

# Solar activity: An overview

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**This review article describes briefly the main characteristics of the active Sun: the different active phenomena, the 11-year cycle of their appearance, and their influence on the environment of our Earth.**

## 1. Solar cycles

Although the Sun illuminating our Earth looks like a steadily shining celestial body, its surface is actually the seat of continuous changes and powerful activity. As the Solar and Heliospheric Observatory (SOHO) spacecraft recently revealed, in ultraviolet lines the solar surface looks like 'boiling' all the time and everywhere one can see variations in brightness, plasma flows, and small ejections of gas, indicating permanent changes of the structures in the solar atmosphere.

But this is not what we call solar activity – all these changes are still considered to occur on the 'quiet Sun'. The real processes, called *solar activity*, which have their impacts also on the Earth environment, appear in limited parts of the solar atmosphere, and their occurrence varies quasi-periodically with time, creating 11-year *cycles of solar activity*. Each new solar cycle is born close to the solar poles and its activity then slowly propagates to lower heliographic latitudes. The real length of one cycle is actually about 22 years, but only the second half of it begins to produce clearly visible active processes on the Sun.

When the Sun is viewed in white light, one observes the lowest level of the solar atmosphere, which is called the *photosphere*. In the photosphere, solar activity manifests itself as sunspots or groups of sunspots (Figures 1 and 2 *a*). Therefore, solar cycles were long characterized (and still are) by the so-called *relative sunspot numbers R*: A daily *R* is the sum of the number of sunspot groups on the Sun plus the number of individual sunspots in all of them. A monthly or yearly *R* is the average daily *R* during a month or a year. Individual solar cycles differ in their lengths and heights – lengths varying between 9 and 16 years, and yearly maximum *R* varying between 46 and 190 have been observed between the half of the 18th century and present days.

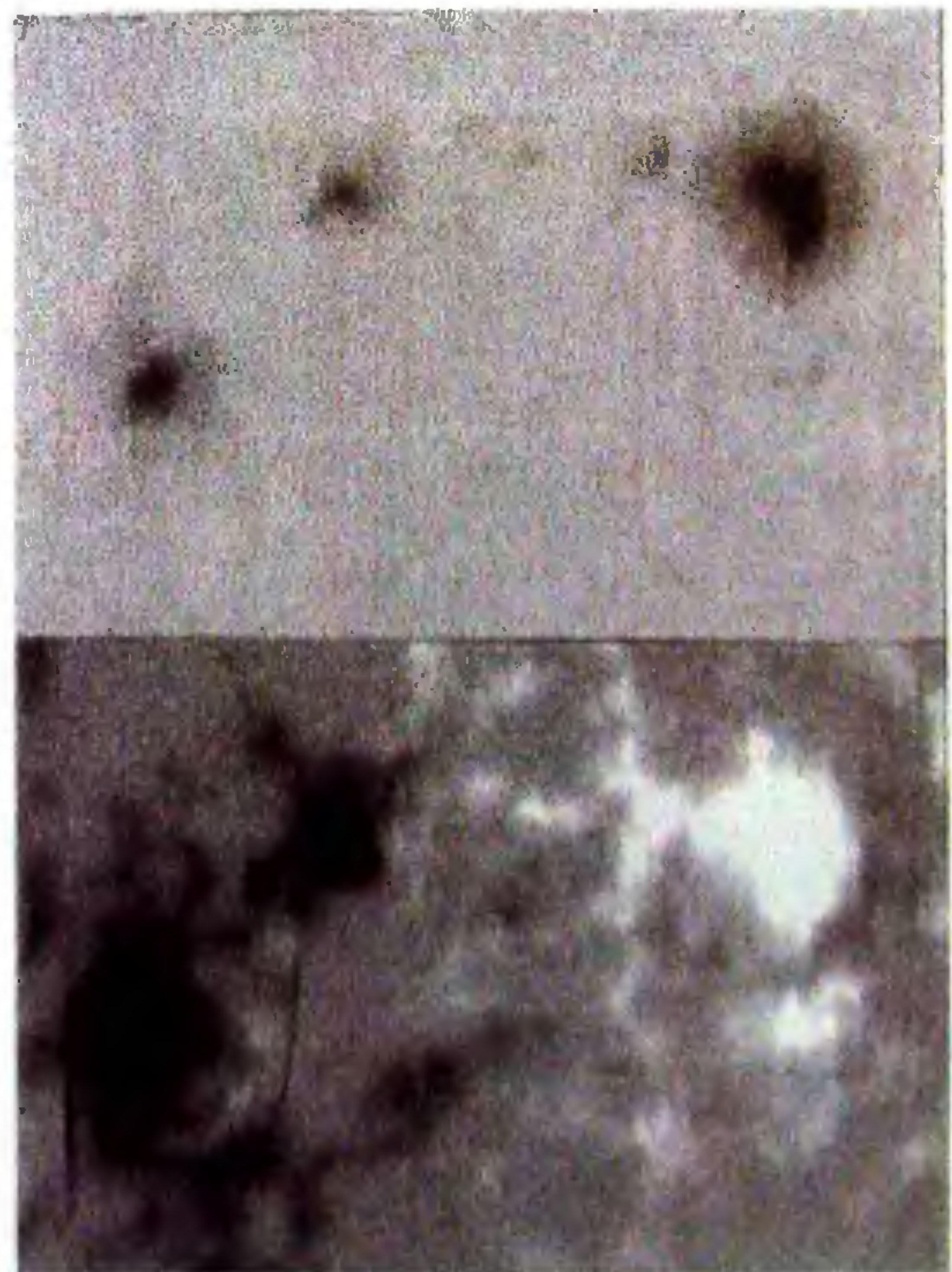
Rare sunspot groups begin to appear first at high latitudes (between 40 and 50 heliographic degrees) and as the frequency of their occurrence increases, their positions move progressively closer to the equator. A few years after the onset of an active cycle, when the spots appear

mostly at latitudes below 25°, the cycle reaches its *maximum*. Thereafter it slowly declines, with the spot occurrence approaching the equator, and eventually reaches a *minimum* when sunspots appearance becomes very rare and for many days the Sun is without any sunspots. However, usually before the last sunspots of the old cycle disappear, new ones begin to appear at high latitudes.

## 2. Active regions

This solar activity is due to magnetic field which exists in the Sun, generated by electric currents. Sunspots become visible in the photosphere when ropes of magnetic flux emerge on the solar surface. The magnetic flux in the central dark *umbra* of a spot is usually between 1500 and 3000 gauss and, as a consequence of this strong field, temperature in a spot is much lower (4000 K or less) than in the surrounding photosphere. This causes the dark appearance of sunspots in which the *umbra* is surrounded by a less dark *penumbra* (Figure 1).

However, as Figure 2 *b* shows, the situation looks quite differently if we observe sunspot groups in the higher



**Figure 1.** A sunspot group in the photosphere (*above*) and the photospheric magnetic field (*below*). Black and white denote the opposite magnetic polarities.



layer of the solar atmosphere, the *chromosphere*. Since about 1930, this layer could be observed in a spectro-helioscope and through filters, which make it possible to observe the Sun in a narrow monochromatic band, usually centered on the hydrogen-Balmer- $H\alpha$  line. In this line, sunspots are surrounded by *bright plages*, and we call these groups of plages and spots the *active regions* on the Sun.

