General Disclaimer

One or more of the Following Statements may affect this Document

- This document has been reproduced from the best copy furnished by the organizational source. It is being released in the interest of making available as much information as possible.

- This document may contain data, which exceeds the sheet parameters. It was furnished in this condition by the organizational source and is the best copy available.

- This document may contain tone-on-tone or color graphs, charts and/or pictures, which have been reproduced in black and white.

- This document is paginated as submitted by the original source.

- Portions of this document are not fully legible due to the historical nature of some of the material. However, it is the best reproduction available from the original submission.

Produced by the NASA Center for Aerospace Information (CASI)

X-693-70-259

PREPRINT

NASA TM X-63969

ON THE ACCELERATION OF RELATIVISTIC ELECTRONS IN SOLAR PROTON FLARES

KUNITOMO SAKURAI

JULY 1970

GSFC

GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

FACILITY FORM 602

N70-32948
(ACCESSION NUMBER) (THRU)
25 1
(PAGES) (CODE)
TMX-63969 29
(NASA CR OR TMX OR AD NUMBER) (CATEGORY)

JUL 1970
RECEIVED
NASA STI FACILITY
INPUT BRANCH

ON THE ACCELERATION OF RELATIVISTIC ELECTRONS IN SOLAR PROTON FLARES

Kunitomo Sakurai*

Laboratory for Extraterrestrial Physics

NASA/Goddard Space Flight Center

Greenbelt, Maryland 20771

---

* NAS-NRC Research Associate with NASA

ABSTRACT

The acceleration mechanism of relativistic electrons in solar flares is considered by taking into account the physical condition of accelerating regions such as plasma density and magnetic field intensity. For the electrons of the kinetic energy range $\lesssim$ 10 Mev, it is shown that the Fermi acceleration is more effective than the betatron acceleration. The most plausible values of the plasma number density and the strength of sunspot magnetic fields in the accelerating regions are estimated to be $\lesssim 10^8 - 10^{10}\ cm^{-3}$ and $10 - 10^2$ gauss, respectively. This suggests that the accelerating regions are located somewhere above the H_α-flare regions. The accelerating regions may be identified with the triggering regions of solar flares where $8\pi P_{kin}/B^2 << 1$ (P_{kin}: kinetic plasma pressure; B: sunspot magnetic field intensity) and so approximately satisfy the force-free condition as regards magnetic field configuration. The accelerated electrons and their relation to the emission of type IV radio bursts are briefly discussed.

1. INTRODUCTION

Boischot (1957) has proposed that type IV solar radio bursts are emitted by the mechanism of the synchrotron radiation from relativistic electrons generated in solar flares. The generation of solar cosmic rays is usually associated with the solar flares which generate the emission of type IV radio bursts (Hakura and Goh, 1959; Reid and Leinbach, 1959; Sakurai, 1960). According to Boischot (1957), the relativistic electrons must have been simultaneously accelerated with solar cosmic ray particles.

Meyer and Vogt (1962) have succeeded for the first time to detect directly the relativistic electrons of Mev energy from the solar proton flare of 28 September, 1961, by the balloon observation. This proton flare was also associated with the emission of intense type IV radio bursts (Maxwell, 1963), which is characteristic to solar proton flares. Recently, Cline and McDonald (1968) have observed the relativistic electrons of 1 - 10 Mev associated with Mev-proton flares by satellite observation. These proton flares were all accompanied by the emission of type IV radio bursts.

These observational results are very useful in considering the acceleration mechanism of relativistic electrons, the physical condition of the accelerating regions and the relation between the emission of type IV radio bursts and the acceleration of solar cosmic rays.

2. THE GENERATION OF RELATIVISTIC ELECTRONS IN SOLAR FLARES

Solar proton flares are generally associated with the emission of type IV radio bursts of broad-band frequencies, which are thought of as being produced by the gyro-synchrotron emission from the energetic electrons of 100 Kev - 10 Mev (e.g., Smith and Smith, 1963; Wild, Smerd and Weiss, 1963; Kundu, 1965). This result indicates that the acceleration of solar cosmic ray particles is usually accompanied by that of energetic electrons. As has been discussed, the electrons of relativistic energy from solar proton flares have recently been observed in the interplanetary space by satellites (Cline and McDonald, 1968; McDonald, Cline and Simnett, 1969). Furthermore, these electrons seem to be partly responsible for the emission of type IV radio bursts.

In order to consider the acceleration of electrons, we must take into account the energy loss processes owing to the collision with ambient particles, the bremsstrahlung and synchrotron radiation . In discussing the acceleration mechanism of relativistic electrons, we assume that the motion of these electrons will fulfills the condition on the guiding-center approximation. The formula for the electron acceleration is, therefore, given by

$$\frac{\partial E}{\partial t} = \alpha E + \beta \frac{P^2 C^2}{E} - \text{(Loss terms)} \qquad (1)$$

and

(loss terms) = (collision loss) + (Bremsstrahlang loss)

+ (synchrotron radiation loss), ... (2)

where E, p, c and t are the total energy and momentum of electrons, the speed of light and time, respectively. The coefficients, α and β give the efficiency of the Fermi and betatron accelerations, respectively (e.g., Hayakawa et al., 1964; Sakurai, 1965a, 1965b). In estimating the efficiency of Fermi acceleration, the electrons being in acceleration are assumed to be redistributed through the scattering due to the head-on or overtaking collisions with the magnetic irregularities in the accelerating regions. The efficiency of both the Fermi and betatron acceleration is schematically shown in Fig. 1. In this figure, the two cases are shown in the cases of $\alpha = \beta$, $\beta = 10\alpha$. It is clear from this figure that the efficiency of Fermi acceleration is usually higher than that of the betatron acceleration in both cases in the non-relativistic energy range $\lesssim 10^6$ eV.

