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A Search for the Time Evolutive Characteristics of the Spectrum of Impulsive Solar Bursts

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By considering alternative explanations in order to account for the time evolutive features of the spectrum of impulsive bursts, a suitable model for these events and accompanying phenomena is presented. Established on the grounds of a few cases, the model looks suitable for all the impulsive class, bringing information on plasma phenomena like Razin effect, polarization reversal, acceleration of particles by shock, relaxation times, three dimensional flare expansion and radiative instatility. It looks also suitable for explaining the spectral cutoffs, rise- and fall-time of burst spectra, associated magnetic fields and other spectral characteristics as well.

Levando-se em consideração explicações alternativas para a evolução de características espectrais de explosões solares do tipo "impulsivo", é apresentado um modelo para esses eventos. Embora apresentado com base em alguns poucos casos, parece todavia aplicável a toda uma classe de explosões impulsivas, informando-nos sobre fenômenos de plasma como: efeito Razin, inversão do sentido de polarização, aceleração de partículas por onda de choque, tempos de relaxação, expansão tridimensional e instabilidade radiativa. Parece aplicável também para explicar os cortes espectrais, as fases iniciais e finais, campos magnéticos associados e outras características espectrais desses eventos solares.

1. Introduction

If we seek an explanatory mechanism for the solcr bursts activity, the weaker and simpler events (e.g., Simple 2, Simple 3) appear to be more fruitful for analysis than the stronger and more complex ones. Therefore, we shall now concentrate our attention on the bursts of sudden rise profile at higher frequencies (Simples 2). Due to their characteristic time protile, spectrum and circular polarization, the gradual rise and fall bursts (Simple 3) seem to occur at different physical conditions in the Sun. We have studied them separately'.

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Up to the present time, the studies on the time profile of the solar synchrotron emission, during outstanding events, are mainly oriented towards an interpretation of their decay phase[2,3]. Hagen and Barney[4], as well as Vesecky and Meadows', considered the initial stages of flares, but from a different point of view. On the other hand, the used spectral informations are drawn from the peak values at each frequency (See the Hachenberg and Wallis spectra reported in the paper by Takakura[6]. See also Castelli, *et al.*[7]).

For the spectral analysis of an event, the distinction between Complex and Simple 2 looks sometimes insignificant, because a solar radio burst showing a typical Simple 2 shape over the entire radio frequency range is hardly probable. In general, an impulsive event at a given frequency becomes Simple 1, or Simple 3, or Spike, or Complex, or Simple 2F, or even an absorption at a lower frequency (See Figures 1, 2, 3 and 4).

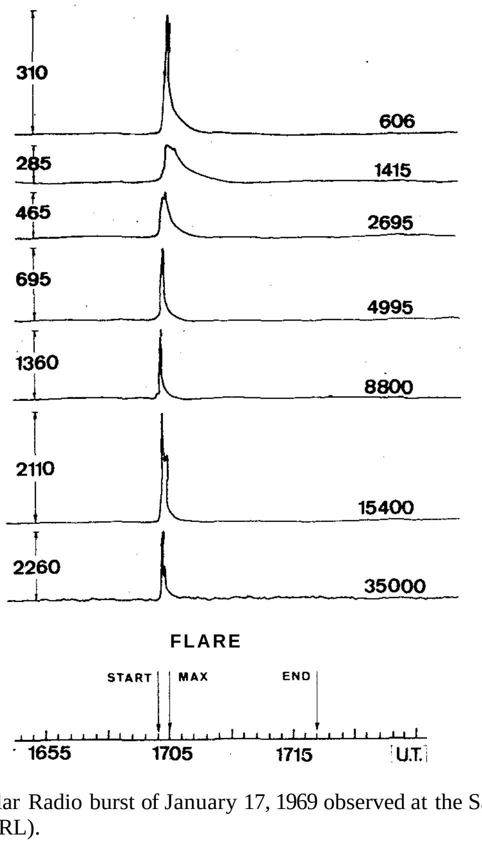

Figure 1 - Solar Radio burst of January 17, 1969 observed at the Sagamore Hill Radio Observatory (AFCRL).

Because of this, the bursts at different frequencies do not, in general, peak simultaneously, so that in a more detailed treatment it is not correct to build spectra with maximum flux values. The example given in Figure 2 illustrates this point. So, we shall consider here cases of even Complex bursts, since they present a sudden rise profile, typical of impulsive bursts, and we shall also consider their spectral evolution in the whole process.

2. Observational Data

The cases we have selected were taken from the Sagamore Hill Radio Observatory Reports (AFCRL) which cover a broad range of frequencies and have the advantage of being referred to the same time standard. This ensures a better precision for the spectral analysis. The spectral data departing, during the burst, from the steady-state equilibrium can be helpful for clarifying the whole process of the solar event.

We chose the events of January 17, 1969 (Figure 1); August 8, 1968 (Figure 2); Novembre 5, 1968 (Figure 3) and August 21, 1968 (Figure 4). The spectral evolution for each event is also shown in the figures. We avoided bursts with secondary structures in which the measurements were affected by greater errors due to different electronic responses and mechanícal inertia of the measuring instruments.

The spectrum departure from equilibrium is associated with the rise phase, while its return to equilibrium is associated with the decay phase.

The distinction between explosive phase and flash phase of a flare must be carefully made. As Zirin[8] has observed, the first corresponds to an outward motion of material, while the second to a period of maximum brightness. It seems therefore more appropriate to correlate the flash phase with the maximum flare. In the cases we consider, the flare maximum occurs after (or, at most, simultaneously with) the radio burst peak. Thus, the assumption that paiticle acceleration occurs during the flash phase is not a sound[9] one. Covington and Harvey[10] observed a coincidence of the starting time of the bursts with the explosive phase of the flare. Another significant observat onal feature noted by these authors is that the bursts associated with the explosive phase are all of the impulsive type and the burst maximum in several cases occurs shortly before the flare maximum.

Another very interesting observed feature, valid at least for these four cases, is that the spectrum during the rise peaks at frequencies which

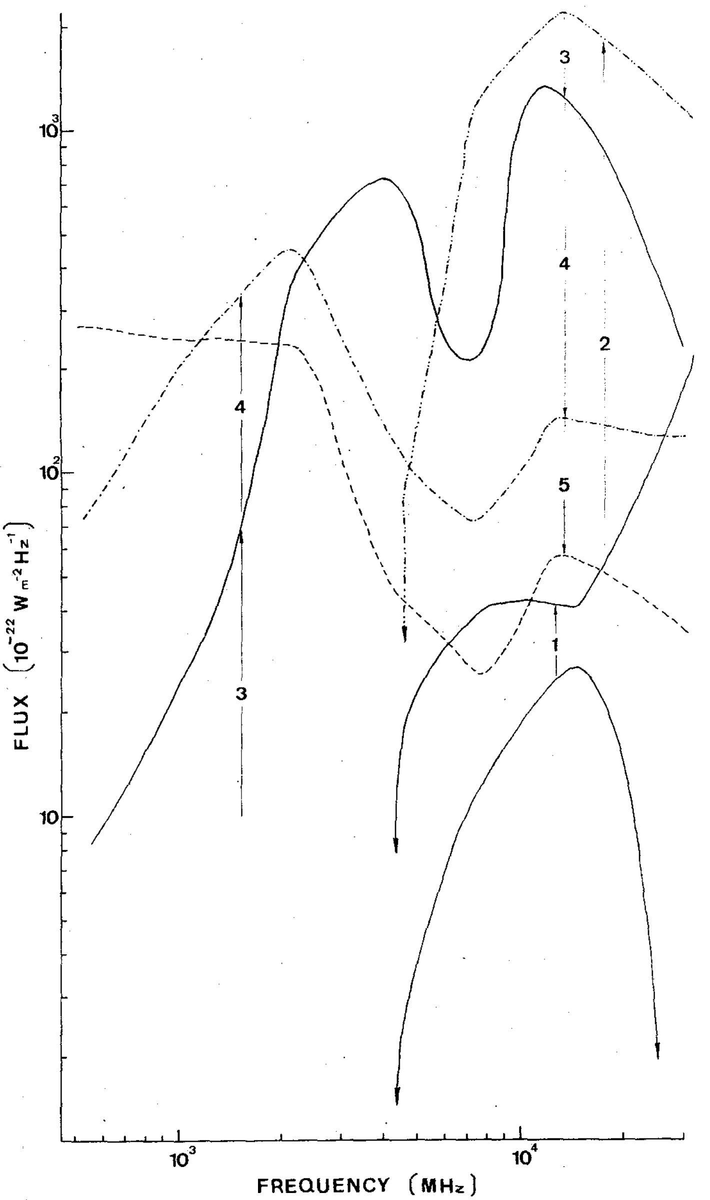

Figure 1A - Successive spectra of the January 17, 1969 radio burst, during the rise-time. The time interval is 1/3 of a minute.

increase with the importance of the simultaneous flare. For -1 importance, the peak occurs around 1,000 MHz, while for $+2$ at about 10,000 MHz.

