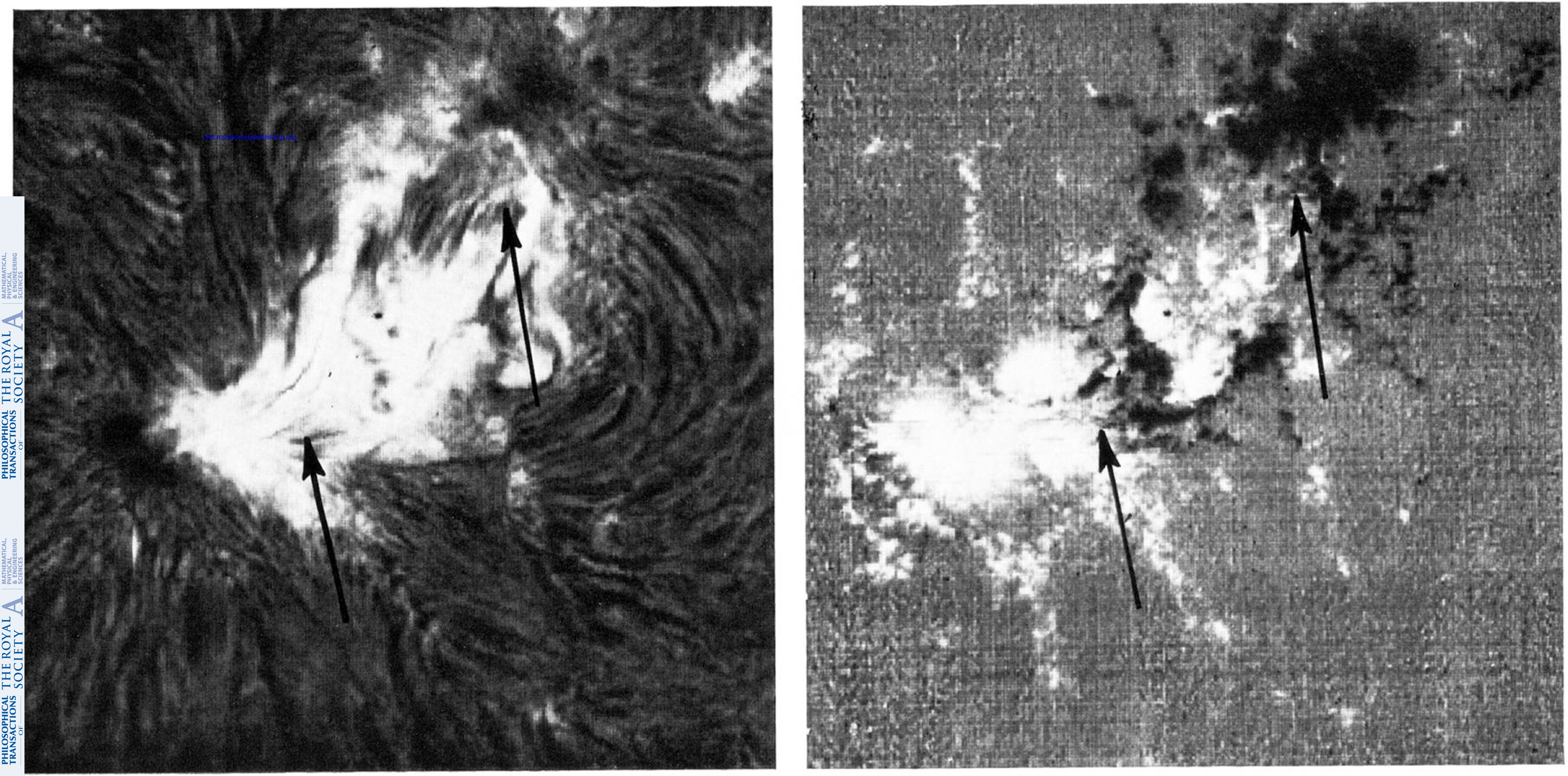

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