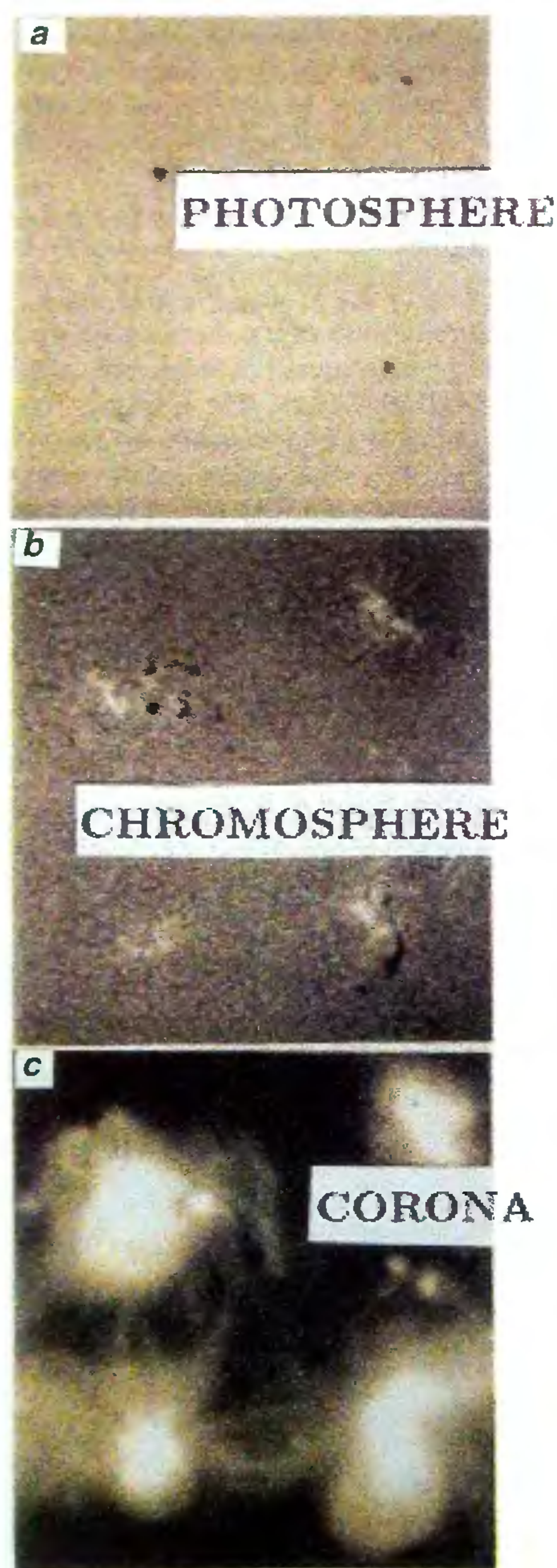


Figure 2. Images of four active regions in (a) white light, (b)  $H\alpha$  line, and (c) X-rays.

And since 1973, when *Skylab* orbited the Earth and imaged the Sun in X-rays, we can also see the highest layer of the solar atmosphere, the *solar corona* in which these active regions appear extensive and bright (Figure 2 c).

Active regions appear where magnetic flux emerges from subphotospheric layers to the solar chromosphere and corona (see the magnetic map in Figure 1). There are many flux emergences on the solar surface, all the time creating *ephemeral active regions* which in X-rays are seen as *bright points* on the Sun (examples – bright dots – can be seen in Figure 2 c). However, only few of them grow further, with newly emerging flux continuously added to them and eventually developing into much larger *active regions* (four of them are seen in Figures 2 a, b and c and many more on the full-disk picture of the Sun in the  $H\alpha$  line in Figure 3).

Most active regions are *bipolar*, with two main spots and surrounding plages of opposite magnetic polarities. The two polarities are connected by chromospheric and coronal *loops*, particularly well seen in X-rays and ultra-violet lines (Figure 4), and are separated by a *neutral line* below the tops of these loops where the longitudinal magnetic field is zero. (Compare the schematic drawings in Figures 9 a and b.) Solar atmospheric gas slowly accumulates along these lines and cools. In the  $H\alpha$  line one can see them along these neutral lines *dark filaments* (many are seen in Figure 3) which on the solar limb look like bright *prominences* (Figure 5). Dark filaments often survive even after the active region decays, and can form outside of active regions as well (like that one to the southwest of the Sun's center in Figure 3).

In some cases, irregular patches of magnetic flux emerge in an active region and cause irregularities in its magnetic structure. Then several different neutral lines exist in the region and more dark filaments can form there. While all active regions are seats of various kinds of active processes, the most powerful events of solar activity occur in these magnetically complex active regions, where both magnetic polarities are mixed. Most active is the so-called  $\delta$  configuration, when umbrae of opposite polarities are embedded in one common penumbra.

### 3. Complexes of activity and interconnecting loops

Solar activity seems to prefer, sometimes for a period of many months, selected *active longitudes* where active regions form more frequently than elsewhere on the Sun, creating there so-called *complexes of activity* (Figure 6). This seems to be due to some irregularities in distribution of the subphotospheric magnetic flux that emerges through the photosphere. Once such an irregularity is formed, it takes a long time before effects of the solar rotation, which slightly varies with the latitude, remove it.

Many active regions in such a complex of activity are connected by coronal loops that very often extend across the equator. We call them *interconnecting loops*. They