As shown in Fig. 2, the energy losses as cited above are dependent on the ambient plasma density and the strength of magnetic fields. Among these three energy loss processes, in the kinetic energy $\lesssim$ 10 Mev, the bremsstrahlung loss is much smaller than the collision and synchrotron radiation losses. In estimating these energy losses, we used the formula on the collision loss calculated by Hayakawa and Kitao (1956) and that on the bremsstrahlung loss obtained by

Heitler (1954) and Ginzburg and Syrovatskii (1964). It is remarked that the collision loss is not dependent on the temperature of the ambient medium in case of the particles of kinetic energy greater than 1 Kev.

For the charged particles to be accelerated, the acceleration rate must overcome all of the energy loss rates. From this criterion, we can calculate the so-called, injection energy of accelerating particles (Fermi, 1949). As is evident from eq. (1), the acceleration rate due to both Fermi and betatron mechanisms is roughly proportional to E since $p^2c^2/E \sim E$ when $E \gtrsim 5 \times 10^2$ Kev. With increasing energy, the energy loss rate due to the collision becomes smaller as shown in Fig. 2, whereas the synchrotron and bremsstrahlung loss rates increase. In the relativistic energy range, these rates become to be proportional to E^2 and E, respectively. Consequently, the acceleration does not take place continuously without limitation since, with increasing energy, the synchrotron energy loss rate lastly becomes higher than the acceleration rate due to the Fermi and betatron mechanisms.

Taking into account eqs. (1) and (2) and the discussion just mentioned, we can estimate the physical state of the regions where the electron acceleration takes place. Let us first assume the acceleration region to be the same regions of H_α-flare brightening, where the ambient plasma number density has been deduced to be $\sim 10^{13}$ cm^{-3} (e.g., Svestka, 1966; deJaer, 1968). The strength of sunspot magnetic fields in the Hα-flare regions seems to be usually 1000-3000 gauss (e.g., Kiepenheuer, 1953; Smith and Smith, 1963). When the electron acceleration takes place within such regions at the initial kinetic energy range of 1 - 10 Kev, which is recognized as the thermal tail of ambient electrons, the acceleration rate must be higher than 10^9 eV sec^{-1} and 1.5 x 10^8 eV sec^{-1} for 1 and 10 Kev electrons, respectively. The reason why the initial kinetic energy of accelerating electrons is here assumed to be 1 - 10 Kev is as follows: Since the ambient electrons seem to be usually thermalized even in the flare regions, where is 10^4 - 10^5 ^oK in temperature, before the onset of solar flares, the thermal tail electrons of such distribution is estimated to be of 1 - 10 Kev as mentioned above.

Since the Fermi acceleration is more effective than the betatron acceleration in the energy range 1 - 10 Kev (see Fig.1), the electron acceleration takes place mainly by the Fermi mechanism. The rate of the Fermi acceleration must, therefore, be higher than that of the energy losses due mainly to the collision: for the electrons of E_k = 10 Kev, (E_k; initial kinetic energy) which is recognized as the injection energy

$$\alpha E > 1.5 \times 10^8 \text{ eV sec}^{-1}$$

$$\alpha > 3 \times 10^2 \text{ sec.}$$

The value of α for the electrons of E_k = 1 Kev is higher than the value just mentioned as deduced from Fig. 2.

Let us estimate the time necessary for electrons of the initial kinetic energy 1 - 10 Kev to be accelerated to 10 Mev, as an example. The order of this time Tacc is given by integrating eq. (1) with neglection of the energy loss terms as follows: $Tacc = (1/\alpha) \log (Em/E_o)$, where Eo and Em are the initial and final energy of the electrons. If the acceleration region is located in the H_α-flare regions where $N \sim 10^{13}$ cm^{-3}, it follows that

$$
\begin{aligned}
Tacc &\lesssim 0.67 \times 10^{-2} \text{ sec } (E_k = 1 \text{ Kev}) \\
&\lesssim 0.9 \times 10^{-1} \text{ sec } (E_k = 10 \text{ Kev})
\end{aligned}
\qquad (3)
$$

The acceleration of solar cosmic rays is nowadays believed to occur during the explosive phase of solar flares which has been estimated to continue $\approx 10^2$ sec (e.g., Ellison, McKenna and Reid, 1961). If the relativistic electrons are assumed to be accelerated simultaneously with solar cosmic ray particles in this phase, the time Tacc obtained above is much shorter than the time scale of this phase. This result indicates that, during one second, electrons can be accelerated to the energy of 10^9 eV or more and, therefore, the kinetic energy of these electrons will become to be 10^{11} eV or more if the acceleration will continue throughout the explosive phase. However, in this case, the synchrotron loss rate becomes higher than the acceleration rate in the energy range higher than about 10^9 eV (see Fig. 2). Consequently, it seems difficult to accelerate those electrons to the kinetic energy higher than $\sim 10^9$ eV.