We shall use the spectral data of the November 5, 1968 burst as a starting point, since it is the simplest one:
a) the spectra always peak at the same frequency $\approx$ 1,415 MHz;
b) the spectra show an almost inverted "U" shape, coming down to zero flux on both sides of the maximum.

The available statistics of solar bursts for the years 1966, 1967 and 1968 (Barron[11]) shows roughly an increasing number of impulsive events (64,180 and 177, respectively), with the frequency at which the incidence of impulsive bursts was maximum decreasing from 8,800 to 4,995 MHz. On the other hand, the corresponding mean rise-time decreases (1.4, 1.2 and 1.0 minutes, respectively). As we shall see later, the increase of sunspot areas with the solar cycle enlarges the chances for special topologies of the magnetic field for the occurence of flares. Apparently, only special field configurations are able to produce impulsive events, but the frequency of maximum flux,

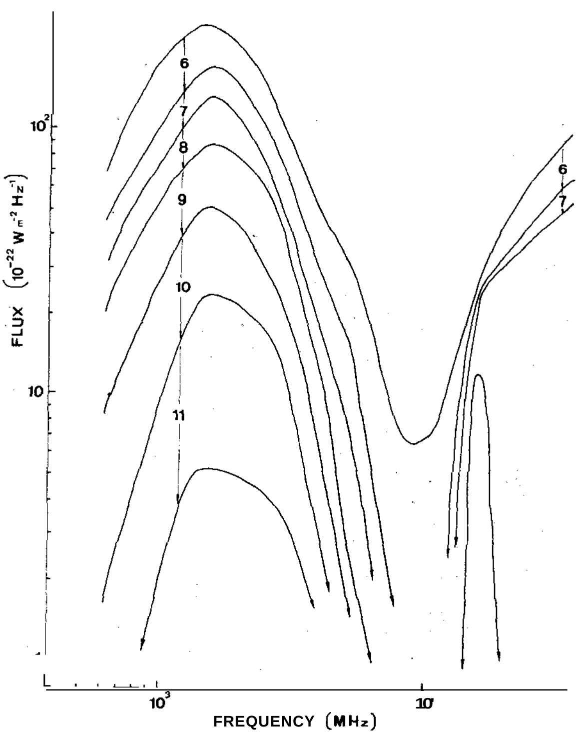

Figure 1B - Successive spectra of the January 17, 1969 radio burst, during the decay phase which can be connected with the energy of the electrons, decreases, since this energy is smaller for stronger fields. The rise-time can decrease because the shock blast speeds up as the field gets stronger.

3. The Rise Phase

Since the spectrum does not show a thermal character, the very fast release of radiation does not appear to be explainable in terms of free-free emission. the rise period being attributed to the synchrotron mechanism[6]. In this paper, we shall use the two following simple alternatives.

3.1. Monoenergetic Spectrum

Let us suppose initially a monoenergetic distribution of electrons. Irrespective of whether their veiocities are isotropically distributed or not, the emission will depend on the content of electrons whose velocities are directed toward the observer. The maximum in the radiation spectrum, from an individual relativistic electron, would occur at the frequency

$$f_m(\mathrm{Hz}) = 4.6 \times 10^{-6}\, B_\perp E^2,$$

where $B_\perp$ (gauss) is the magnetic field perpendicular to the velocity of the electron and E (eV) is the electron energy[12].

We shall assume a constant magnetic field, since its characteristic length L (for which the variation AB of the field equals B) is of the order of 10^9 cm in the direction perpendicular to the solar surface. This value was derived from the Kakinuma – Swarup model for the sources of the S-component of microwave radiation[13]. This size is larger than that of the flare at earlier stages, since the volume 10^{30} cm^3 refers to a later phase. The cutoff at lower frequencies does not enable us to determine the levels producing the emission; the emissive cloud appears in general to grow somewhere above the 10.000 MHz critical level. So, we shall assume the value $B_\perp = 2 \times 10^2$ gauss, which is the value of the field itself given by the Kakinuma – Swarup model for heights in the interval 4×10^9 cm $< h < 5 \times 10^9$ cm. These coronal altitudes are quite reasonable if we consider that synchrotron emission is directive and that a statistical analysis of impulsive events showed some peculiar features which were interpreted in terms of the radiation emerging from the higher parts of magnetic loops[14]. In the present shortage of magnetic field models, we can also use Lantos' model'', assuming a photospheric quadrupole iield of 3,500 gauss in free space. The isogauss for 200 gauss reaches up to about 2 x 10^9 cm. In this way, we are led to conclude that, if the frequency f_m of the observed maximum flux is constant, the monoenergetic electrons keep a constant energy value. The increase in amplitude would mean a larger number of electrons taking part in the emission process. It is unlikely that a batch of electrons would be accelerated instantaneously from equilibriurn energy to a definite final energy $E \approx 10^6$ eV. This spectral behavior apparently excludes the possibility of stochastic acceleration of particles. A symmetric solitary shock wave, or *soliton*[16], carries net symmetric electric fields in each of its halves; if the accelerated electrons are close to the shock and if the acceleration time to quasi-relatívistic speeds is of the order of $1-1.5$ minutes[11], the required electric fields would be of the order of 10^{-5} V cm^{-1}. Such a field is able

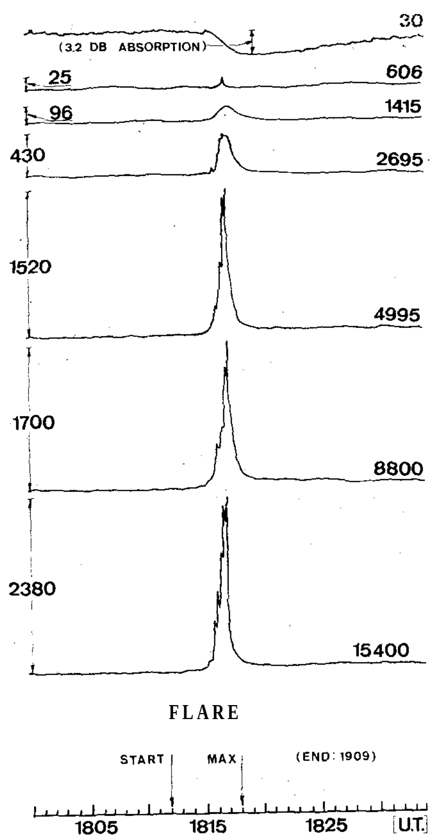

Figure 2 - Solar event of August 8, 1968 observed at the Sagamore Hill Radio Observatory (AFCRL).

to raise the energy up to 10^4 eV, if it acts over an effective length of about 10^9 cm. The resulting electrons, however, would present a monoenergetic instantaneous spectrum, the energy increasing continuously with time.