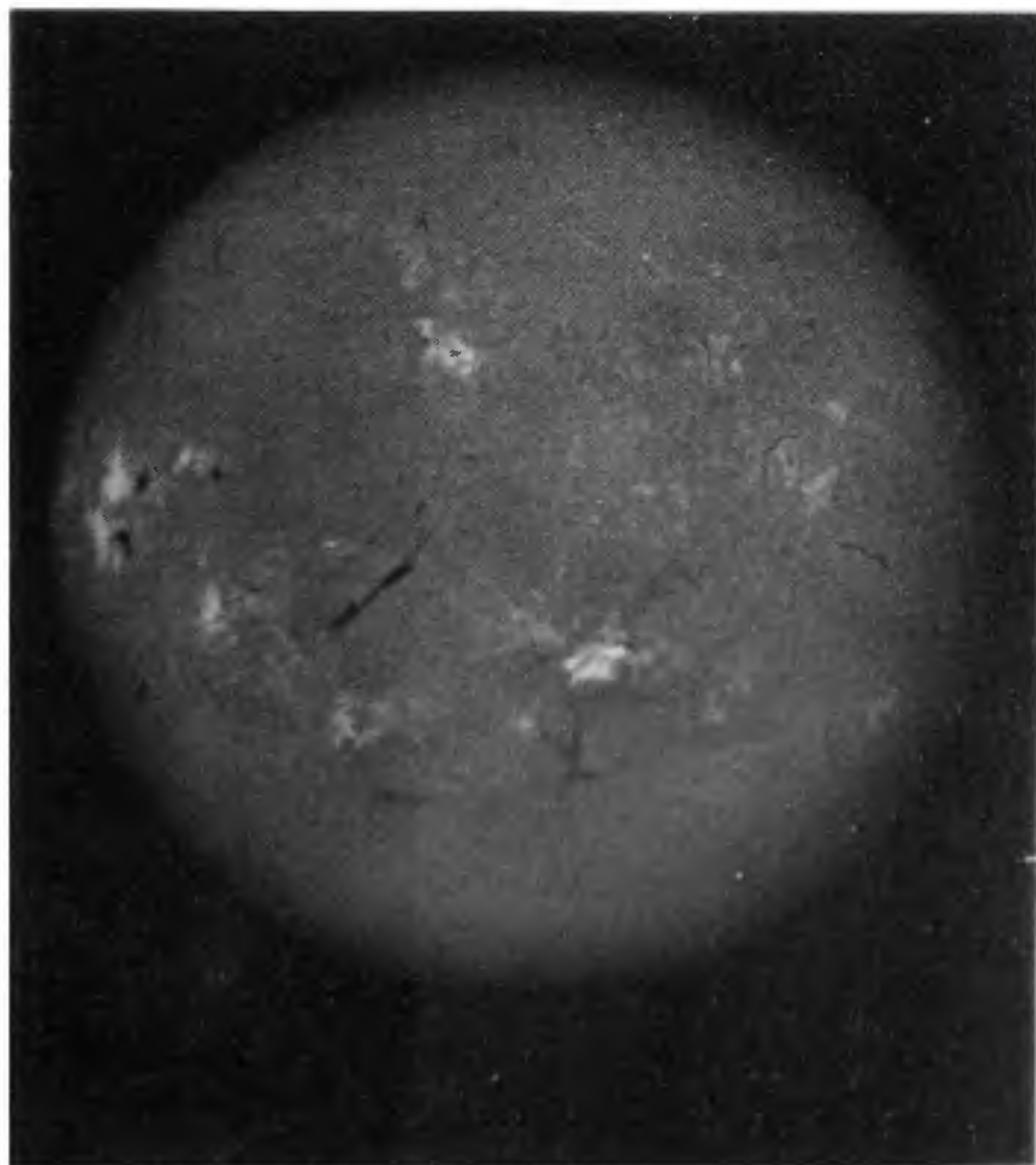


can be best observed in soft X-rays, as was first done on *Skylab* in 1973 (an example is shown in Figure 2 c) and presently by *Yohkoh*. Due to magnetic field variations in the interconnected active regions, these connections vary all the time in their shape and brightness. In the new solar cycle, when active regions begin to emerge at high latitudes, these interconnections have been found very long, up to 60 heliographic degrees (700,000 km, i.e. 55 diameters of the Earth, Figure 7).

It is quite impossible that such long connections could possibly exist below the photosphere and emerge through it into the corona. The most plausible explanation is that they are formed by magnetic field-line reconnection in the solar corona.

#### 4. Surges, jets, and sprays

In most active regions, variations in brightness occur all the time reflecting either new emergence of magnetic flux or old-flux decay or interactions between individual active region loops. Small short-lived brightenings in active regions have been called *Ellerman bombs* or *moustages*. In the magnetically complex regions also ejection of material occurs, mostly rooted inside tiny patches of magnetic polarities embedded inside, or penetrating into, a region of opposite polarity which the moustages prefer.



**Figure 3.** Image of the active Sun in the  $H\alpha$  line (made at Big Bear Solar Observatory). One can see here several active regions with bright plages and dark spots, dark filaments (prominences in projection on the disk), and a two-ribbon flare south-west of the disk center. North is up and east is to the left.

In the  $H\alpha$  line the most common ejection is a bright or dark *surge* (Figure 8 a) in which solar material first moves upward into the corona along magnetic field lines and subsequently falls back to the chromosphere. In X-rays, the Japanese satellite *Yohkoh* observed many bright jets (Figure 8 b) which have some features common with surges, but apparently are not exactly the same phenomena. Most probably, as the new satellite TRACE recently revealed, both have a similar cause, but the hot jets and cold surges move along different trajectories through the corona. In the past few years, the sophisticated spacecraft SOHO and TRACE could detect some jets even in the quiet Sun regions, reflecting the complexity of magnetic field structure even outside the active regions.



**Figure 4.** Image of the active Sun in soft X-rays (made on *Yohkoh*). Note the sets of bright loops that cross the neutral lines in active regions.



**Figure 5.** Prominence observed on the limb in the  $H\alpha$  line (Big Bear Observatory photograph). It would be seen as a dark filament in projection on the solar disk.



A much more powerful phenomenon seen in  $H\alpha$  images is a *spray* (Figure 8 c), in which large amounts of active region plasma are abruptly ejected into the corona, and often escape into interplanetary space, possibly being one of the sources of *coronal mass ejections* (cf., Section 6).

## 5. Solar flares

However, the most powerful brightening in an active region is a *solar flare*. In the optical range almost all flares can be seen only in monochromatic light (most observations are made in the  $H\alpha$  line), but the most powerful ones also emit in the white light and the first flare ever detected was discovered by Carrington on 1 September 1859 when he observed a large sunspot group looking at the photosphere. After Hale's invention of the spectrohelioscope, which made it possible to observe continuously the whole solar surface in the  $H\alpha$  line, from early thirties flares have been observed regularly at many solar observatories throughout the world and listed in monthly reports.

As the resolving power of solar instruments was improving, smaller and smaller flares and flare-like phenomena could be detected in active regions on the Sun. Thus first the category of *subflares* has been added to the original flares, and later the categories of *microflares* and still smaller *nanoflares*. Obviously, flare-like processes can be detected in an active region on all scales and an idea – originally due to Parker – is that nanoflares occur everywhere on the Sun and are the actual source of coronal heating.

Generally, flares are of two different kinds: *Confined flares*, where preexisting loops in an active region suddenly brighten and thereafter slowly decay; and *eruptive flares*, where the whole configuration of loops crossing a neutral line in an active region is disrupted and

