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Solar particle events

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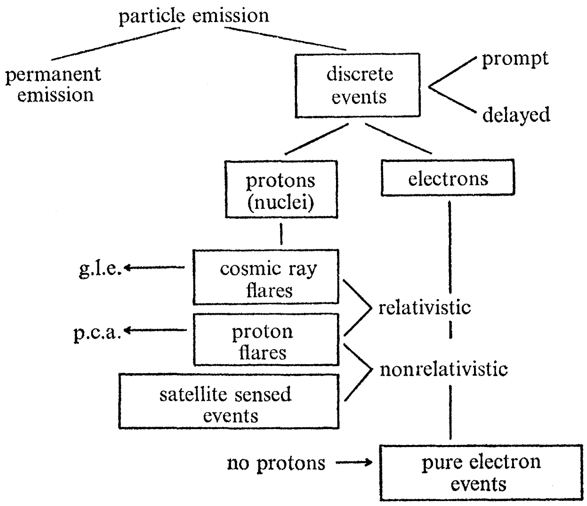
In the last few years, the very sensitive detectors on board satellites and space probes have revealed that the emission of particles from the Sun is a much more frequent phenomenon than had been supposed before, and that the recorded particle events greatly differ as to their character. The following scheme tries to demonstrate the variety of phenomena we meet with when speaking about particle emission from the Sun:



Permanent emission of protons with energy close to and below 1 MeV is associated with some specific active regions. Spacecraft detect it on about the second day after the appearance of the region on the eastern solar limb and particles are then recorded permanently until the region moves to about 40° behind the western limb (Fan *et al.* 1968). It is not yet clear whether this flux manifests a permanent acceleration of particles in the active region or a storage of low-energy particles in space remaining there as remnants of individual discrete particle events. In any case, however, these active regions are the seats of discrete particle events, and thus they represent regions where favourable conditions for acceleration processes have been formed (Švestka 1970*a*).

The *discrete particle events* can be classified from two points of view. First, we distinguish prompt and delayed events (figure 1). The *prompt events* set in tens of minutes or a few hours after the particle ejection on the Sun, and are directly connected with an acceleration process in the solar atmosphere. *Delayed events*, on the other hand, occur tens of hours after the suspected flare on the Sun, and often their association with acceleration processes in the solar atmosphere is not clear. Some events consist of both these components, and the delayed event is often associated with magnetic inhomogeneities or with shock waves in space (figure 1).

The second classification is according to the species of the recorded particles (table 1). These may be either atomic nuclei, among them protons as the most common sort, or electrons. Since on some occasions only one of these two components is observed, it is useful to distinguish and discuss the proton and electron solar events separately.