If the acceleration continues for $\approx 10^2$ sec as mentioned above, the electrons of 10^8 - 10^9 eV, say, will be successively generated during this time. When these electrons are immersed in the magnetic fields of strength 10^3 gauss, they are able to emit optically visible and ultraviolet continuum by the synchrotron radiation mechanism for $\approx 10^2$ sec. The frequency range of the synchrotron radiation by these electrons is, therefore, not confined in the radio frequencies as 10^3 - 10^4 MHz, but optically visible and ultraviolet wave range. Thus, we cannot explain the observational characteristics of type IV radio bursts by using the synchrotron radiation mechanism. In order to solve this difficulty, we will consider whether or not the acceleration region is the same as the H_α-flare region.

As has been considered by many authors (e.g., Sakurai, 1965c, 1967; Sturrock, 1967), the regions where solar flares are triggered and some associated hydromagnetic instability will develop , however, seem to be located in the regions higher than the H_α-flare regions. In reality, the triggering of solar flares usually starts somewhere in the upper chromosphere or in the inner corona above sunspot groups. Since the plasma number density in these regions is estimated to be about equal to 10^8-10^{10} cm^{-3} (e.g., deJager, 1968), the collision energy loss rate is reduced by three to five orders of magnitude compared to the case of 10^{13} cm^{-3}. If the electron acceleration takes place in such regions, the acceleration rate necessary to overcome this energy loss is reduced by the same orders of magnitude just mentioned. When the initial kinetic energy of electrons is, say, ~ 10 Kev as referred to earlier, the rate of Fermi acceleration must fill the following condition:

$$\begin{aligned} \alpha E &> 10^5 \text{ eV sec}^{-1} \text{ for } N = 10^{10} \text{ cm}^{-3} \\ &> 10^3 \text{ eV sec}^{-1} \text{ for } N = 10^8 \text{ cm}^{-3}, \end{aligned} \qquad (4)$$

as estimated from the result shown in Fig. 2. In this case, the time Tacc necessary for electrons to be accelerated to 10 Mev (Em) is given by

$$\begin{aligned} T_{acc} \simeq \frac{1}{\alpha} \log \left(\frac{E m}{E o} \right) &\lesssim 10 \text{ sec for } N = 10^{10} \text{cm}^{-3} \\ &\lesssim 10^3 \text{ sec for } N = 10^8 \text{cm}^{-3} \end{aligned}$$

Those times seem to be applicable to the idea that the acceleration usually takes place during the explosive phase of solar flares.

Since the strength of sunspot magnetic fields in the triggering regions of solar flares is estimated to be 10 - 10^2 gauss, the frequency range of the synchrotron radiation by the electrons of 1 - 10 Mev energy is 10^2 - 10^4 MHz as is shown in

Fig. 3. This frequency range covers the whole spectrum of type IV radio bursts which are usually observed in association with solar proton flares.

The mean collision time of the accelerating electrons with magnetic irregularities is estimated to be $\sim 10^{-5}$-10^{-3} sec in the above case, which time is much shorter than the deflection time of accelerating electrons due to the coulomb force of ambient protons which has been estimated to be 0.1 second or less (Takakura, 1961). If the acceleration satisfying eq. (4) works in the flare regions in reality, we do not need consider the redistribution of accelerating electrons due to the deflection by ambient electrons as has been suggested by Takakura (1961), since the collision of these electrons with magnetic irregularities necessarily produces the randomization of their distribution.

As is evident from Fig. 1, even if we assume $\beta = 10\alpha$, the Fermi acceleration is more effective compared with the betatron one in the non-relativistic energy range when the initial kinetic energy of electron is 1 - 10 Kev. In order that the latter acceleration overcomes the former one at the initial energy of $\sim$ 10 Kev, for example, the following condition must be fulfilled: $\beta \gtrsim 10^2\alpha$. Since $\alpha > 0.2$ and $\alpha > 2 \times 10^{-3}\text{sec}^{-1}$ for the cases $N \sim 10^{10}$ and 10^8cm^{-3}, respectively, it follows that $\beta > 20$ and 0.2 sec^{-1}. If we refer to the acceleration theory(Hayakawa et al., 1964; Sakarai, 1965a, 1965b), β is given by

$$\beta = < \frac{\sin^2\theta}{B} \frac{\partial B}{\partial t} > \simeq \frac{1}{2B} < \frac{\partial B}{\partial t} > \qquad (6)$$

where θ is the pitch angle of accelerating electrons. If we assume that $B \sim 10^2$ gauss, it follows that $< \frac{\partial B}{\partial t} > \sim 4x10^3$ and 40 gauss sec^{-1} for each of the two cases cited above. Since, at present, we do not have any observational evidence on such high-changing rates of sunspot magnetic fields and, furthermore, on the fully developed deformation of sunspot magnetic field configuration, this result suggests that, in triggering regions of solar flares, the role of the betatron mechanism is negligible compared with the Fermi mechanism. It thus seems that the assumption $\beta > 10^2\alpha$ is unreasonable. The Fermi mechanism is, therefore, always dominant compared with the betatron one in the energy range of $< 10^3$ Kev.

The synchrotron radiation loss works competitively with the acceleration during the energization of electrons in the kinetic energy higher than $\sim 10^2$Kev. The electrons thus accelerated would become the radio sources responsible for type IV radio bursts. The observational characteristics of these bursts also suggest that the strength of sunspot magnetic fields within the accelerating regions is 30-100 gauss as is estimated from the relation among E_k,B and f_m as shown in Fig. 3.