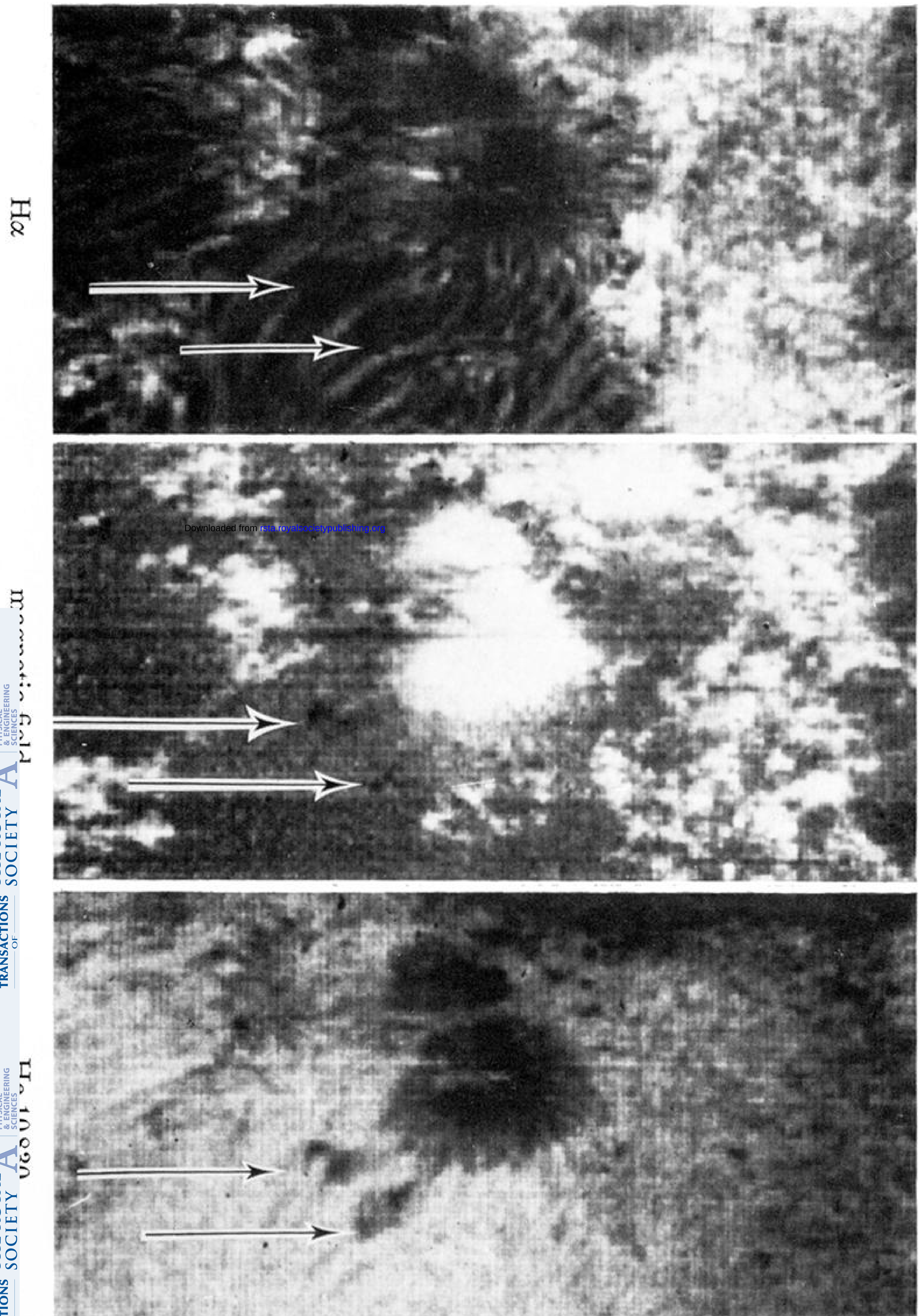

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