Among the usually invoked acceleration mechanisms, the betatron mechanism still remains to be considered. Its equation for the relativistic case is given by Takakura[6]. First of all, in this process the energy increases up to a maximum ratio $(B + \Delta B)/B$, where B is the initial field and ΔB, the field variation. This is quite a stringent limitation. Indeed, if the electrons on the tail of the thermal distribution, with energy of about 10^3 eV, are accelerated to a kinetic energy of the order of 10^5 eV, then ΔB would be 10^6 gauss for $B = 2 \times 10^2$ gauss. There is, however, no evidence for such high transient changes at coronal levels. Severny[17] performed, near the magnetic neutral points, some optical measurements of the gradient ∇B (gauss cm^{-1}) before and after the flares. He measured, along a direction perpendicular to the line of sight, the gradient of the component of the magnetic field along the same direction. So, a rough estimate for $\Delta B/\Delta t$ (gauss sec^{-1}) can be obtained by computing

$$[(\nabla B)_{\text{before}} - (\nabla B)_{\text{after}}] \frac{R}{\Delta t} \approx \frac{\Delta B}{\Delta t},$$

where R (cm) is an estimated value for the sunspot radius and Δt (sec) is assumed to be 10^2 sec, i.e., the impulsive rise-time, since we compressed in this phase all the magnetic changes. We obtained $\Delta B/\Delta t \approx 10^8$ gauss sec^{-1} for strong flares! We are inclined to believe that this figure is not realistic. The time interval Δt could be much larger and would correspond to a realignment of the tubes of force, i.e., to an increase of the component perpendicular to the solar surface. This description agrees with the fact that the magnetic fields of older spots reach higher heights and showing also, at later times, an open structure[18]. On the other hand, in order to get reasonable values of ΔB, which are smaller than 10^2 gauss, B should be 10^{-1} gauss but, at this scale of fields, the process would become a magnetohydrodynamic shock. It seems therefore that the assumption of a monoenergetic distribution cannot apparently account for the accelerating process. We then turn to a second alternative.

3.2. Power-Law Spectrum

A cutoff at high energies could produce the very steep spectral-cutoff at high frequencies in accordance with the dependence $f^{1/2} \exp(-f)$ on the frequency f (Ref. 19).

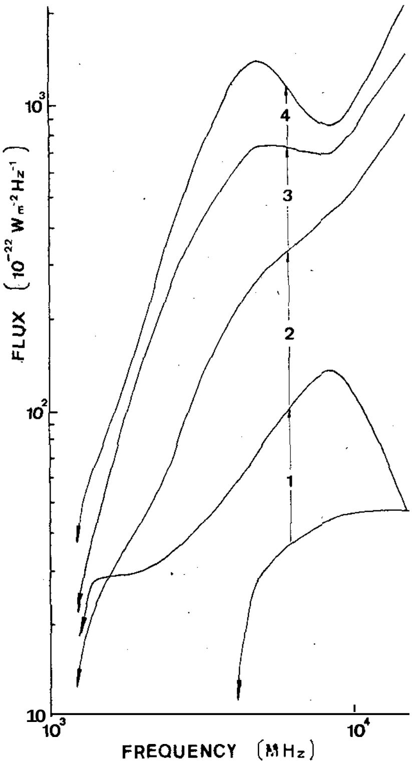

Figure 2A - Successive spectra of the August 8, 1968 event during the rise-time.

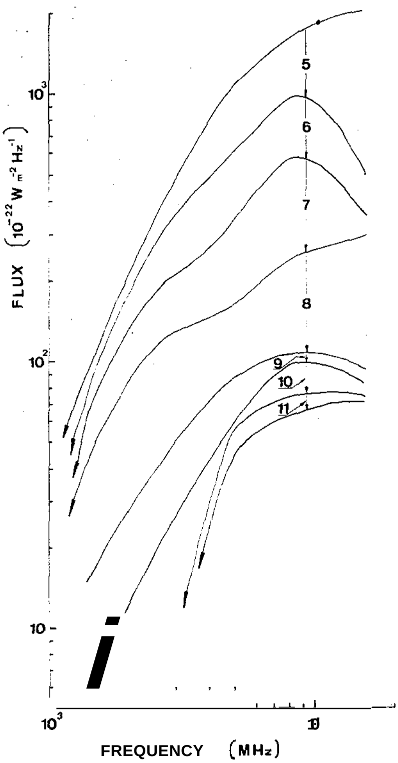

Figure 2B - Succesive spectra of the August 8, 1968 burst during the fall phasc.

We also calculated the power-law spectral index a for the three spectra displayed in Figure **3A.** The index can be calculated from the relation

$$(f_1/f_2)^{-\alpha} = S_1/S_2\,,$$

where f_1 and f_2 are the frequencies and S_1 and S_2 the corresponding flux values. The values obtained are plotted in Figure 5. The scattering of the points could be due to the existence of a small number of electrons obeying different power-law energy distributions, since such a burst shows four steps during the accelerations (see Figure **3).** The important conclusion however is that the index a decreases before the burst peak. Since the spectral index a is related to the energy spectral index γ by[12] a = (y – 1)/2, one can see that γ decreases from a maximum value ≈ 6 to a minimum value ≈ 1. 4s y decreases, the energy of the electrons increases accordingly.

Now let us consider the low frequency cutoff. This cutoff frequency f_c could be of the order of 1,415 MHz. It is not explainable by a low energy cutoff of the electrons since $f_c(\mathrm{Hz}) = 1.6 \times 10^{13} B_\perp E^2_{\min}$ (Ref. 19), where $B_\perp$ is given in gauss and $E_{\min}$ (eV) is the lowest energy of the electrons. We find $E_{\min} \approx 10^{-3}$ eV, which is too low. Apart from this difficulty, the index a would be -0.3, too different from the value obtained above. Thus, such a cutoff seems unlikely.

In a magnetic field $B_\perp \approx 2 \times 10^2$ gauss, the oscillator frequency given by the gyrofrequency $f_B(\mathrm{Hz}) = 3 \times 10^6 B_\perp$ (where $B_\perp$ is given in gauss) is 600 MHz, smaller than, or comparable to the local plasma frequency $f_0(\mathrm{Hz}) = 10^4 \sqrt{N}$, where N ($\mathrm{cm}^{-3}$) is the electron density: $f_0 \approx 1{,}000$ MHz. The plasma therefore may act as a controlling agent for the oscillator emission in the low frequencies. However, the free-free absorption by an external dense plasma also looks untenable, since the flux would follow the law[19]

$$S(f) \propto f^{-\alpha} \exp[-(f_m/f)^2],$$

the self-emission of the external cloud being neglected. Assuming $f_m =$ 1,415 MHz and taking $S(f)$ at $f = 600$ MHz, the observed ratio $S(f_m)/S(f)$ is seen to decrease with time from a value of about 10^3 down to 5. On the other hand, the same ratio computed from the formula given above, ranges from 10^3 to 10^2. So, the influence of a dense plasma attenuating the waves can be important only during the initial period of the rise.

Absorption produced by an ionized gas internal to the source would result in a spectrum with a frequency dependence[19]

$$S(f) \propto f^{\beta}, \qquad \text{where} \qquad \beta = -\alpha + 2.$$

Since α decreases with time, β would increase up to about 2. However, this general trend is not observed. The synchrotron self-absorption also implies a constant frequency dependence $f^{2.5}$ (Ref. 19) which is not in agreement with the experimental evidences.