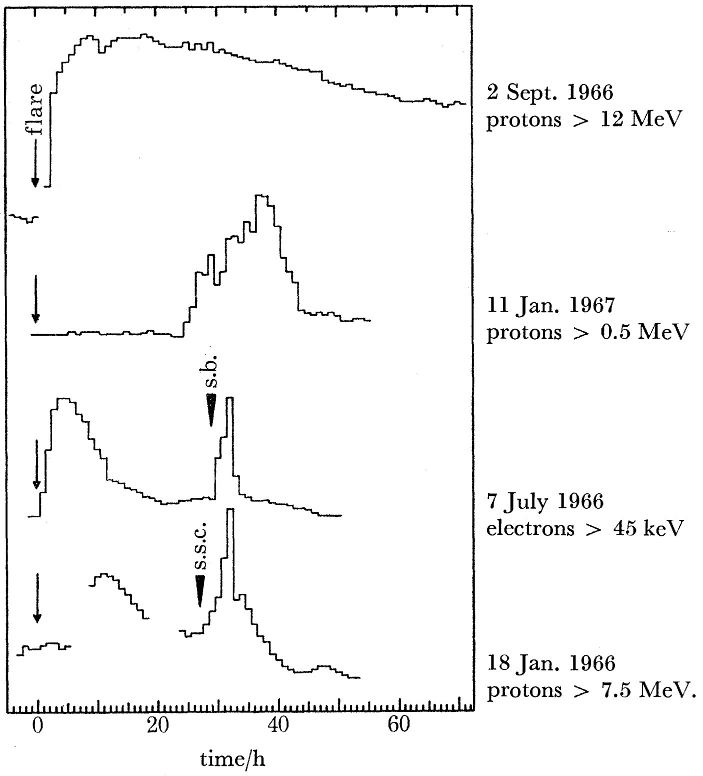


Figure 1. Examples of prompt and delayed particle events: 2 September 1966—prompt (Lindgren 1968); 11 January 1967—delayed (Anderson 1969); 7 July 1966—prompt and delayed, associated with a sector boundary (s.b.) crossing (Kahler & Lin, 1969; Švestka 1968); 18 January 1966—prompt and delayed, associated with a sudden commencement (McCracken 1969).

We shall pay most attention to *prompt solar proton events*. According to their size, we distinguish *cosmic-ray flares*, which cause a ground-level effect (g.l.e.) in records of neutron monitors at sea level, and in which there must be enough protons with energy above 500 MeV at the Earth's distance from the Sun. These are extremely rare phenomena, and since 1942 only less than 20 cosmic-ray flares have been recorded (Hultqvist 1969; Dodson & Hedeman 1969). Next we distinguish events that produce polar cap absorption (p.c.a.) in the polar ionosphere, which means that there must be a strong flux of protons with energy above 10 MeV close to the Earth, even when relativistic protons are absent. Particle emissions of this type have been called *proton flare events* and about 170 such cases have been recorded since 1956 (Fritzová-Švestková & Švestka 1966; Hultqvist 1969). And then there are hundreds of smaller *satellite-sensed events* which never could be recognized at ground-based stations.

Generally, the size of an event, as recorded at the Earth or at a spacecraft, is determined by three parameters: the total number of accelerated particles in the flare-region, N; the shape of the energy spectrum, which can be characterized, e.g. by the γ exponent in an integral power-law energy spectrum,

$$N(>E) = CE^{-\gamma};$$

and by the angular distance θ of the particle source on the solar disk from the root point of the magnetic-field-line which directly connects the Sun with the detector.

Figure 2 shows schematically the distribution of particle sources on the solar disk, which cause strong events, weak events, and permanent emission, respectively. 84 % of all strong p.c.a. before 1963 had their origin in flares situated between 10° E of the central solar meridian and the western limb (Švestka 1966). On the other hand, when all events are considered, not taking into account their importance, there is no striking prevalence on the western hemisphere, and in fact, such events are recorded from flares that occur from within 70° E to far behind the western solar limb (Fritzová-Švestková & Švestka 1966), which approximately is the extent in longitude from where the permanent particle emission also is recorded (Fan *et al.* 1968).