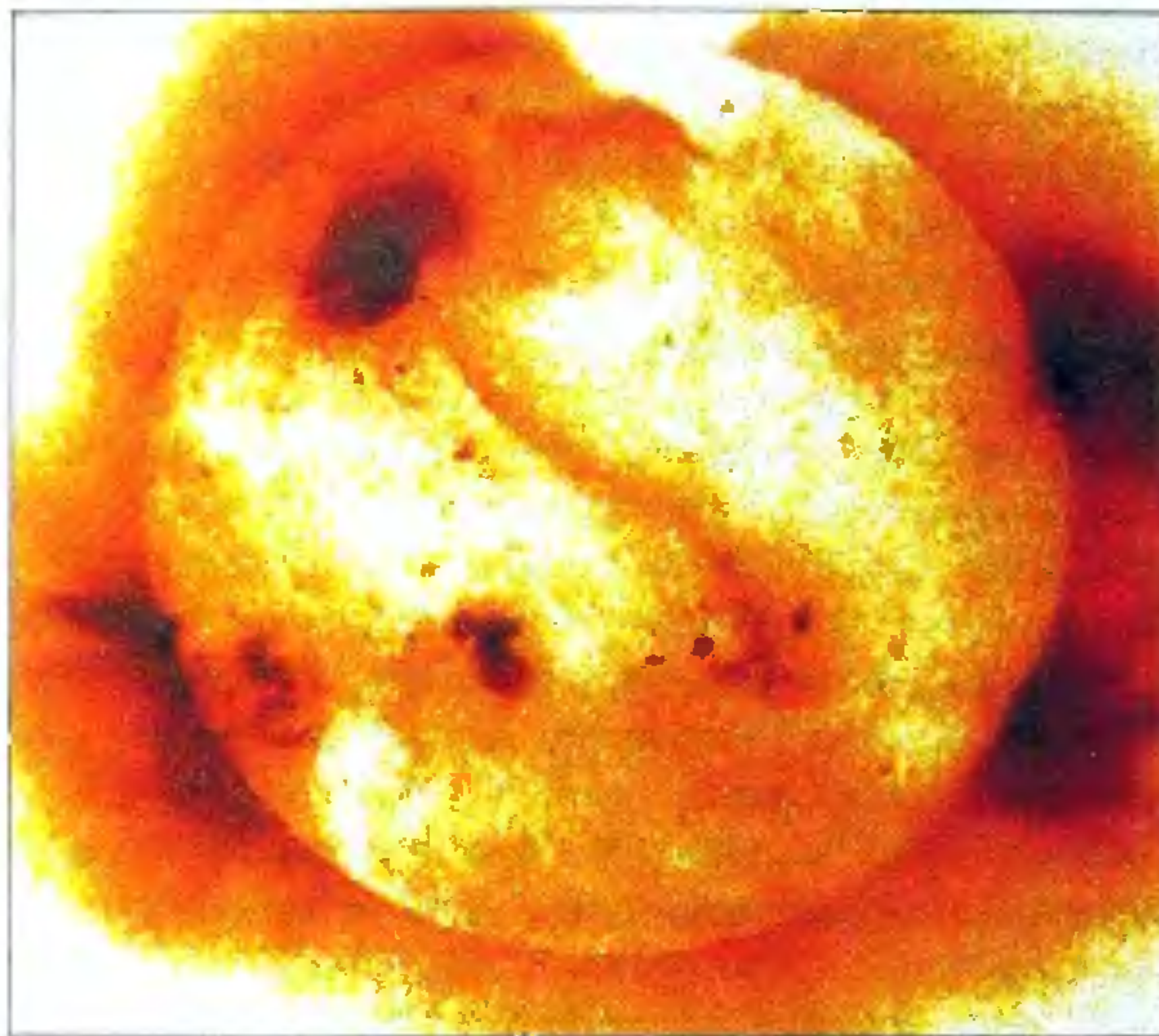


Figure 7. The longest transequatorial interconnecting loop of the new solar cycle connecting active regions over the distance of 700,000 km. (Yohkoh soft X-ray image of the Sun.)

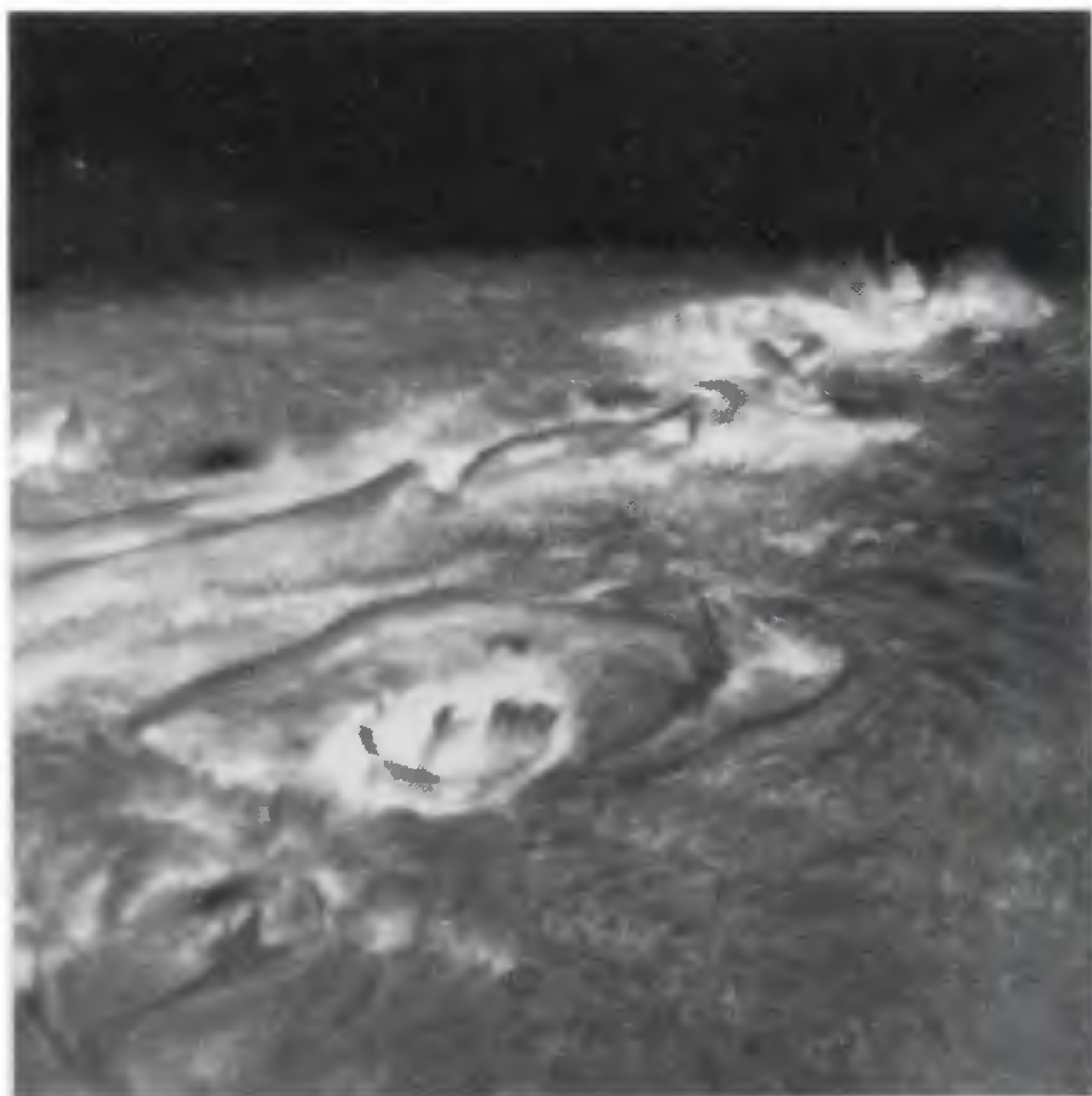


Figure 6. High-resolution photograph of a complex of activity near the western solar limb. Some sunspots and many dark filaments can be seen and new magnetic flux is emerging in the middle foreground and at the limb (upper right). See also the fine structure of the surrounding 'quiet' chromosphere. North is to the left and west to the top. ( $H\alpha$  line, Ottawa River Solar Observatory.)