By considering the asymptotic behavior of the low-frequency cutoff curves, we observe that they look as changing only in slope, keeping a constant cutoff frequency. This is an indication of the Razin effect[20]. The hypothesis of a selfabsorption would imply an almost constant slope and, as a consequence, different cutoff frequencies. According to Holt and Ramaty[20], either the self-absorption or the Razin effect prevails according to whether the ratio $(3/2)(f_B/f_0) = 5 \times 10^2 B_\perp N^{-1/2}$ ($B_\perp$ in gauss and N in cm^{-3}) is greater or smaller than 0.5. Admitting $B_\perp = 2 \times 10^2$ gauss

and $N = 4 \times 10^{10}$ cm^{-3}, we have almost the intermediate condition separating the two possible effects. The variation of this ratio looks very critical, due to the fractional portion of coronai electrons involved in the relativistic process and also to possible radiative instabilities, which we shall refer to later on. The apparent presence of the Razin effect seems to indicate that the condensation presents an electron density greater than 4×10^{10} cm^{-3} during the later period of rise-time, irrespective of the variation of size of the radiation source. This effect was also invoked by other authors (e.g., Boischot and Chevelier[21]), in the case of meter-wave bursts of type IV (Michael *et al.*[22]). Yukon[23] also emphasized the polarization increase concomitant with the Razin effect at low-frequencies. This effect could be connected with the circular polarization reversal somewhere in the range 2,000 MHz $< f <$ 4,000 MHz, at which the polarization is the smallest. A spectral time profile of the polarization would be helpful in confirming these results. Hold and Ramaty[20] link the Razin effect to the polarization reversal from the ordinary to the extraordinary mode. It occurs somewhat below the frequency at which the ratio source becomes optically thin. If the source is optically thin for all frequencies, such a reversal is not to be expected. The Bremsstrahlung spectra prevailing in the later stages of the burst can show the transition from thick to optically thin plasma in the range 1,000 $< f <$ 10,000 MHz. This mechanism would explain the circular polarization reversal with the frequency in terms of a more intrinsic physical condition than the mode coupling[''].
The probable value for the cutoff frequency due to the Razin effect is[19] $7\,N/B$ (Hz), where N (electrons cm^{-3}) and B (gauss). For a coronal condensation of $N > 10^{10}$ cm^{-3} and $B \approx 10^2$ gauss, we obtain $f_c > 700$ MHz. The slopes of the cutoff curves seem to show a radiation cutoff at about 1,000 MHz for the majority of the selected cases, with only one case at 5,000 MHz (which could imply a density N almost ten times as great).

On the ground of a quasi-constant density, we can deduce the volume increase by making a few reasonable approximations. At a fixed frequency, we can derive the emissive volume relative-increase

$$\frac{V_2}{V_1} = \frac{S_2}{S_1}\left[\frac{6 \times 10^{20}}{f}\right]^{(\gamma_1 - \gamma_2)/2},$$

where the indices 1 and 2 refer to the preceeding and succeeding times. In spite of the dispersion of values, a most probable value of 10^5 is obtained for this ratio. The final volume being assumed to be 10^{30} cm^3, the initial linear dimension results to be $\approx 10^8$ cm. The total number of electrons

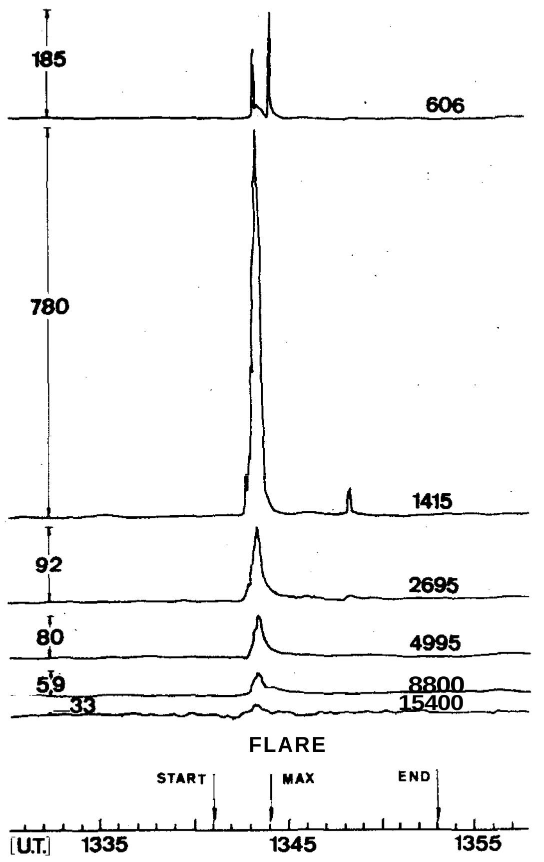

Figure 3 - Solar burst of November 5, 1968 observed at the Sagamore Hill Radio Observatory (AFCRL).

involved would increase in the same proportion. If the value of γ decreases with time (the mean density N being kept constant), it then follows that the energy increases, in agreement with an acceleration process.

4. Acceleration Process

Admitting that during the rise phase a power-law electron distribution is built up, with γ decreasing with time, the problem is then to see how these electrons are accelerated. The strong correlation, found by Covington and Harvey[10], between the flare explosive phase and the burst starting time, seems to favor the presence of a shock mechanism in the acceleration. We have considered the formation of such a shock elsewhere[2'].

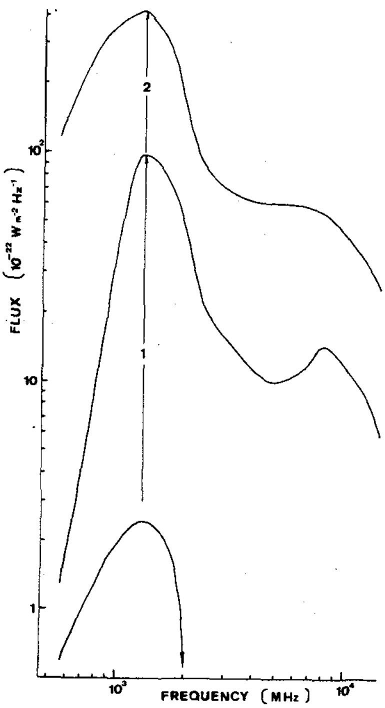

Figure 3A - Successive spectra of the November 5, 1968 event during the first rise peiod.

The active region is a seat of instabilities for which plausible models have been proposed, e.g., the one of Sturrock[26] based on the resistive tearing mode. Since, in this model, shock fronts can develop and travel in open magnetic fields streaming outwards in the corona, this explanation is more suitable for type III bursts[27] than for those of type IV which often accompany microwave impulsive events. The best evidence for shocks is the Moreton wave, related to the hydromagnetic fast mode blast produced during strong flares and reaching velocities of about 1,000 km sec^{-1} (Ref. 28).

The Alfvén number M_A is defined as the ratio of the typical velocity of the plasma by the local velocity of the transverse hydromagnetic waves (Alfvén waves). The quantity M_A^2 measures the ratio of the dynamic and the magnetic pressures. Normally, above chromospheric heights[29], the gas pressureis much smaller than the magnetic pressure. Therefore, it seems plausible to admit $M_A << 1$ for a quiet solar atmosphere. However, $M_A \geq 1$ during flares. The ratio of the temperatures of disturbed and undisturbed regions can be calculated by the classical jump conditions using the Rankine-Hugoniot equation[30]. Indeed, let us now assume a rapid damping of the shock front. Then, by equating the gas pressure to the pressure of the superimposed magnetic field, one can compute[31] the ratio of temperatures using the usual Mach number M (which is about 10 times larger than M_A in the regions we are considering):

$$\frac{T_2}{T_1} = \frac{2\gamma M^2(\gamma - 1)}{(\gamma + 1)^2},$$

in which γ means now the ratio of the specific heats. Let us further suppose that $\gamma = 5/3$. In the solar atmosphere, at the heights we are interested in, the electron temperature is about 10^4 °K (Ref. 32). Even the presence of an S-component does not appear to increase the electron temperature at heights below 10^9 cm (Ref. 13). We obtained $T_2 \approx 3 \times 10^7$ °K