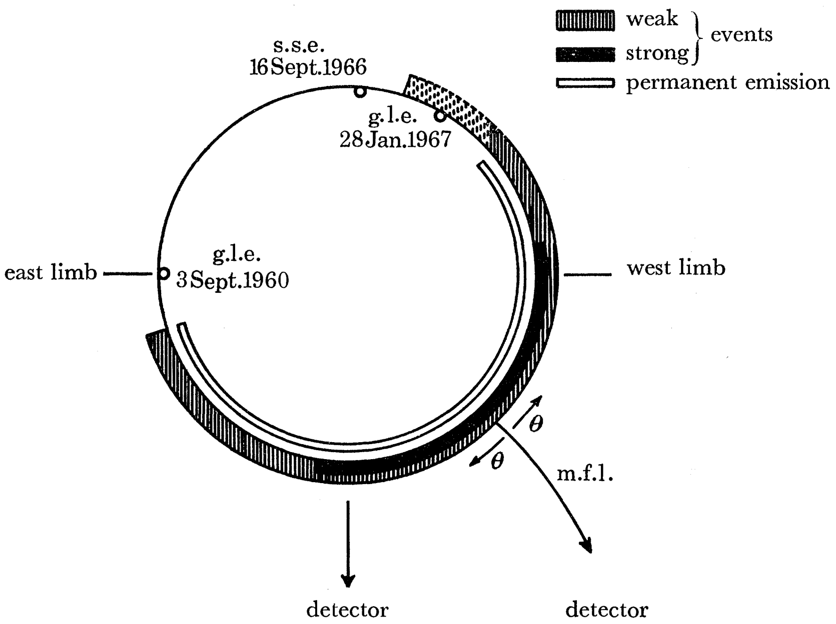


FIGURE 2. Schematic drawing of the distribution of sources of strong and weak proton events on the solar surface. θ measures the angular distance from the magnetic field line that directly connects the Sun with the detector. The figure also shows the range within which permanent proton emission is recorded from particular active regions. Examples of three exceptional events are shown by circles and dates.

Of course, there are exceptions, probably caused by anomalous diffusion either in the solar corona or in interplanetary space, when protons succeed in reaching the Earth or spacecraft even from the most remote part of the solar surface (Dodson, Hedeman, Kahler & Lin 1969), or when events with quite large θ values become unexpectedly strong (see, for example, Dodson & Hedeman 1969). Examples of three such anomalous events are shown in figure 2.

This concerned the parameter θ. In order to demonstrate the role of the parameters N and γ, figure 3 shows examples of energy spectra of several selected proton events. On 23 February 1956 and 2 September 1966, N was very high, and the number of protons was about the same in the energy range which determines the p.c.a. size. P.c.a. also were of about the same strength, 13 dB. But the exponent γ for energies above 100 MeV was about twice as high in the September event as in that of February. In consequence of it there were many protons with energy exceeding 500 MeV in the February event, and an extremely strong cosmic ray increase was recorded, while protons with such high energies were absent in the September event, and no g.l.e. was recorded at all. On the other hand, the well-known cosmic-ray flare of 7 July 1966 was characterized by a very small N. The γ exponent, however, was very small, the spectrum was very hard, and a small g.l.e. was recorded by ground-based neutron monitors, in spite of N being two orders of magnitude lower than in the September event, when no g.l.e. was observed.