The generation of relativistic electrons are always associated with solar proton flares. This fact shows that the acceleration of electrons is closely connected with that of proton and heavier nuclei. As has been concluded by Hayakawa et al. (1964), Sakaurai (1965a, 1965b) and Wentzel (1965), the acceleration of solar cosmic ray nuclei is due mainly to the Fermi mechanism at the initial stage of flare development. We can thus conclude that the Fermi mechanism is responsible for the acceleration of all electrons, protons and heavier nuclei as suggested by Sakurai (1966).

3. PHYSICAL CONDITION OF ACCELERATING REGIONS

As estimated in the last section, the strength of the sunspot magnetic fields and plasma number density in the accelerating regions are given by $10 - 10^2$ gauss and 10^8-$10^{10}\,cm^{-3}$. If we assume the temperature to be $10^4 - 10^5\,{}^oK$ before the onset of solar flares, we can estimate the relation between the kinetic and magnetic pressures, which are here denoted as P_{kin} and P_{mag}, respectively: in the case of $N = 10^{10}\,cm^{-3}$ and $B = 10^2$ gauss,

$$P_{mag} \gtrsim 1.4 \times 10^3\, P_{kin} \text{ for } T = 10^4\,{}^oK$$

$$\gtrsim 1.4 \times 10^2\, P_{kin} \text{ for } T = 10^5\,{}^oK.$$

Even if $N \lesssim 10^{10}\,cm^{-3}$ and $B \gtrsim 10$ gauss, it follows that $P_{mag} \gg P_{kin}$.

The configuration of the upper portion of sunspot magnetic fields, therefore, seems to be of force-free type. This information is very important when we consider the cause of solar proton flares in relation to the configuration of sunspot magnetic lines of force above the sunspot groups (e.g., Sakurai, 1967, 1969a; 1970; Sturrock, 1967).

4. ENERGETIC ELECTRONS AND TYPE IV RADIO BURSTS

Although the energetic electrons are simultaneously generated with solar cosmic ray nuclei, the magnetic rigidity of these electrons is much smaller than that of these nuclei in the kinetic energy range lower than 100 Mev (Sakurai, 1961). As a result, the major portion of accelerated electrons can not escape from the accelerating region even when accelerated protons and heavier nuclei do so. These electrons thus seem to become the radio source of type IV radio bursts while being trapped by sunspot magnetic lines of force. A part of these electrons would be injected into the lower chromosphere and the photosphere and excite the X-ray and Hα-line emissions through the collision with ambient atoms and ions.

Solar proton flares are generally associated with the emission of type II radio bursts in addition to type IV radio bursts. The initial emitted frequencies of type II radio bursts is generally lower than about 100 MHz (Maxwell and Thompson, 1962). If we assume the plasma distribution in the solar atmosphere as deduced by Newkirk (1961, 1966), this suggests that the hydromagnetic shock waves would usually be excited at the regions about 0.2 solar radius or higher above the photosphere. These waves would produce shock-heated electrons responsible for the emission of type II radio bursts. By generating magneto-turbulence, these shock waves also seem to generate energetic electrons, along their path in the solar corona, which produce the moving metric component of type IV radio bursts, being now known as type IV mA bursts (Wild, 1962). The cause of these hydromagnetic shock waves seems to lie in the finite amplitude magnetosonic waves which propagate upward from the triggering regions of solar flares as shown in Fig. 4. The relation among acceleration of energetic electrons, radio and other emissions and hydromagnetic shock waves is schematically shown in Fig. 4. The source of hydromagnetic shock waves seems to be initially released from the triggering regions of solar flares, as mentioned above, and furthermore grow up to such shock waves due mainly to the decrease of ambient plasma density. In the initial stage of the development of type IV radio bursts, the emissivity of the decimetric component is much lower than those of the microwave and metric wave components as well known (Castelli et al., 1967, 1968; Sakurai, 1969b). This fact may be related to the growth of hydromagnetic shock waves.

5. SUMMARY

By studying the acceleration mechanism of relativistic electrons in solar flares, the following conclusions have been obtained. (1) The regions of the electron acceleration is different from the Hα-flare regions and located in the upper chromosphere or the inner corona, above sunspot groups, where the ambient plasma number density and the strength of sunspot magnetic fields are 10^8-10^{10} cm^{-3} and 10-10^2 gauss, respectively.

(2) The relativistic electrons are mainly accelerated by the Fermi mechansim in the kinetic energy range 1Kev-10 Mev, while, when $\alpha \lesssim \beta$, the betatron mechanism becomes effective on the electron acceleration in the relativistic energy range, $\gtrsim$ 10 Mev (Fig. 1).

(3) When the electron acceleration starts at the initial kinetic energy 1 - 10 Kev, it is estimated that the energy range of accelerated electrons is from 10 to 10^4 Mev if the strength of sunspot magnetic fields is 10^3 gauss. If this strength is 10^2 gauss, the highest energy of accelerated electrons is $\sim 10^2$ Mev at most. In this case, the energy range of accelerated electrons is 100 Kev - 100 Mev and is applicable for the interpretation of the characteristics of type IV radio bursts (Fig. 3) and the observed energy range of solar relativistic electrons (Cline and McDonald, 1968; McDonald, Cline and Simnett, 1969).