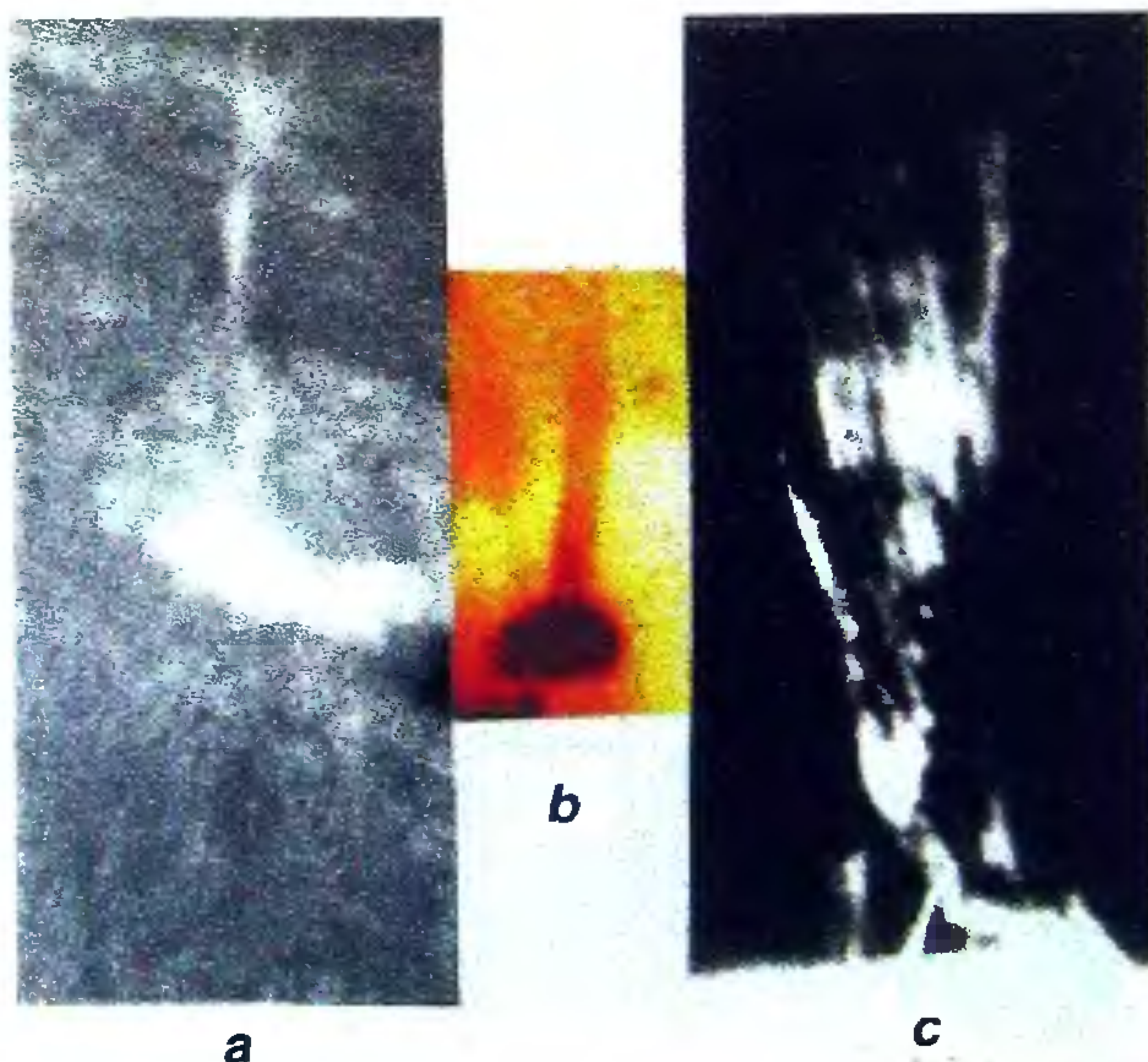


Figure 8. a. Bright surge in the  $H\alpha$  line, observed at Big Bear Solar Observatory; b. X-ray jet observed by Yohkoh; and c. a spray, observed at Wrocław Observatory.



must be newly rebuilt. Most flares, and essentially all small flares are confined flares, and quite often they originate through an interaction of two active region loops which magnetically reconnect. But the most powerful and energetic phenomena are the eruptive flares which are also one of the sources of coronal mass ejections (cf. section 6).

Figure 9 shows schematically the development of an eruptive flare, following the original suggestion of Kopp and Pneuman in 1976, later improved and further developed by many other authors. The originally closed magnetic field in an active region, in which a filament (prominence) is embedded, suddenly opens. Reasons for it can be a newly emerging magnetic flux, a confined flare nearby, a wave disturbance coming along the solar surface from another source of activity, or some internal instability (e.g. a shear of field lines which exceeds a certain critical limit). As field lines open (Figure 9 c) plasma begins to flow from the dense chromosphere upward to the corona, so that gas pressure decreases and magnetic pressure begins to prevail. That leads to sequential reconnections of the open field lines, which begin to create new loops in the active region (Figure 9 d). The reconnection process produces intense heating at the top of each new loop which is conducted downward to the chromosphere, and it also accelerates particles which flow along the loop to its footpoints. Thus the gas at the chromospheric footpoint is strongly heated and evaporates into the newly formed loop, making it visible in X-rays and high-temperature lines as a *flare loop*. The loop then cools, but in between other loops are formed above it through reconnection of other field lines and the whole process is repeated in each of them. Thus the loop system

gradually grows. After some time, the lowest loops cool to about 10000 K and begin to be visible in the  $H\alpha$  line. This takes some time, so that earlier, when no X-ray observations of eruptive flares were available, these structures were called *post-flare loops*.

While in compact flares energy is suddenly released and thereafter the flare structure cools and decays, in eruptive flares energy is released during each reconnection and thus this process of energy release, though decreasing in efficiency, can continue for many hours. Because each reconnection produces new X-ray flux, one can see enhanced emission in X-rays during the whole time of the repeated reconnections. Therefore, based on these X-ray records, eruptive flares are also often called *long-duration events*.

When looking at the chromospheric image of an eruptive flare in the  $H\alpha$  line, one observes at the footpoints of newly formed coronal loops the heated chromosphere, in the form of two bright ribbons, which slowly separate as the flare loop system grows. Therefore, these phenomena were earlier called (and often still are) *two-ribbon flares*. The two ribbons are connected by bright or dark loops. Figure 3 shows an example of such a flare (to the southwest of the center) and the bright patches between the bright ribbons are tops of the loops that connect them. And a more detailed photograph of an eruptive flare, composed from three different images, is shown in Figure 10: we see there the sunspot group in the photosphere, the two bright ribbons in the chromosphere, and the 'post'-flare loops seen in the  $H\alpha$  line above the limb. Both in the  $H\alpha$  line and in X-rays one can see how in all eruptive flares the loop system, while decaying, slowly grows, sometimes for many hours.