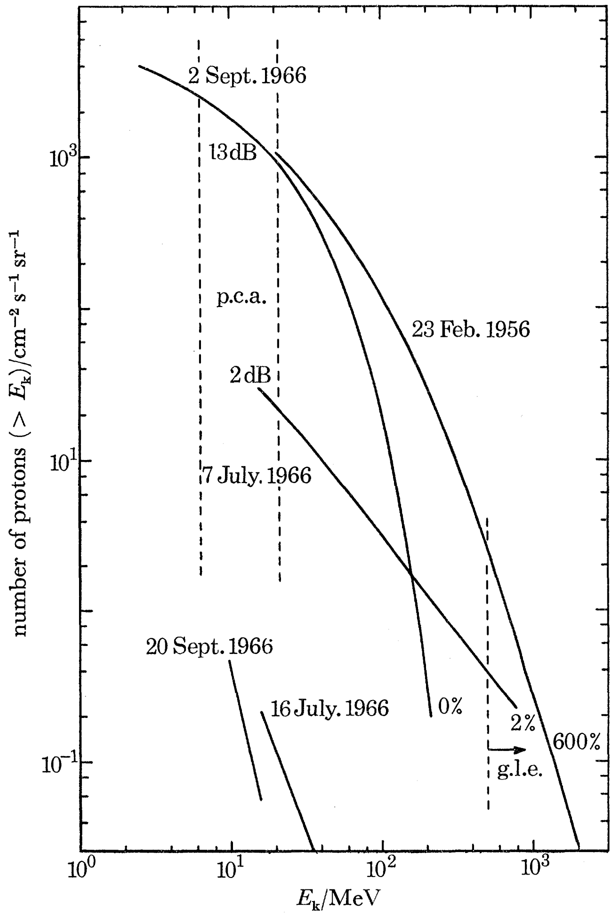


Figure 3. Energy spectra of selected particle events showing the role of the parameters N and γ in p.c.a. and g.l.e. production: 23 February 1956 cosmic ray flare: $N(> 20\text{ MeV}) = 1070$, γ (> 100 MeV) = 3.2, both g.l.e. and p.c.a. strong; 7 July 1966 cosmic ray flare: N (> 20 MeV) = 23, γ (> 100 MeV) = 1.3, both g.l.e. and p.c.a. weak; 2 September 1966 proton flare: N (> 20 MeV) = 1000, γ (> 100 MeV) = 6.0, strong p.c.a, no g.l.e.; satellite sensed events of 16 July and 20 September 1966: N (> 20 MeV) $\lesssim 0.1$, no effects at the Earth. Data taken from Baker, Santina & Masley (1969), Hultqvist (1969), Kinsey & McDonald (1968), McCracken, Rao & Bukata (1967), Smart & Shea (1969), and Švestka (1970*a*).

Let us now discuss briefly the *electron events* (table 1). On rare occasions *relativistic electrons* have been recorded in space (Cline & McDonald 1968; Datlowe, L'Heroux & Meyer 1969; Koechlin *et al.* 1969), and as far as data are available, all these events were observed in association with proton flares or cosmic ray flares (Lin 1970*a*). Thus relativistic electrons obviously are produced by the same acceleration process, which gives rise to protons of the same kinetic energy, of the order of millions or tens of millions of electronvolts. The situation, however, is quite different with *non-relativistic electrons* having energies of tens of thousands of electronvolts, which are observed very frequently in association with proton events of all types, but often they occur without any associated proton component at all. Thus we observe very often *pure electron events* in space, which leads to the conclusion that there are two separate particle acceleration mechanisms on the Sun, one of which produces low-energy electrons and the other produces solar protons and relativistic electrons (Lin 1970). According to Lin & Anderson (1967; Lin 1970) the electron events are still more concentrated to the western solar hemisphere than the proton events. Larger values of θ only occur in so called complex events which are accompanied by a type I radio noise storm region.

There are contradictory opinions on the problem of whether particle emission of some kind is a general characteristic feature of all solar flares. What I believe is that this is not true. All flares obviously are associated with a heating of a limited volume in the corona to temperatures of some millions or tens of millions of kelvins, if the flare is big. Thus a hot condensation is formed above the flare, but the average kinetic energy of electrons in such a condensation does not exceed few thousands of electronvolts. Electrons from the high-energy tail of the energy spectrum might escape into space, but their number is necessarily very low. In order to get an increased number of high-energy electrons and protons, an impulsive process must set in, which accelerates some fraction of particles to substantially higher energies. And this impulsive process obviously is not present in all flares.

There are several direct manifestations of impulsive acceleration processes on the Sun (figure 4). One of them is the radio type III burst, produced by accelerated electron streams in the solar corona. Most pure electron events are associated with type III bursts, often accompanied by a type V continuum (Lin 1970; Švestka 1969), which indicates trapping of accelerated electrons high in the corona. Type III bursts, however, are not associated with proton events and therefore they obviously do not represent the most efficient acceleration process which produces the proton flares. Proton flares, on the other hand, are generally associated with radio type IV bursts, i.e. strong continuous emission throughout the whole radio spectrum. This emission is due to synchrotron radiation of mildly relativistic and relativistic electrons and therefore is direct evidence that an efficient acceleration process occurred in the flare region.

Further direct evidence of an impulsive acceleration can be found in records of X-ray bursts (figure 4). While soft X-rays are purely thermal in their origin, this thermal component weakens with increasing energy and it finally disappears, leaving only an impulsive short-lived X-ray burst for energies above about 50 keV. As Kane (1969) has shown, there are flares which do, and other flares which do not contain the impulsive component, which is evidence that impulsive acceleration does not occur in all flares.