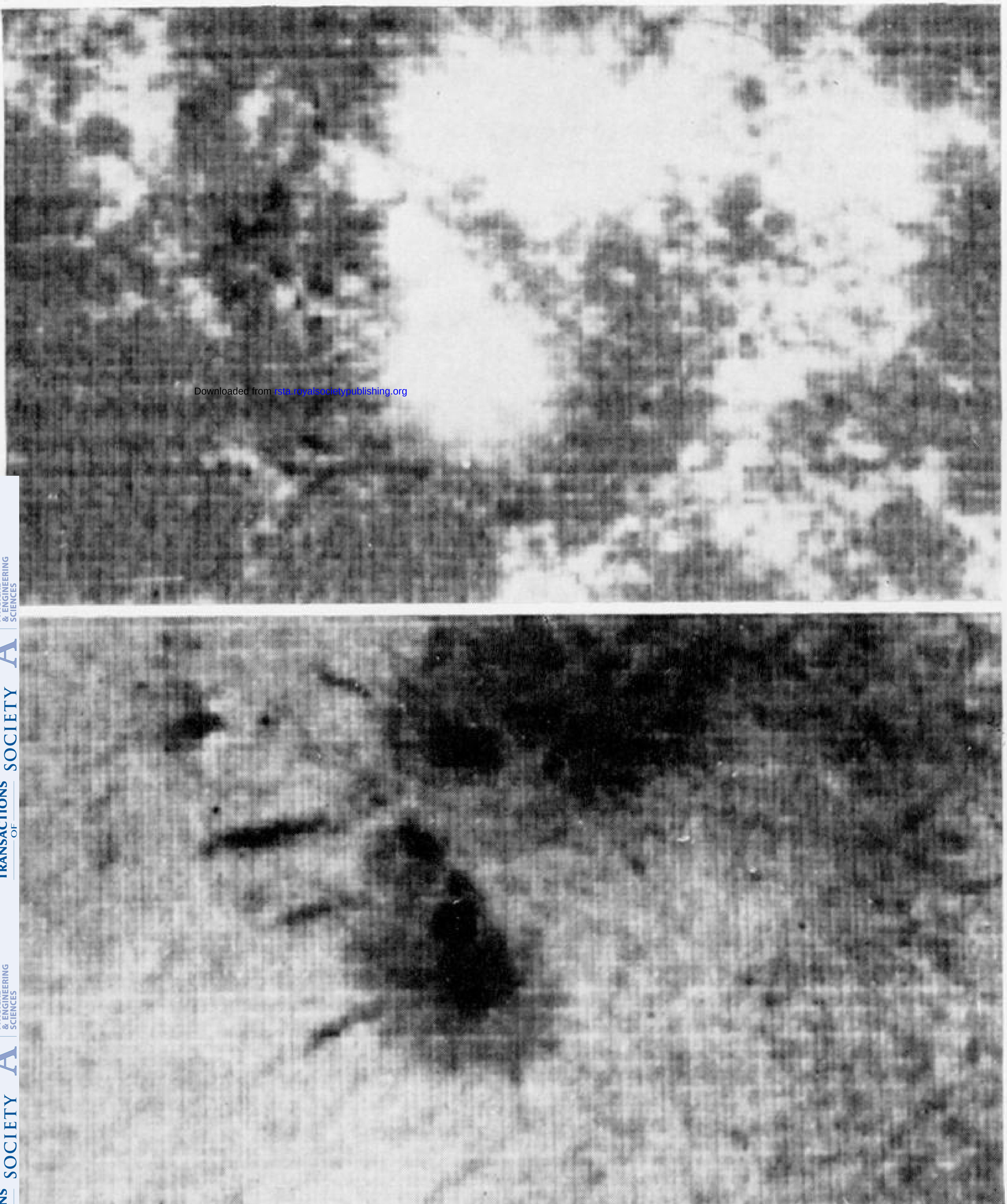

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