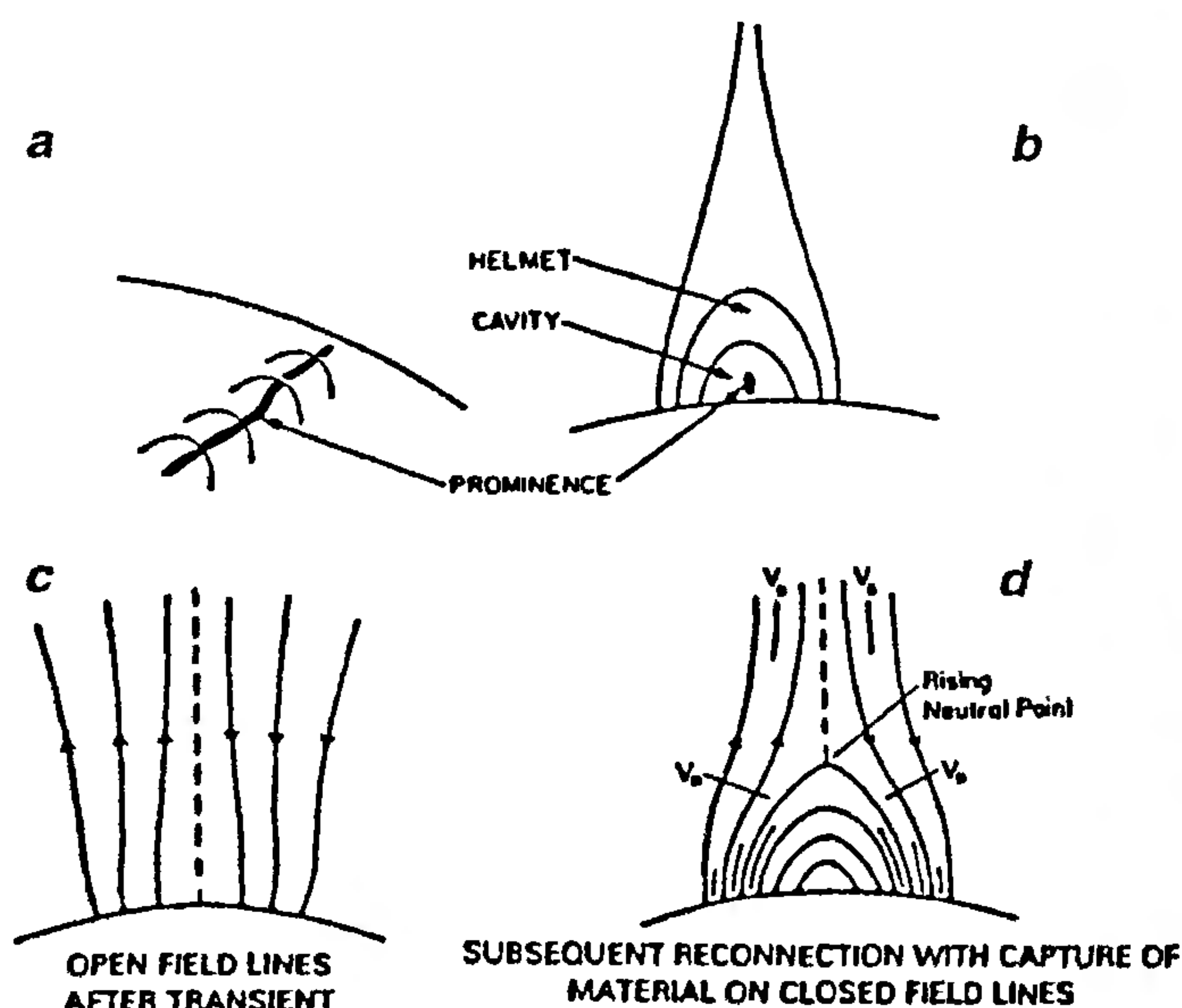


Figure 9. The interpretation of eruptive flares. *a* and *b*, Two different views of the preflare situation when a dark filament (prominence) extends along a neutral line and is embedded in a system of loops forming a coronal helmet structure; *c*, Opening of magnetic field lines; *d*, Subsequent closing of field lines, creating the flare loops.

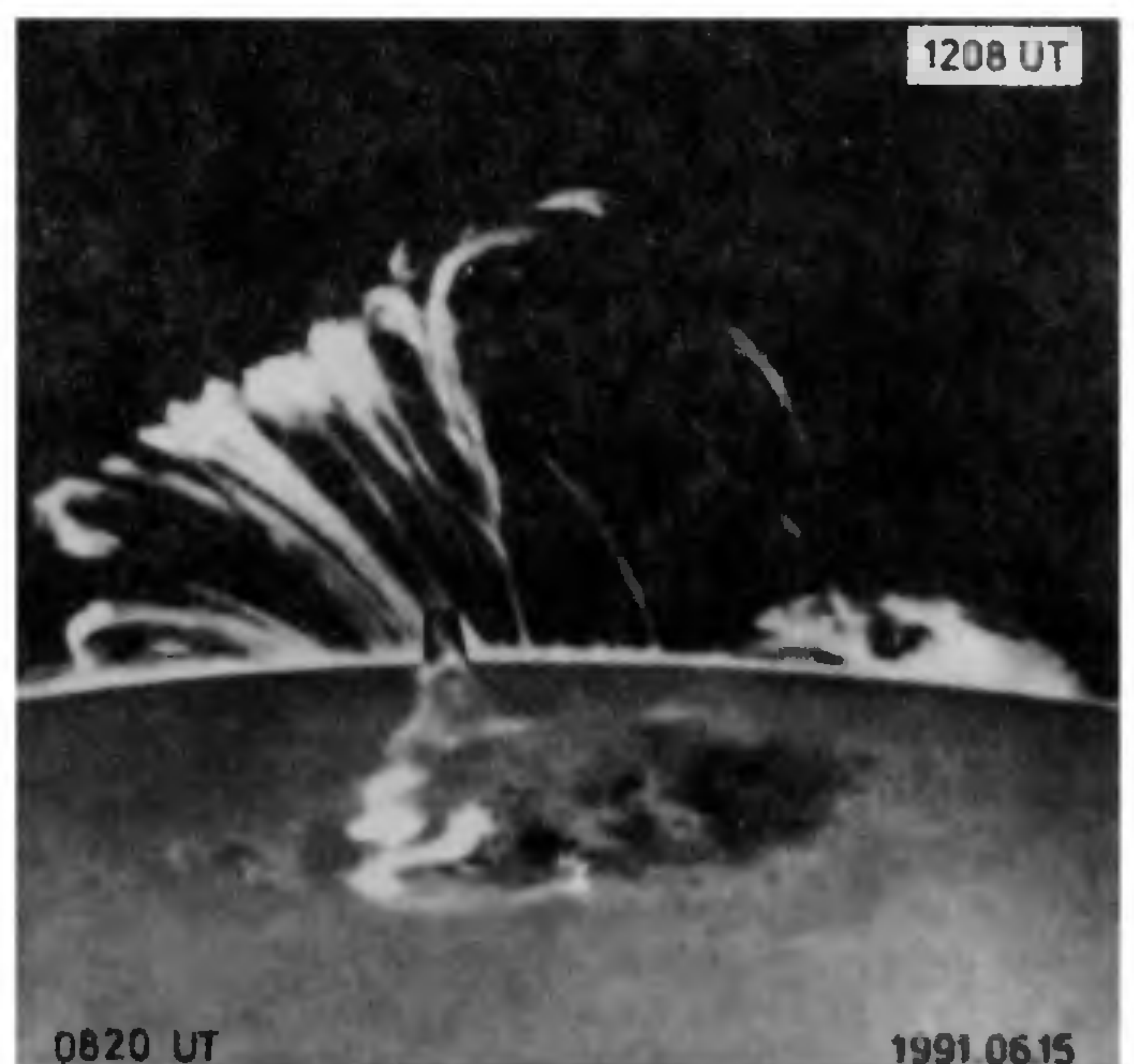


Figure 10. Composed image of an eruptive flare near the solar limb. A quiescent prominence, like that in Figure 5, can be seen in the background. (Images made and composed at Wrocław Observatory.)



## 6. Coronal mass ejections

The opening of magnetic field lines which initiates an eruptive flare is connected with ejection of material. This was first recognized some 30 years ago on metric radio waves, when strong outbursts of radio emission were seen high in the corona, some continuously moving upward. But only spacecraft observations (first by *Skylab* in 1973) showed plasma ejections from the Sun, now called *coronal mass ejections* (CMEs), which moved with high speeds into interplanetary space. (See examples in Figure 11.) Eruptive flares are one of the sources of these CMEs which, as we know now, play the most important role in solar-terrestrial relations. But eruptive flares are not the only source of the CMEs. Everywhere on the Sun magnetic field lines, closed across a neutral line, can be disrupted, open, and eject solar plasma into space. Eruptive flares are only one special – and apparently the most energetic – case of the field-line opening when strong magnetic field inside an active region is involved in the process.