All the effects that manifest an impulsive acceleration process occur in the early, flash phase of flare development, before the flare maximum in Hα light (Zirin & Russo Lackner 1968; Švestka & Simon 1969; Švestka 1970*b*). Since there is no indication of any acceleration process later in the flare's development, it is reasonable to suppose that the whole acceleration is accomplished in this relatively very short flash phase of the flare.

Let us put a question as to what is the reason why some flares are associated with an impulsive acceleration process and some others are not. There, most probably, the decisive factor is the magnetic field configuration in the flare region.

An illuminating example has been presented by Švestka & Simon (1969, Figures 3*a–c*), who have studied the flare activity in the region that produced two proton flares, on 28 August and 2 September 1966. Before 26 August the flares—and there were many of them—had almost no response in radio waves, hence no significant acceleration processes occurred in the active region at that time. The situation, however, completely changed on 26 August, since when strong radio activity appeared, more than one half of all flares and subflares were accompanied by radio bursts, and the low-energy (> 0.6 MeV) proton flux began to increase. Thus, after 26 August, acceleration processes began to occur very often in the active region.

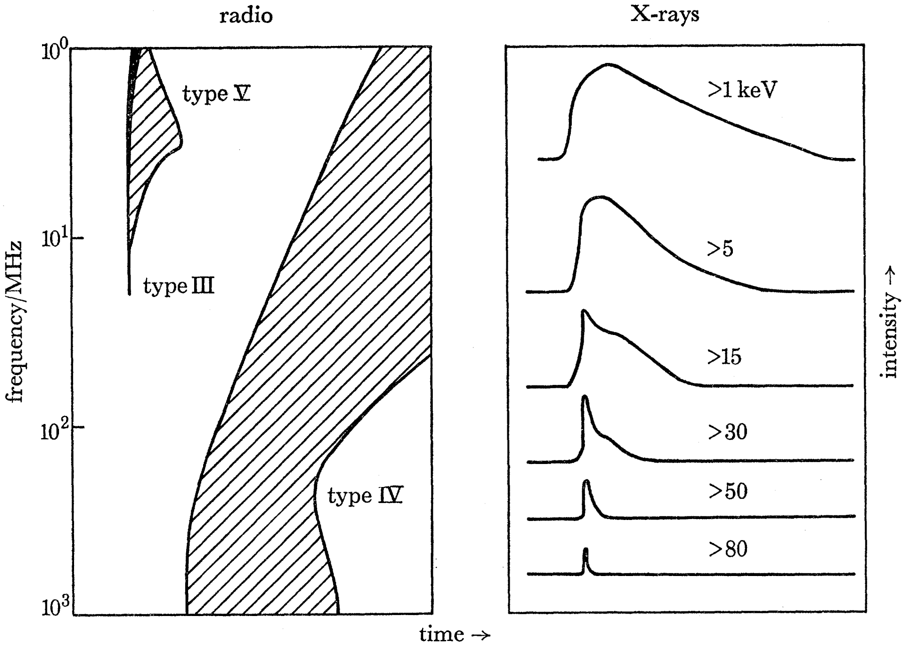


FIGURE 4. Examples of direct evidence of impulsive acceleration processes on the Sun.

What happened in the active region on that particular day? Figure 5 shows the sunspot group in the morning hours of 26 August, when southern and northern polarities were distributed quite regularly in the active region. During this day, however, new big spots of northern polarity developed very close to the southern polarity area (cf. the situation on 27 August in figure 5), the active region became magnetically complex and gradients of the magnetic field in this part of the active region strongly increased. The magnetic complexity of the group and an increase in the magnetic-field gradient, manifested by a close approach of spots of opposite polarity, are the most general characteristics of active regions in which proton flares are produced (Severny 1963; Gopasyuk, Ogir, Severny & Shaposhnikova 1963; Avignon, Martres & Pick 1963; Avignon, Caroubalos, Martres & Pick 1965). Another characteristic feature is an embedding of spots of opposite polarity within a common penumbra (Warwick 1966), which also developed in this active region a few days later (cf. the situation on 30 August in figure 5).