(4) The highest energy of the accelerated electrons are determined by the synchrotron radiation loss. This loss rate becomes higher than the acceleration rate at the energy

defined approximately by the equation

$$E_c \gtrsim \frac{\alpha + \beta}{\eta} ,$$

where η is the coefficient of the synchrotron radiation loss. In cases of $N = 10^{10}$ and 10^8 cm^{-3}, $E_c \simeq$ 5 Bev and $\simeq$ 50 Mev, respectively. These values give the upper limit of the energy of accelerated electrons.

(5) Solar flares initially develop due to some instability connected with the sunspot magnetic fields in the upper chromosphere or the inner corona above the sunspot groups. The configuration of the sunspot magnetic fields seems to be of force-free type.

(6) Major part of the accelerated electrons become the source of type IV radio bursts since they are trapped by the sunspot magnetic field lines in and near the accelerating regions.

ACKNOWLEDGMENT

I wish to thank Dr. R. G. Stone and Dr. J. Fainberg for their discussion and criticisms throughout this work.

REFERENCES

Boischot, A., Compt. Rend., 244, 1326 (1957).

Castelli, J.P., Aarons, J. and Michael, G. A., J. Geophys. Res., 72, 5491 (1967)

Castelli, J.P., Aarons, J. and Michael, G. A., Astrophys. J., 153, 267 (1968).

Cline, T. L. and McDonald, F. B., Solar Phys., 5, 507 (1968).

de Jager, C., in Mass Motions in Solar Flares and Related Phenomena, p. 171, edited by Y. Öhman, J. Wiley, New York (1968).

Ellison, M. A., McKenna, S.M.P. and Reid, J.H., Dunsink Obs. Publ., 1, 51 (1961).

Fermi, E., Phys. Rev., 75, 1169 (1949).

Ginzburg, V. L. and Synovatskü, S. I., The Origin of Cosmic Rays, Pergamon, New York (1964).

Hakura, Y. and Goh, T., J. Radio Res. Lab., 6, 635 (1959).

Hayakawa, S. and Kitao, K., Prog. Theor. Phys., 16, 139 (1956).

Hayakawa, S., Nishimura, J., Obayashi, H. and Sato, H., Prog. Theor. Phys. Suppl. No. 30, 86(1964).

Heitler, W., The Quantum Theory of Radiation, 3rd ed., Oxford, Clarendon Press, Oxford (1954).

Kiepenheuer, K.O., in The Sun, p. 322, Univ. of Chicago, Chicago (1953).

Kundu, M.R., The Solar Radio Astronomy, Interscience, New York (1965).

McDonald, F. B., Cline, T. L. and Simnett, G. M., Trans. American Geophys. Union, 50, 305 (1969).

Maxwell, A., Planet. Space Sci., 11, 897 (1963).

Maxwell, A. and Thompson, A.R., Astrophys. J., 135, 138(1962).

Meyer, P. and Vogt, R., Phys. Rev. Letters, 8, 387 (1962).

Newkirk, G., Astrophys. J., 133, 982 (1961).

Newkirk, G., Annual Rev. Astron. Astrophys., 5, 213 (1967).

Reid, G. C. and Leinback, H., J. Geophys. Res., 64, 1801 (1959).

Sakurai, K., J. Geomag. Geoel., 11, 152 (1960).

Sakurai, K., J. Geomag. Geoel., 12, 70(1961).

Sakurai, K., Rep. Ionos. Space Res. Japan, 19, 421(1965a).

Sakurai, K., Publ. Astron. Soc. Japan, 17, 403 (1965b).

Sakurai, K., Rep. Ionos. Space Res. Japan, 19, 408 (1965c).

Sakurai, K., Publ. Astron. Soc. Japan, 18, 77 (1966).

Sakurai, K., Rep. Ionos. Space Res. Japan, 21, 113 (1967).

Sakurai, K., J. Geomag. Geoel., 21, 463 (1969a).

Sakurai, K., Goddard Space Flight Center X-615-69-431(1969b).

Sakurai, K., Planet. Space Sci., 18, 33 (1970).

Smith, H.J. and Smith, E. v.P., Solar Flares, MacMillan, New York (1963).

Sturrock, P.A., in Plasma Astrophysics, p. 168, edited by P. A. Sturrock, Academic Press, New York (1967)

Svestka, Z., Space Sci. Rev., 5, 388 (1966).

Takakura, T., Publ. Astron. Soc. Japan, 13, 166 (1961).

Wentzel, D. G., J. Geophys. Rev., 70, 2716 (1965).

Wild, J. P., J. Phys. Soc. Japan, 17, Suppl A-II, 249 (1962).

Wild, J. P., Smerd, S. F. and Weiss, A. A., Annual Rev. Astron. Astrophys., 1, 291 (1963).