Because in many cases the neutral line inside an active region is marked in  $H\alpha$  line images by a dark filament, the opening of magnetic field is often first made apparent by its activation. The filament structure begins to change, parts of the filament slowly rise into the corona, the speed of the rise accelerates, and finally the whole filament erupts. Only later on, when the open field lines begin to reconnect, bright flare loops begin to appear, but at that time the ejected material (often with the filament embedded in it) already propagates with a speed of a few hundred km/s high in the corona into interplanetary space.

We can often see a very similar process far from any active region. A quiescent filament (several are seen in Figure 3) becomes activated and eventually erupts. Only, on the quiet Sun, we do not see in  $H\alpha$  any eruptive flare, because magnetic field there is not strong enough to produce all the flare effects which we see in active regions. These activations of quiescent filaments have been known for some 50 years and called *disruption brusques*, but only in the seventies space observations in X-rays revealed that these disruptions can have equally important effects in interplanetary space and at the Earth as major flares in active regions.

However, field lines crossing neutral lines can open also at places where no dark filament exists, so that no eruption at all is visible in the  $H\alpha$  line. In X-rays or in spectral lines corresponding to high temperatures, all these field openings have some detectable effect, but such observations are not carried out so often as in the  $H\alpha$  line, so that these responses can easily be missed. This fact is one of the reasons why for a long time the real sources of many CMEs remained unknown. Another reason probably is that not all CMEs originate in this way. Some may be connected with ejections of material along magnetic field lines, for example in sprays (cf., Section 4).

## 7. Accelerated particles

Many active processes on the Sun are apparently due to magnetic field-line reconnections, and every reconnection process can accelerate electrons and atomic nuclei to higher energies. In addition to that, eruptions in the chromosphere and corona incite wave motions which propagate both along the solar surface (these waves are often called *Moreton waves*) and upward through the corona into interplanetary space. Some of these disturbances develop into shock waves, which can be another source of particle acceleration, or can produce second-step acceleration of particles accelerated earlier elsewhere on the Sun.

Therefore, the active Sun is a rich source of energetic particles, mainly electrons, protons, and helium nuclei, which in some events can reach energies of hundreds of MeV, and exceptionally particles are recorded even in the BeV range. The most energetic source of accelerated particles are eruptive flares and CME-associated shocks, but also confined flares are sometimes sources of intense flows of accelerated particles, in particular electrons.

Particles accelerated in the solar atmosphere are responsible for various kinds of radio emission recorded from the Sun. Clouds of particles, captured in magnetic traps above active regions, cause radio noise storms on metric waves which can last for many days. They have been called *Type I* radio bursts. Shock waves from flares produce travelling radio disturbances, called *Type II* bursts. Very frequent radio events are short-lasting *Type III* bursts which are caused by accelerated electrons streaming along open magnetic field lines high into the corona and in particularly intense events deep into interplanetary space, up to the Earth distance. And particles trapped in magnetic clouds associated with CMEs produce powerful *Type IV* bursts, partly stationary and partly moving upward.

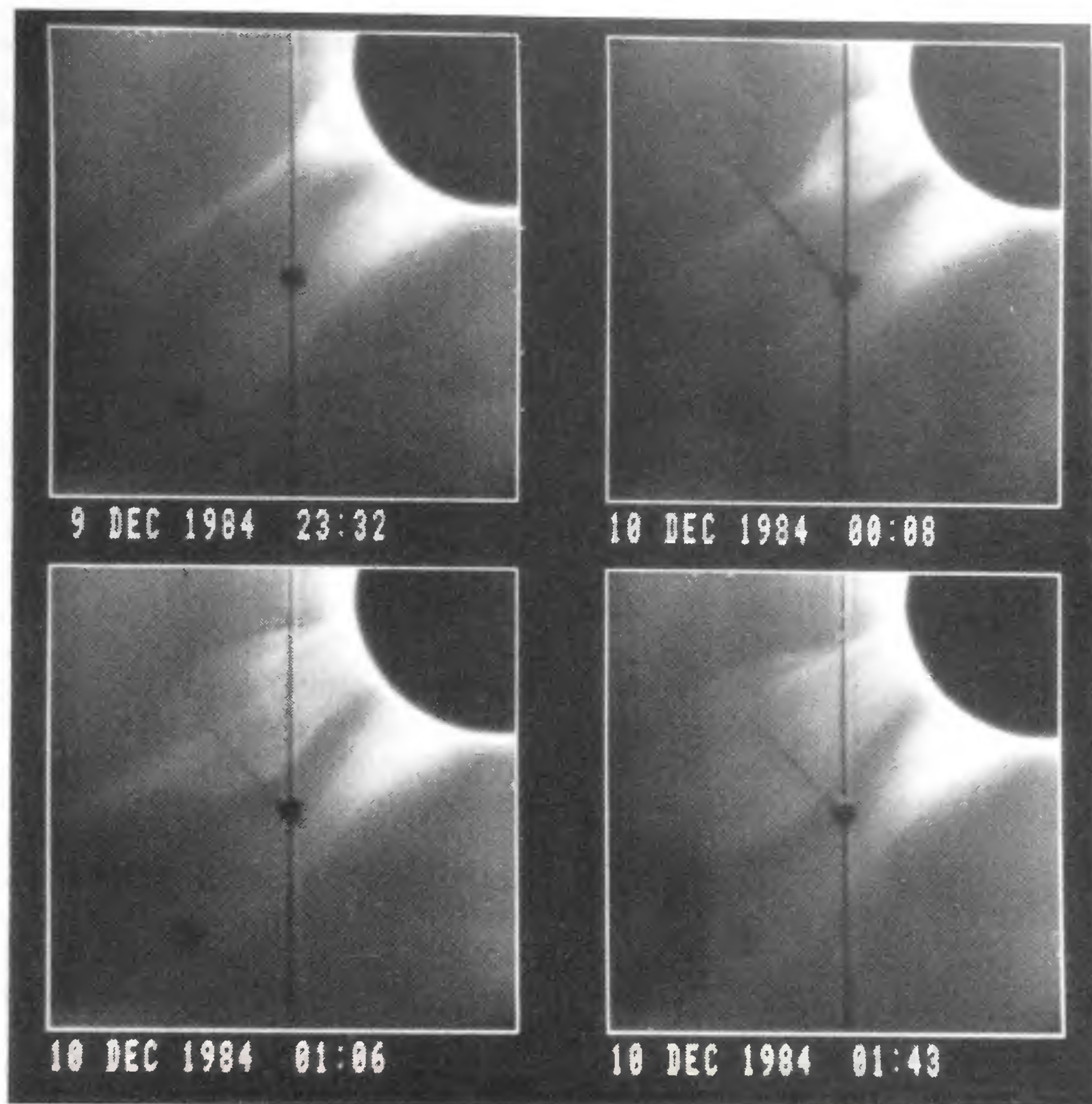
Accelerated electrons also give rise to *hard X-rays* in solar active regions by bremsstrahlung, and particles accelerated to high energies produce in some flares  $\gamma$ -rays which are partly continuum, originating through bremsstrahlung of relativistic electrons, and partly lines excited through electron-positron annihilation, neutron capture by protons and helium nuclei in the photosphere, or by transitions in excited nuclei of heavier atoms.