Generally, these characteristic conditions begin to develop two or three days before the proton flare occurrence. These days of preparation are also characterized by an intensification and a hardening of both the microwave (Tanaka & Kakinuma 1964; Tanaka, Kakinuma & Enomé 1969), and X-ray spectrum (Friedman & Kreplin 1969; Křivský & Nestorov, 1968; Švestka & Simon 1969). During the same time, the association of flares with X-ray and microwave bursts is strongly increased (Eliseev & Moiseev, 1965; Křivský & Nestorov 1968), which indicates that small acceleration processes already occur in the active region, while the area is preparing for the production of a big particle event several tens of hours later. All these facts suggest that some particular magnetic configuration must be formed, before significant acceleration processes can occur.

When a proton flare develops in the region, it usually has a typical shape of two roughly parallel bright ribbons, which first form along the line $H_{\parallel} = 0$, which separates the polarities, and then move away from each other, first rapidly and then with a decreasing velocity, until they meet and cover large spots. The phase of fast expansion coincides in time with the acceleration process as established previously from the radio and X-ray data (Křivský 1963; Valníček 1967; Zirin & Russo Lackner 1969; Švestka & Simon 1969; Křivský & Švestka 1970).

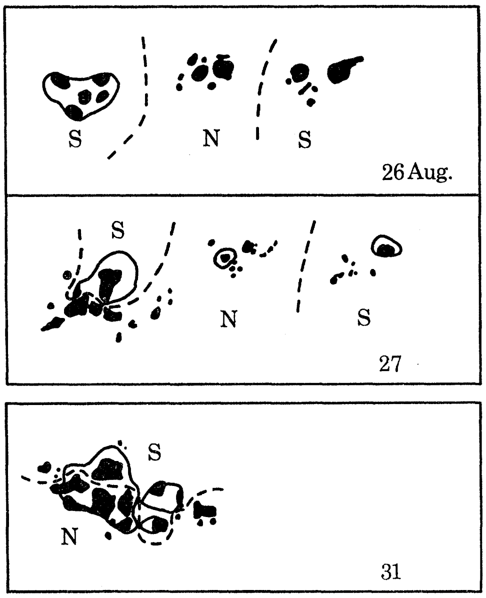


Figure 5. The sunspot group which produced the proton flare of 28 August 1966, one and two days before the proton flare occurrence (after Mogilevsky *et al.* 1969). ■, umbra, □, penumbra. The dashed lines separate the northern (N) and southern (S) magnetic polarities. Note the increased magnetic complexity of the group, and the close approach of spots of opposite polarity, on 27 August. The last picture shows the group 3 days later, when a δ-configuration developed (spots of opposite polarity within a common penumbra). Another proton flare occurred in the region on 2 September.

We can tentatively visualize the whole process in the following way (Švestka 1970*b*). Figure 6 shows drawings of the sunspot group which produced the proton flare of 23 May 1967. Spots of opposite polarity have been embedded within a common penumbra, fairly close to one another, and the main part of the proton flare formed along the zero-line of the magnetic field between these spots. All the drawings refer to the same time, coinciding with the maximum of the microwave radio burst and hard X-ray burst, hence to the phase when the acceleration process was in action. The two bright ribbons observed in the Hα line (figure 6*b*) can be considered as visible roots of a system of loops, which formed a hot thermal condensation above the sunspot group (figure 6*c*). As the condensation was expanding, an impulsive acceleration process set in in that part of the condensation where the magnetic-field gradient was the highest (figure 6*d*). Characteristics of the volume in which the acceleration took place are given in the legend to the figure. The accelerated electrons produced an impulsive X-ray burst through bremsstrahlung, and a microwave burst by synchrotron radiation in the strong magnetic field, in which the acceleration occurred. Accelerated protons penetrating to the lowest chromosphere and upper photosphere gave rise to a short-lived white-light emission at the roots of the loop system, inside which the acceleration occurred (figure 6*e*).