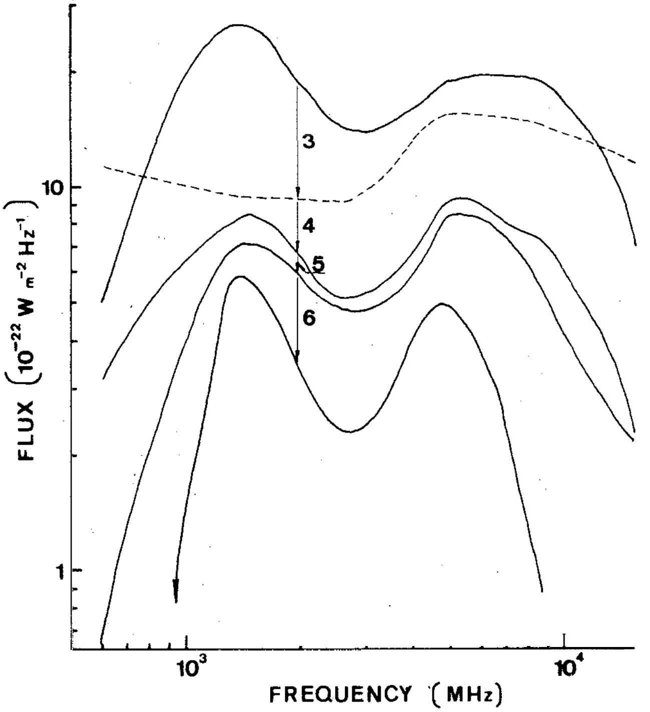

Figure 3B - Successive spectra of the November 5, 1968 event during the decay phase observed in the first component observabie at 606 MHz. .

and, for this temperature, the mean kinetic energy is larger than 10^3 eV. The suprathermal electrons at the tail of the Maxwell distribution can be easily accelerated to greater velocities. Several times we observed a small enhancement of the solar flux just before the rise phase, associable to the pre-heating described above.

Among the several proposed mechanisms of acceleration implying shocks, the most plausible one seems to be the one proposed by Wentzel[33] which is a variátion of the Fermi mechanism. In this case, the shock would be steeper than could be accounted by collisions. We remark that any shock reaching the higher parts of the atmosphere, becomes a collisionless magnetohydrodynamic shock front, traveling upwards along the magnetic field lines. This determines different jump conditions and entropy than those which would be expected for ordinary shocks. Apart from the Piddington collisional damping and the Joule dissipation of the shock (stronger for smaller Mach numbers), the two-streams instability, the Landau damping, etc, will define the new state of the compressed plasma. The spike-like activity occurring simultaneously at lower frequencies appears to indicate such oscillations, since it is not correlated with the synchrotron emission (see Figure 4). It may be radiation due to a linear interaction between plasma oscillations peaking at f_0 and $2f_0$. The thickness of the collisionless shock is of the order of a proton-cyclotron radius, at which distance the magnetic field must jump sharply and considerably. This thickness would be of the order of 10^3 cm. The dimensions of the radiating region are much larger than this thickness, so that the time profile of the impulsive burst should be modulated by these shocks[16]. This reinforces the idea of homolog flares[34].

In the blast discontinuity, the field lines are refracted, so that the shock constitutes the neck of a kind of a magnetic bottle. If the pitch angle of the electrons is greater than the critical angle θ_c, given by the usual equation for magnetic mirrors, namely,

$$\sin^2 \theta_c = B/(B + \Delta B),$$

(B being the initial steady field strength and $B + \Delta B$ the field behind the shock front) the particle is trapped in the magnetic bottle and accelerated to higher energies. The bottle volume does not necessarily decrease to zero, since the shock is highly dissipative, slowing down at about 5×10^{10} cm (Ref. 8).

In order that the energy gain be higher than the collisional losses, the mean free path λ must be large. So, for a hydrogen plasma[3''] using the expression

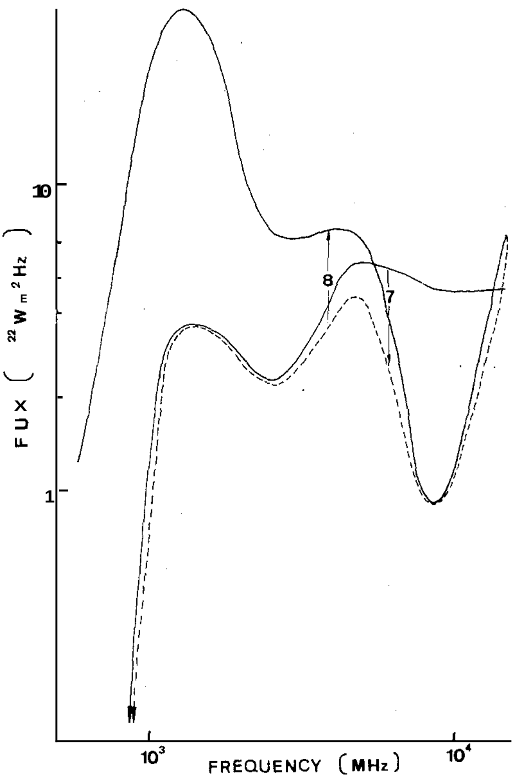

Figure 3C - Successive spectra of the November 5, 1968 burst during the nse period of the second component observable at *606* MHz.

$$\lambda\,(\mathrm{cm}) = \frac{1.3 \times 10^5\, T^2}{N \ln \Lambda}\ ,$$

where N (electrons cm^{-3}), T (°K) and, on this case, ln Λ = 20, one obtains $\lambda \gtrsim 2 \times 10^7$ cm. The characteristic length 1 an electron can travel before getting reflected in a magnetic mirror, in a medium density gas, as in our case, is much larger than 1: $I \gg \lambda \approx L$, where I was defined above. The strong preference of the impulsive bursts for magnetic spots of the E, F and G types (Zurich classification) is perhaps because they present arches with dimensions smaller or comparable to the mean free paths[25]. The bursts on August 21 and November 5, 1968, are referred to the same heliographic position and they would be generated by a train of shock fronts having almost the same amplitude and reaching the same place with time delays of about 3 or 5 minutes. The structure in the January 17, 1969, burst supposes a train of two shocks, 20 seconds apart from each other. Normally, the shocks in a train are separated by about 5 minutes and each one would correspond to one multiple step or bouncing acceleration. According to the soliton theory, the solitary wave-pulses in a train move at a speed proportional to their amplitudes and depend on the dispersion parameter of the Kortveg-de Vries equation[36]. If we admit that the assemblage of N-shaped waves is released instantaneously and since the pulses can overlap in space without loosing their identity, the shocks of smaller amplitude would reach the radiation source later. There are, however, examples of Complex bursts consisting of a sequence of bursts of increasing amplitudes, suggesting that the train is produced successively and that each pulse travels over short distances.

In the motion of a shock frontalong the field lines (as we are considering) there is no considerable electric field and the steady initial field does not influence the front, as is the case when the motion is across the field. The small deviation in the values of the rise-time, ranging between 1 – 1.4 min (Ref. 11), appears to be correlated to the shock dissipation length or to the magnetic loop size[25].