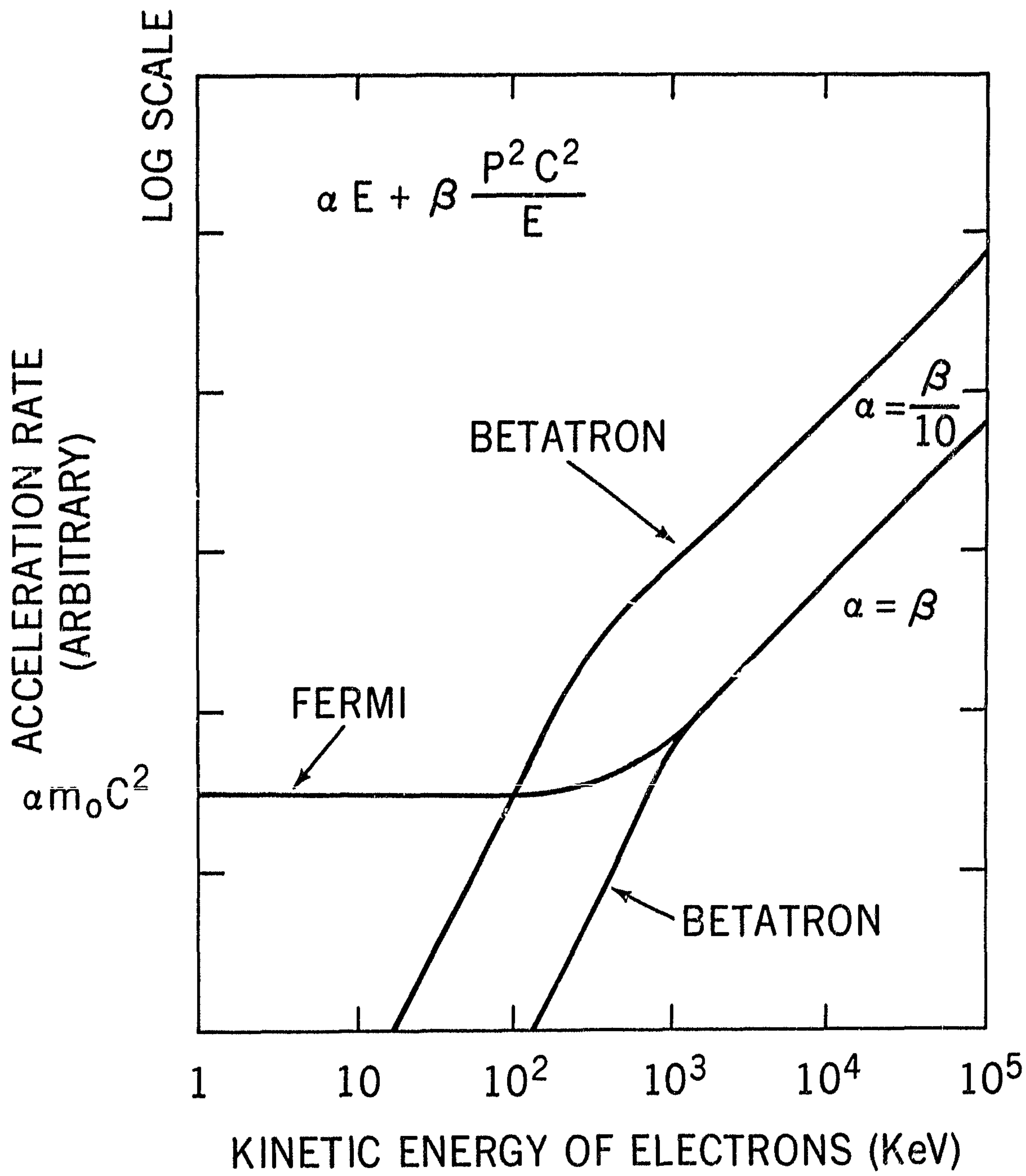

Fig. 1 Schematic diagram of the acceleration rate of the Fermi and betatron accelerations as regards the kinetic energy of electrons.