Particles propagating through interplanetary space produce disturbances in the Earth environment, about which we will talk more in the last section of this review.

## 8. Effects of solar activity at the Earth

The Sun, as the central body of our planetary system, has very serious impacts, of various kinds, on interplanetary space and the environments of planets. Near the solar poles the magnetic field lines are open and solar plasma flows continuously into space, creating there the *fast solar wind* blowing around the Earth deep into outer regions of





**Figure 11.** *Above:* the development of a coronal mass ejection observed by the Solar Maximum Mission spacecraft. *Below:* a more recent observation of a coronal mass ejection by LASCO on board SOHO on 5 November 1996. The Sun is hidden behind the black disk.



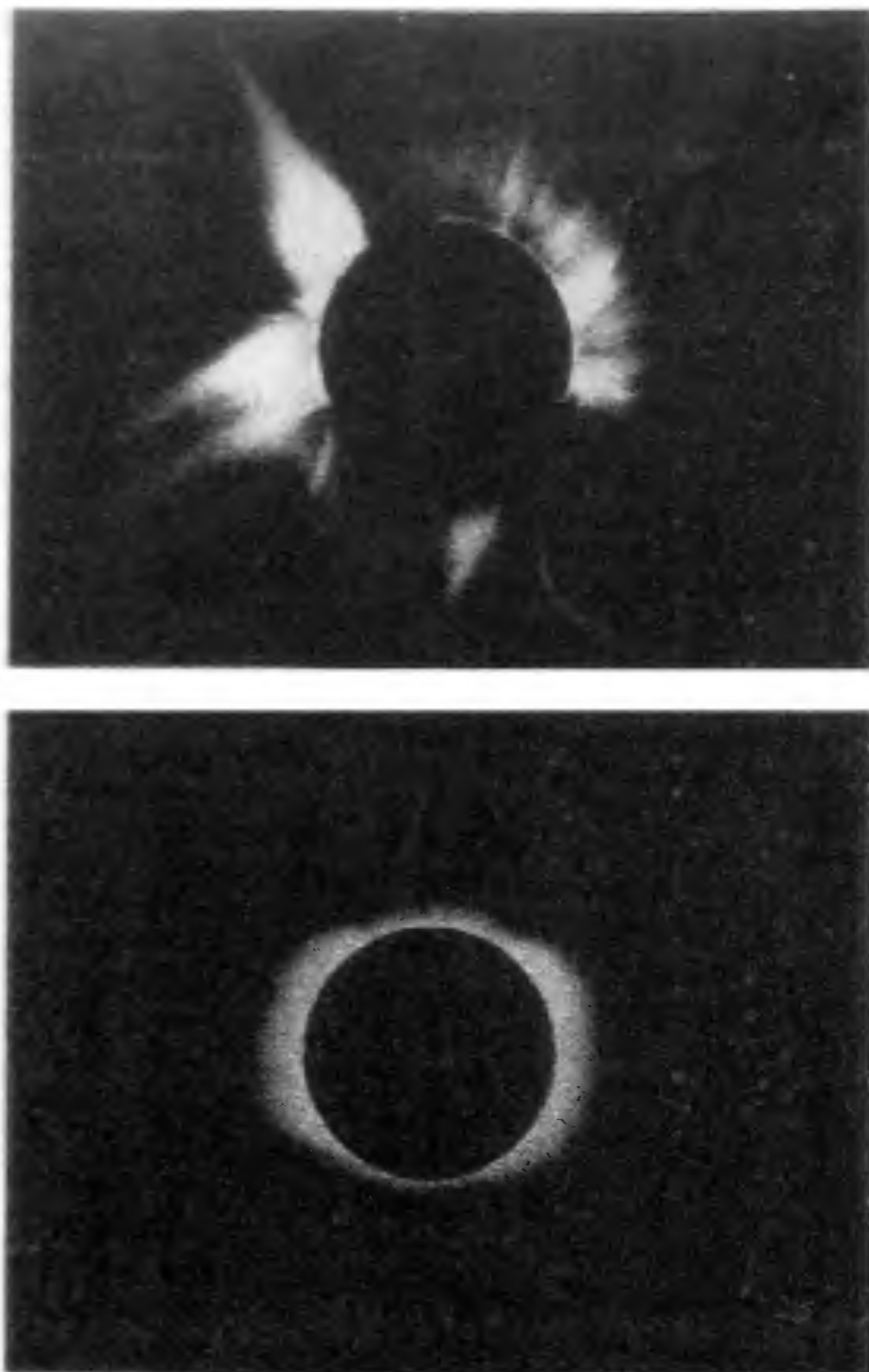


Figure 12. Images of the solar corona in the maximum (*above*) and minimum (*below*) of solar cycle. Many coronal helmet streamers dominate the maximum corona.

the planetary system. At lower latitudes, coronal helmet streamers (like that one shown in Figure 9 and those in Figure 12) and active regions during periods of field-line openings are sources of *slow solar wind*. Streams of accelerated particles, both electrons and atomic nuclei, propagate at various places through interplanetary space. And in addition to these streams of plasma and particles, coronal mass ejections send shock waves and plasma clouds in various directions through interplanetary space and eventually cause other particle accelerations there. All this creates highly variable and very complex conditions in the space between the Sun and the Earth and in the last decade we began to speak about, and regularly study, the *space weather*. In particular, during periods of high solar activity weather in space is very stormy, as one can imagine from a look at Figure 12, which shows the solar corona at the maximum and minimum of the solar activity cycle. For us, of course, most important is the impact at the Earth itself.

When a flare appears on the Sun, it is the source of X-rays which influences Earth's ionosphere and thus causes disturbances in radio communications around the Earth. A major eruptive flare can disturb radio contacts for many hours. This disturbance is the same for flares occurring everywhere on the visible solar surface.

If a flare (or another active phenomenon on the Sun) accelerates particles, they also can arrive at the Earth, but not from all positions on the solar surface, because they are guided by interplanetary magnetic field lines which – due to the solar rotation – are curved into Archimedean spirals. The most intense particle events come from about 45° west from solar central meridian, and generally from the western solar hemisphere. The most energetic flares emit protons with energy exceeding 500 MeV which arrive at the Earth some 15 min after the flare onset, produce streams of neutrons in Earth's atmosphere, and cause the so-called *ground level effect*. Flares that produce protons of such high energies are sometimes called *cosmic ray flares*. Flares that emit protons with energies higher than 10 MeV are often called *proton flares*. Particles of lower energy are guided by the Earth magnetic field to the polar regions and cause there absorption of radio waves (*polar cap absorption*) and intense *aurorae*. All these effects are delayed by tens of minutes or several hours after the flare onset, depending on the energy of the propagating particles.

And then, moving with much slower speeds of a few hundred to 1000 km/s, a coronal mass ejection, often with a shock wave, arrives at the Earth, if it propagates in the right direction. This arrival – two or three days after its origin on the Sun – has a strong impact at the Earth magnetosphere and causes a *geomagnetic storm* which sometimes can last for several days and has serious impact on communications all around the Earth.

Without any doubt, active processes on the Sun also influence the weather at the Earth, but these effects are indirect – depending on the behaviour of the magnetosphere and ionosphere – and very complex: the same effect on the Sun can have quite different consequences at different places of the Earth. Therefore, we still know very little about it. But the active Sun is surely a very important factor in our life.

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