The size of the volume in which the acceleration is accomplished determines the parameter N, and depends on the magnetic-field configuration. One can suppose that in the vast majority of cases this volume is much smaller than in the large event investigated here, and then only small particle events are recorded. In other, rather exceptional cases, the volume is very extensive, or several such volumes form inside the hot condensation, and then we meet with a particle event of great intensity. Of course, apart from this, also the efficiency of the acceleration process probably is different from one case to another, depending again on the detailed magnetic configuration in the region where the acceleration occurs, and this determines the value of the parameter γ.

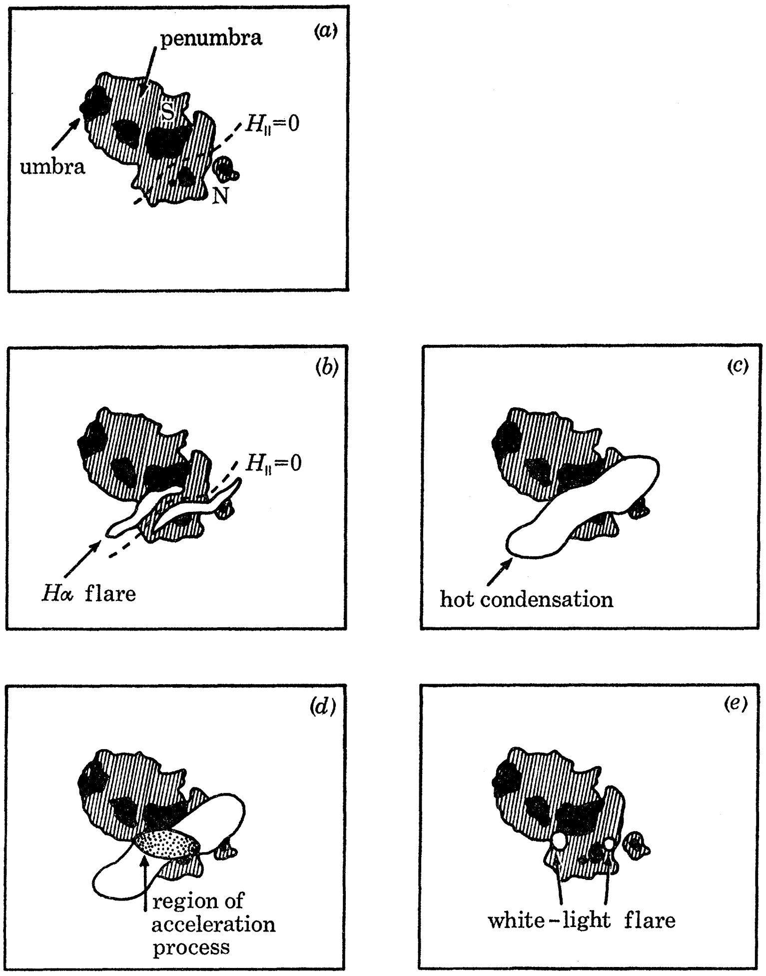


FIGURE 6. Drawings of the sunspot group which produced the proton flare of 23 May 1967 at 18h40. (*a*) The δ configuration. (*b*) The brightest parts of the two bright ribbons in the Hα line going parallel to the $H_{\|} = 0$ line and partly covering the sunspots. (*c*) The core of the expanding hot condensation composed of a system of loops, the feet of which produce the bright ribbons in the Hα line. (*d*) The region of the impulsive acceleration process in the part of the condensation where the magnetic-field gradient was the highest. (*e*) White-light flare emission at position of the roots of loops inside of which the acceleration process occurred. (*a*), (*b*), (*e*) observed (DeMastus & Stover 1967), (*c*) and (*d*) hypothetical. Acceleration process: volume $= 5 \times 10^{27}$ cm³; density $\approx 10^{10}$ cm^{-3}; $N\,(> 100\ \text{keV})/N_{\text{total}} = 1/50$; $N(> 100\ \text{keV}) = 10^{36}$.

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