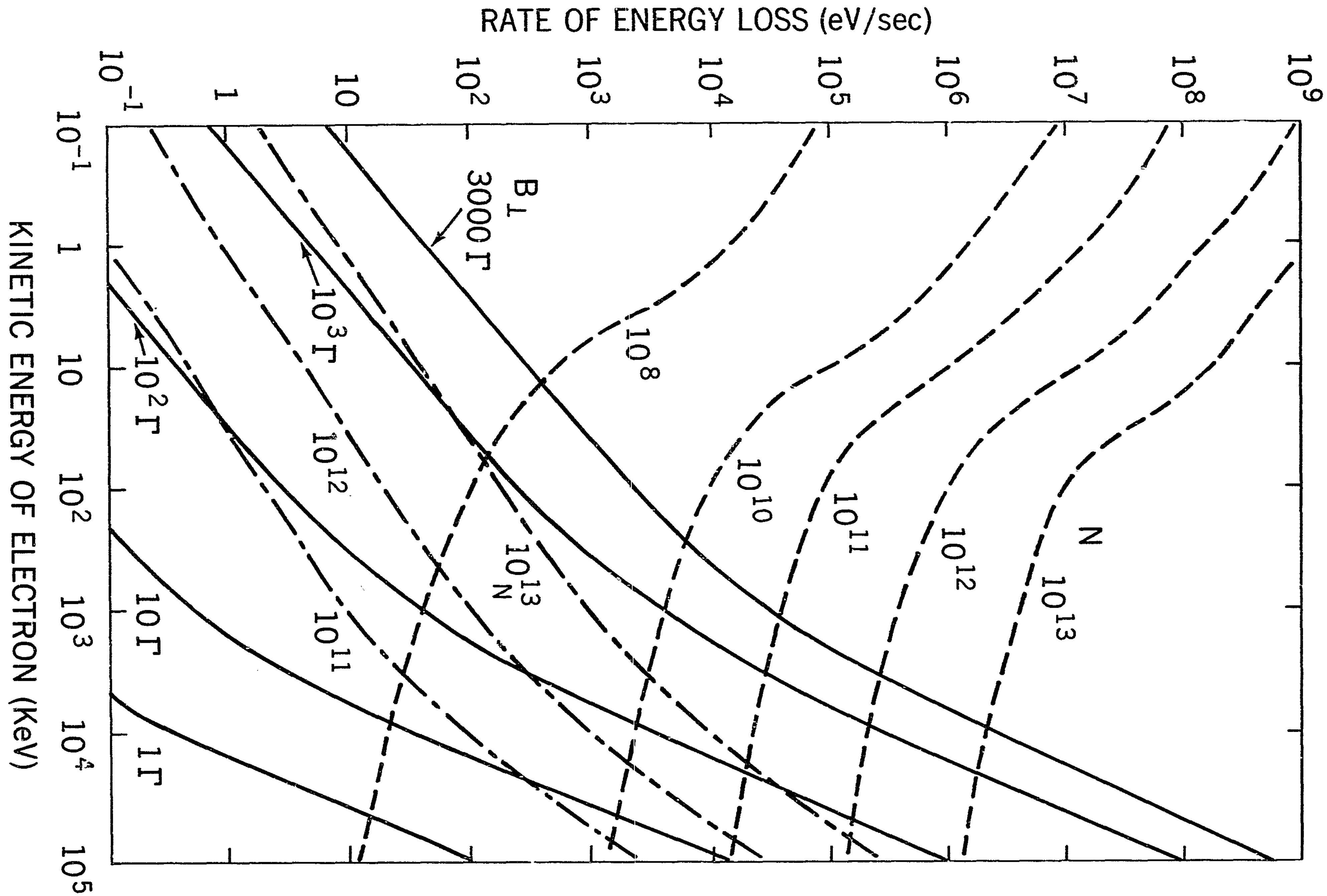

Fig. 2. Various energy-loss rates for solar flare electrons. The loss rates due to the synchrotron radiation (____), the collision (-----) and the bremsstrahlung (—-—-—-) are estimated by assuming the strength of transverse magnetic yield ($B_\perp$) and proton number density (N).