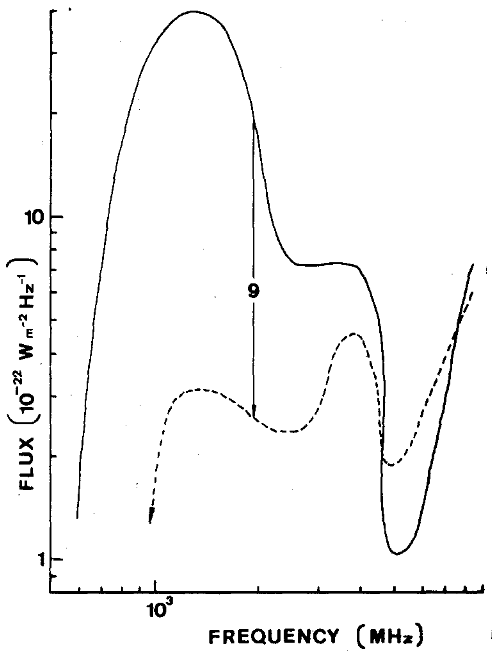

Figure 3D - **Successive spectra of the November 5, 1968 burst during the fall phase of the second component observable at 606 MHz.**

The velocity $v_\perp$ (transversal to the field) does not appear to be governed by a kind of random walk, since the small structures of the burst, during the rise-time, show some sort of periodicity. Since $v_\perp$ takes energy from the $v_\parallel$-component when the particle batch is closer to the mirror, there the synchrotron radiation must be stronger and time-correlated with the small structures exhibited during the rise-time. On the other hand, the released energy, estimated in terms of the importance index of the flare, shows some proportionality with the maximal emission frequency (as expected by the synchrotron theory), but it is not correlated with the number of small structures. Since the amplitude of the spectrum increases retaining tbe general shape, during these small structures, we are inclined to believe that, in each step, the shock accelerates another batch of available charges up to an upper-limit energy. This upper-límit is determined by the magnetic fields involved, being the greater the smaller the critica1 pitch angle is. If B $= 2 \times 10^2$ gauss, and $\Delta B = 50$ gauss, then $\theta_c \approx 70''$. For isotropic distributions of pitch angles, the relative loss of particles will be $\int_0^{\theta_0} \sin\theta \, d\theta \approx 0.5$. The greater this dimensionless number is, for a given bouncing period of particles, the larger the loss of particles. Since the increment for the steady initial field cannot be much larger, this angle is smaller if the initial field is so. This is in good agreement with the measurements of the microwave burst polarization and its intensity[14] if one assumes an optically thin plasma, in agreement with the results of Basu and Covington[36].

The bouncing model seems to fit well the observed quasi-periodic structures, each of them repeating itself every 10 sec, approximately. The circular polarization does not reverse itself necessarily when the electrons bounce back, since (for a high electron-energy-range) its type is a function of the geometry of the field; this geometry, however, does not change much over the flare region.

If sometimes, in the same radiation source, a subsequent burst peaks at a higher frequency, this could be understood as if, in the first acceleration process, the electrons had not been sufficiently energized up to the limiting energy.

The deflection time, t_D (Ref. 38), for coronal temperature and relativistic electrons with a ratio $\beta = v/c \approx 0.1$, is about 10^3 sec, a time much larger than the rise-time. This time accounts only for the deflections due to collisions. The hypothesis of a redistribution by Coulomb collisions during the

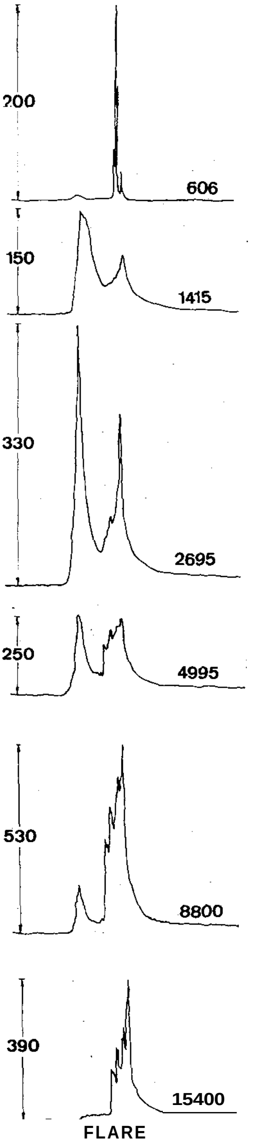

Figure 4 - Solar event of August 21, 1968 observed at the Sagamore Hill Radio Observatory (AFCRL).

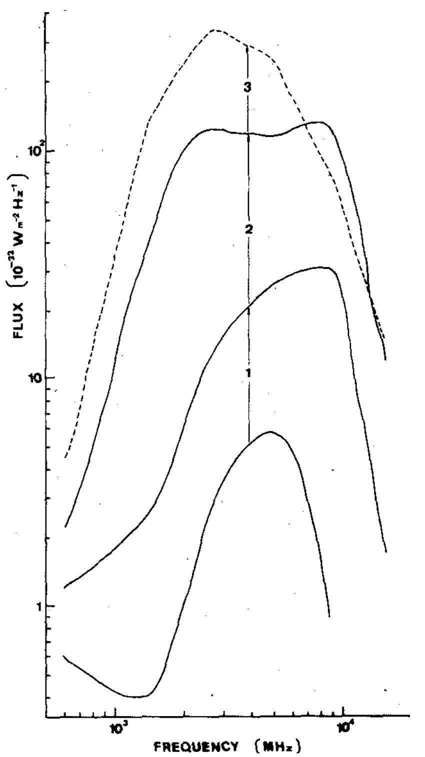

Figure 4A - Successive spectra of the August 21,1968 event during the rise period of the first component observable at 1,415 MHz.

acceleration, as invoked by Takakura[39], is hardly acceptable (since such collisions are quite rare) and rather inefíicient as the electron energy increases. The picture supposing small-scale magnetic inhomogeneities can explain better a rapid redistribution of velocities which endures a large fraction of electrons spiralling with relativistic transversal velocities $v_\perp$. These inhomogeneities do not invalidate the homogeneous field structure, since the polarized radiation supports that the field is not completely at random. Anyway, some mechanism providing this redistribution is necessary because head-on collisions, between particles and shocks, increase only the parallel velocity $v_\parallel$, at the same time decreasing the pitch angle and establishing the escape of particles trough the magnetic neck.

Let us discuss now the limiting energies. At lower energies, their losses by a charged particle is mainly due to the Bremsstrahlung or collision of fast electrons with protons. In the range 10^3 eV < E < 10^4 eV, Bremsstrahlung is an effective loss process. A very low value of about 120 eV is found, when we try to get the critical injection energy (for which the net energy gain-loss rate becomes positive) assuming Fermi acceleration as the energy gain process. So, a pre-heating of the plasma is not essentially required for this acceleration mechanism.

There is, however, an upper-limit defined when we equate the rate of synchrotron loss with the Fermi acceleration rate[40]. So, we get the maximum energy

$$E_m \text{ (eV)} = 6 \times 10^{14}/(dB^2)$$

where d (cm) is the distance between the shock fronts, within which the electrons collide. This maximum energy shows inverse relation with the square of the magnetic field. We believe that this is physically consistent to explain the connection of more energetic bursts with weaker fields. As time goes, d decreases down to a limiting value and E_m increases, so that the index α decreases. But when the longitudinal velocity $v_\parallel$ increases very much, the losses due to the escape of particles become important.

If we assume the mean rate of the energy increase to be given by Fermi acceleration[40]

$$\dot{E}_{\text{Fermi}}(\text{eV s}^{-1}) = \frac{u^2 v}{c^2 \lambda} E$$

[u is the shock velocity (cm s^{-1}), v the electron velocity (cm s^{-1}); λ, the mean free path (cm) and c the speed of light], the differential energy spectrum of the statistically accelerated particles will have the index γ given by[40]

$$\gamma = 1 + \frac{c\lambda}{u^2 \beta\tau} ,$$

where τ (sec) is the mean time over which each particle is accelerated. Since, before the peak, the most probable value of γ, when $\tau = 1.2 \times 10^2$ sec, $u \approx 10^8$ cm sec^{-1} and $\beta = 0.2$ (corresponding to 10^4 eV electrons), is 4, we get $\lambda = 2 \times 10^7$ cm in agreement with its value derived before. In the peak, y tends to 2. In the limit, when $\lambda \to 0$, i.e., when acceleration cari no longer occur, $\gamma \to 1$, or a $\to 0$, which agrees with the observations.

Finally, we know that the circular polarization peaks somewhere betweea the starting time and the peak of impulsive burts[41]. Since in a progressively accelerated plasma the cone of synchrotron emission decreases, it is expec-, ted that circular polarization becomes linear.