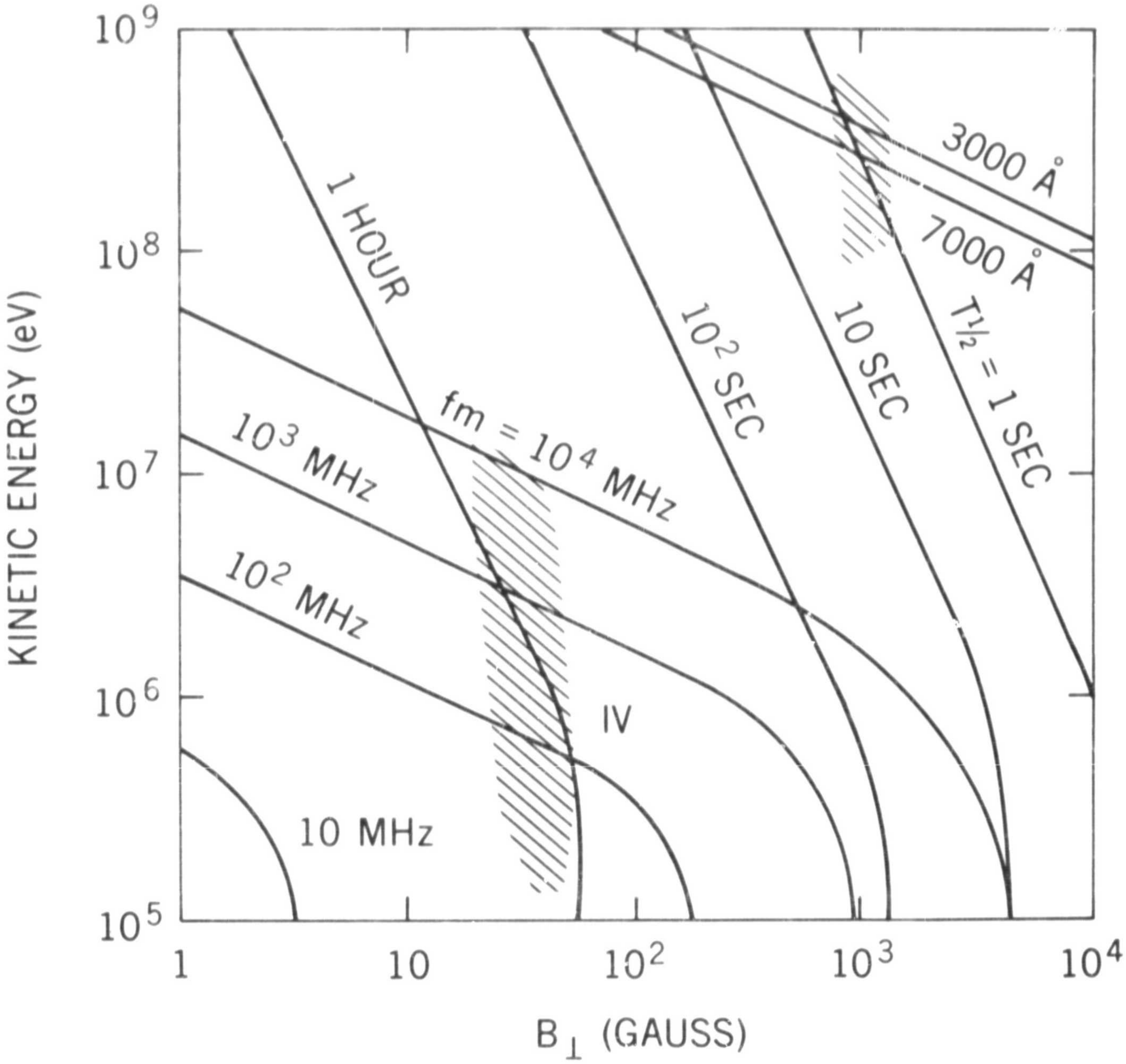

Fig. 3. Relation between the frequency and the life time of synchrotron radiation. The most probable radio frequency fm and the half life $T_{\frac{1}{2}}$ of synchrotron radiation are given as functions of the strength of transverse magnetic field $B_{\perp}$ and the kinetic energy of electrons. Hatched areas indicate representative sources explicable for type IV radio bursts and white light emissions.

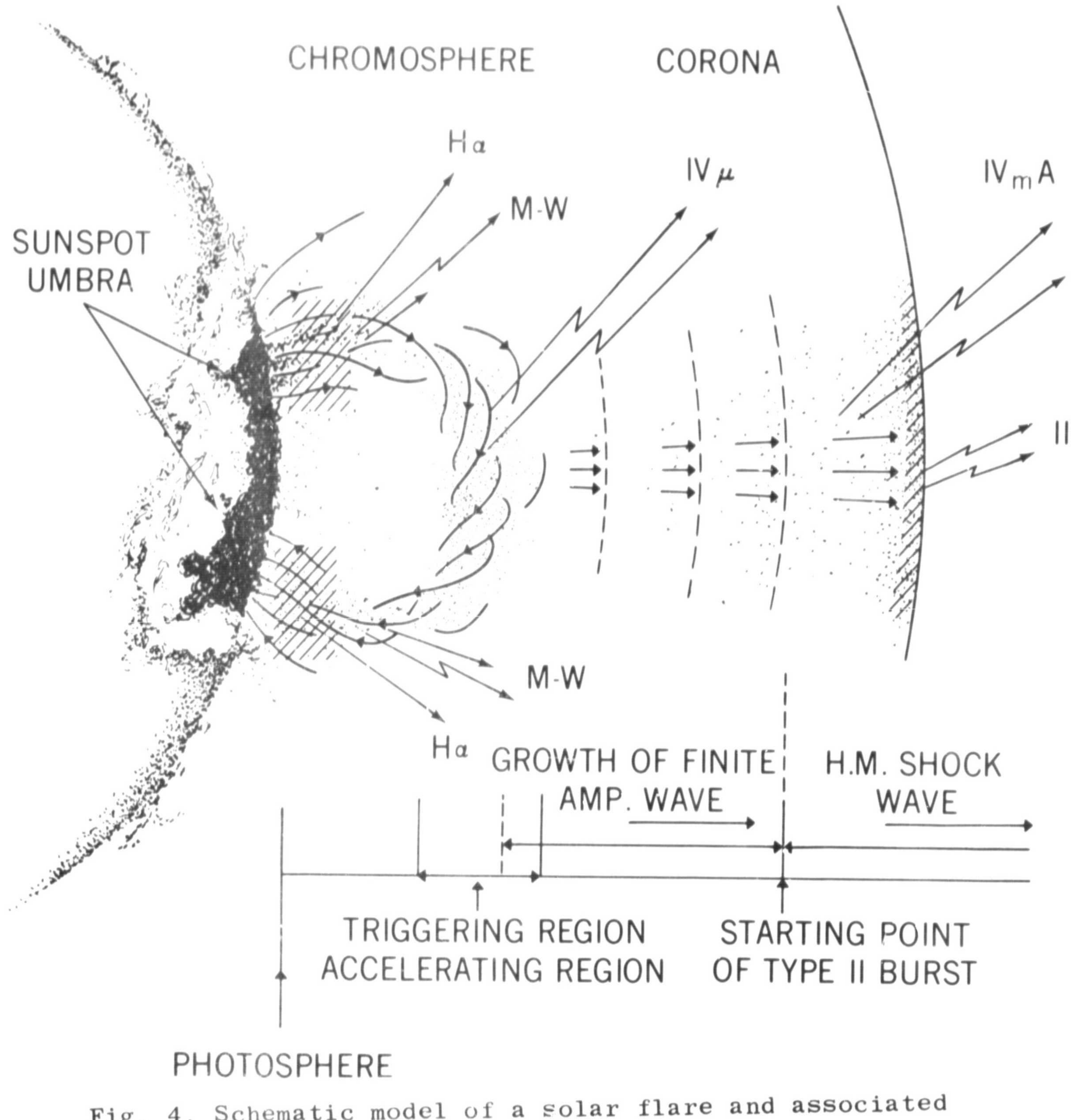

Fig. 4. Schematic model of a solar flare and associated phenomena. Vertical cross section through the main preceding and following sunspots.