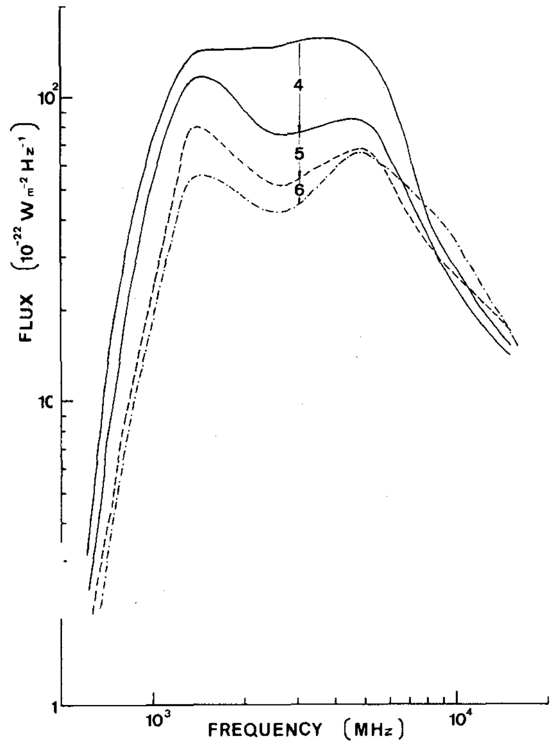

Figure 4B - Successive spectra of the August 21, 1968 event during the fall period of the first component observable at 1,415 MHz.

5. Decay Phase

The energy loss rate by synchrotron radiation given by $\dot{E}_{synchr}$ (eV s^{-1}) $= - 4 \times 10^{-15} B_{\perp}^2 E^2$ (Ref. 42) is proportional to E^2. So, when the gain exceeds the loss, the radiation increases because the net gain also increases. But when the acceleration stops (apparently before the electrons reach the maximum critical energy E_{max}) the radiation loss continues to be very efficient, and the net gain becomes suddenly negative. Thus, the particles energy is maximum just at the time when the acceleration stops. Since the synchrotron flux is proportional to NE^2, the burst peak must occur at about the time when the acceleration stops. In other words, at the peak, the net value of $\dot{E}_{Fermi} + \dot{E}_{synchr}$ is zero, being positive before and negative after. As a result, some storage of particles energy must occur, corresponding to the net gain of energy during the rise-time. The time profile of the radio bursts, at a fixed frequency, leads us to conclude that the integrated flux satisfies the inequality

$$\int_{start}^{peak} S_f\,(t)\,dt < \int_{peak}^{end} Sf\,(t)\,dt.$$

The energy released in the second half is the energy stored and the above inequality shows that the stored energy exceeds the radiated one in the first half of the burst. This implies that the energy gain by the Fermi mechanism exceeds the synchrotron losses. The ratio between both processes is

$$\frac{5 \times 10^7}{E\ (\mathrm{eV})}$$

Even for E $= 10^6$ eV this ratio is about 50. At lower energies, ($\approx 10^4$ eV) the storage is more effective.

After the peak the spectrum shows an almost flat plateau between the cutoffs on both sides (see Figure 4B). This flat portion comes down with time in a quite different way compared to the rise phase. Since $a = 0$, we have $\gamma = 1$. There is a high frequency cutoff due to the high-energy cutoff of the electrons. This cutoff decreases as expected. The low frequency cutoff in Figures 1B, 3B and 4B appears to indicate synchrotron self-absorption with spectral index 2.5, decreasing and keeping almost constant slope. It appears that, rather than Razin effect, self-absorption occurs, which requires a decrease in the electron density. We have to admit that the expansion of the emissive plasma during the fall phase decreases the electron density and masks any eventual mechanism of condensatíon. Therefore, the photon-field interacts now with a more rarefied plasma.

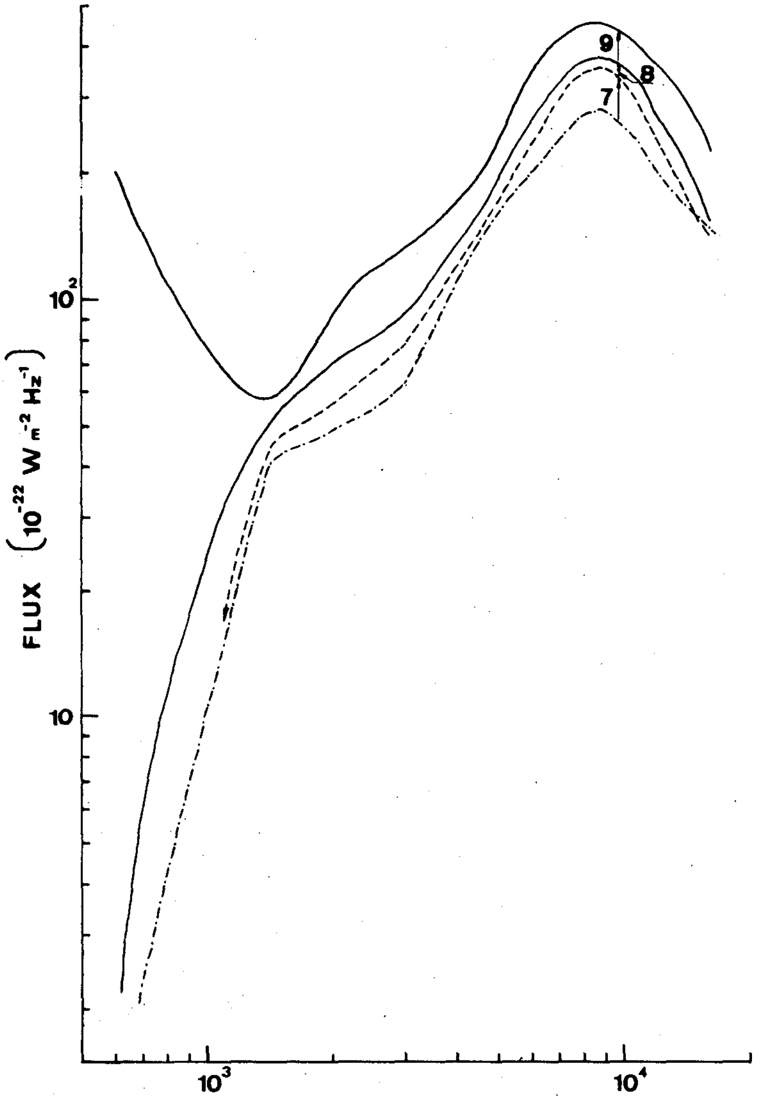

Figure 4C - Successive spectra of the August 21, 1968 event during the rise time of the second component.

During the decay phase, the flare volume refers to the volume of energetic electrons and must be in agreement with the observation of flare-expansion, greater in the direction perpendicular to the solar surface than in the projected area[5]. This volume contains also the thermalized particles which were accelerated in the rise-time and lost through the magnetic necks. The synchrotron emission during this period is smaller than that in the first half of the burst, a fact which indicates the absence of an acceleration mechanism. Now the emitting energy is that stored before. Just after the peak, the decrease is constant in the frequency bandwidth, which agrees with the synchrotron theory when $\alpha = 0$ and $\gamma = 1$, that is

$$\Delta S \propto f^0.$$

In this period the losses are still mostly due to the synchrotron radiation, since there was no time for the thermalization of the electrons energy. The spectrum does not show a sharp decrease at high-frequencies, a characteristic of the predominance of emission from a cooling thermal plasma. After Spitzer[38], the relaxation time for this thermalization process is the self-collision time t_c. Let us consider a plasma totally confined in a magnetic field with supra-thermal energies. The accelerated electrons coexist with thermal electrons (10^6 °K). This anisotropic distribution tends towards a Maxwell-distribution in a time $t_c \approx 10^2$ s. This estimate agrees with the observed times in which the spectrum changes (about 1.5 min after the peak).

At later stages of the decay phase the flux decreases at lower frequencies with the law of free-free emission of a thick plasma, $\Delta S \propto f^2$, (see Figure 2B) and at higher frequencies, where the plasma is optically thin, with the law $\Delta S \propto f^0$ (see Figure 2B and 4D). The transition frequency for thin to thick plasma ranges between 3,000 and 4,000 MHz. The optical thickness is about unity in this range. Since the equipartition time is short ($t_E = 3 \times 10^{-2}$ sec), let us suppose $T = 10^6$ °K (corona temperature). Thus, the expression for the unity optical depth $N^2h/(f^2\, T^{3/2}) = 1$ [$N(\mathrm{cm}^{-3})$, f(Hz) and T(°K)] gives us a geometrical depth $h \approx 10^9$ cm. But when this plasma started to emit strongly the free-free radiation, its temperature was about 10^8 °K. This temperature decreased to the corona temperature of 10^6 °K in a quite short time. Therefore, the small and almost constant flux of radiation observed at different frequencies in the later phases of the flare should be due to an enhancement of the emission measure $\int N^2 dh$, where h is the geometrical depth of the emitting region. How was the electron density enhanced?

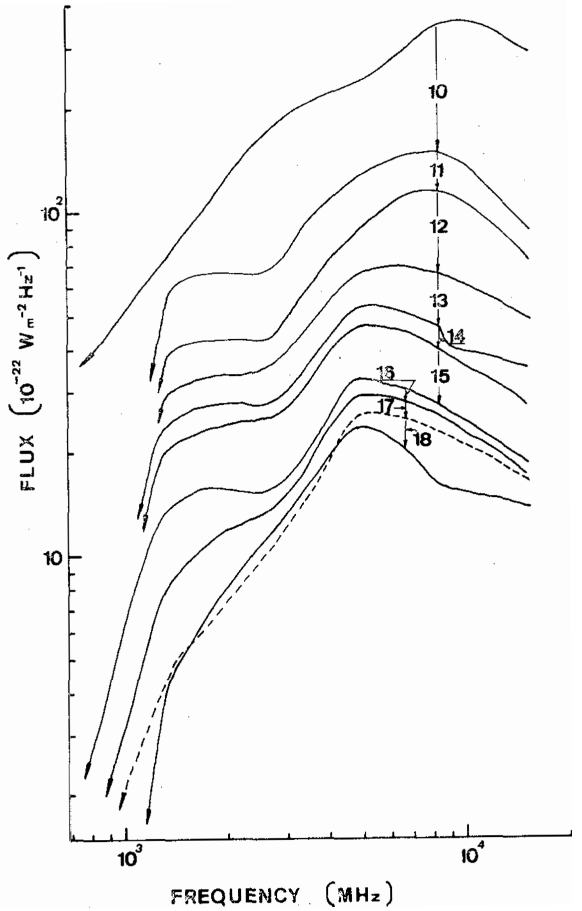

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Figure 4D - Successive spectra of the August 21, 1968 cvent during the fall phase of the second component.

6. Radiative Instability

When the temperatures become equal for the ambient plasma and for the flaring plasma, taking into account the plasma diamagnetism, the pressures are such that

$$N_f\, k\, T_f = N_a\, k\, T_a + \frac{B_a^2}{8\pi},$$

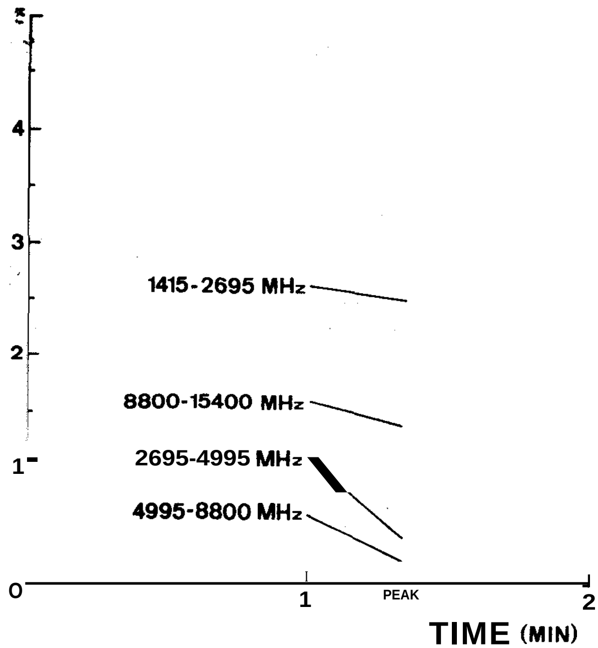

Figure 5 - Values of the spectral index a for different ranges of frequencies. The start time zero refers to the beginning of the optical flare and the peak corresponds to the maximum of the burst.

where the indices f and a refer to the flaring and ambient plasma $T_f \approx T_a$, since the heat transfer is more effective than the particle-diffusion. Thus, the condensed plasma could expand from its magnetic confinement or falls down under gravity. At this point, the mechanism appears to be that invoked for interpreting Simple 1 or Simple 3 bursts'.

We do not know if due only to this mechanism the flaring plasma is dense enough and stable as required, or if some special mechanism must be invoked for explaining a density enhancement. For example, Manley and Olbert[43] presented a way for estimating the parameters of a radiative instability while deriving a X-ray star model. The cooling rate $\dot{T}$ is more controlled by the electron density gradient than by the temperature gradient. When the plasma radiates strongly by synchrotron process, an instability sets in corresponding to a fast densification of the plasma. The characteristic size L (cm) of the condensed matter is given by

$$L^2 < 3 \times 10^{11} K \frac{T^{1/2}}{N^2 k},$$

where K (cal °K^{-1} cm^{-1} s^{-1}) is the thermal conductivity, k (erg °K^{-1}) is the Boltzmann's constant. The lowest estimated value of the right hand side in the above inequality is 1.5 x 10^{19} cm^2, so that L must be shorler than 4 x 10^9 cm. Considering that the thermal conductivity perpendicular to a magnetic field is by far smaller than the parallel one, the calculated upper-limit could be smaller in the above inequality. The low-frequency cutoff firstly ascribed to the Razin effect and after to self-absorption, does not appear to be affected by an electron density increase due to the radiative instability because this instability occurs about 2 min after the peak.

Another very peculiar feature is observed in the event on August 8, 1968. Absorption was observed at 606 MHz, beginning during the rise, lastirig about 10^3 sec and reaching a maximum about the time when the thermal Bremsstrahlung starts to be strong. The only reasonable explanation could be the backscattering of radiation due to a condensation arising in a high coronal level, in which the plasma frequency exceeds the frequency of the radiation emitted by the underlying plasma. These absorptions can sometimes occur even associated with small flares and surges', which agrees also with the above description. This is not in contradiction with the excess of emission observed at higher frequencies, since at these frequencies the plasmoid becomes optically thin. The emission is due to an excess of electron density, as theoretically expected (see Figures 2B and 4D). This event should show that either some dense plasmoid reaches the level of the critica1 frequency.

7. Conclusions

It is shown that Snijders[3] theoretical description of radiative losses is approximately correct. The evolutionary study of impulsive bursts shows important details of the whole development of this class of events. But better time resolution on radio bursts records would improve the quantitative analysis, helping for a better description of the relaxation times, Razin and self-absorptive effects, power-law indices, emitting volume and densities. The Vesecky and Meadows' models of flare expansion could be tested. The derivation of spectra from peak values is criticized; the concept of impulsiveness (I) acquires a deeper meaning if connected with the observed frequency. The acceleration mechanism has to fit the observed spectral data. It appears that impulsive events are very indirect manifestations of instabilities. There is an intervening shock and there are in *situ* physical parameters, mostly the magnetic field configuration, predetermining the burst. Further work is needed to clarify the correlations which exist between flare type and frequency, f_m.

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