

## **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.

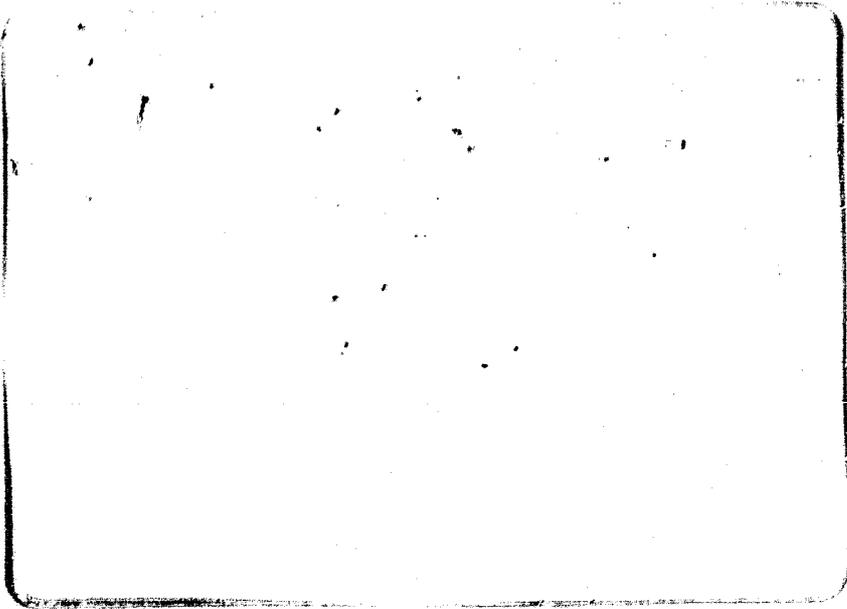


SECRETARIA DE PLANEJAMENTO DA PRESIDÊNCIA DA REPÚBLICA  
CONSELHO NACIONAL DE DESENVOLVIMENTO CIENTÍFICO E TECNOLÓGICO

(NASA-TM-85427) MULTIPLE ENERGETIC  
INJECTIONS IN A STRONG SEIKE-LIKE SOLAR  
BURST (NASA) 40 p HC A03/MF A01 CSCL 03B

N83-35983

Unclas  
G3/92 36676



~~RECEIVED BY  
NASA STI FACILITY  
DATE: 10-6-83  
DCAF NO. 02949  
PROCESSED BY  
 NASA STI FACILITY  
 ESA-SDS  NAA~~



INSTITUTO DE PESQUISAS ESPACIAIS

1. Publication N <sup>o</sup> <i>INPE-2860-PRE/397</i>	2. Version	3. Date <i>August, 1983</i>	5. Distribution <input type="checkbox"/> Internal <input checked="" type="checkbox"/> External <input type="checkbox"/> Restricted
4. Origin <i>CAS</i>	Program <i>RADIO</i>		
6. Key words - selected by the author(s) <i>SOLAR BURSTS-HARD X-RAY, SOLAR BURSTS-MM-MICROWAVES, MULTIKERNEL BURST EMISSION, ULTRAFAST BURST STRUCTURES, ENERGY RELEASE MODELS</i>			
7. U.D.C.: <i>523.745</i>			
8. Title <i>MULTIPLE ENERGETIC INJECTIONS IN A STRONG SPIKE-LIKE SOLAR BURST</i>		10. N <sup>o</sup> of pages: <i>39</i>	
		11. Last page: <i>26</i>	
		12. Revised by  <i>Pierre Kaufmann</i>	
9. Authorship <i>P. Kaufmann E. Correia J.E.R. Costa B.R. Dennis* G.H. Hurford** J.C. Brown***</i>		13. Authorized by  <i>Nelson de Jesus Parada</i> General Director	
Responsible author <i>Pierre Kaufmann</i>			
14. Abstract/Notes - <i>An intense and fast spike-like solar burst was observed with high sensitivity in microwave and hard X-rays, on December 18, 1980, at 19h 21m 20s U.T. It is shown that the burst was built up of short time scale structures superimposed on an underlying gradual emission, the time evolution of which showed remarkable proportionality between hard X-ray and microwave fluxes. The finer time structure were best defined at mm-microwaves. At the peak of the event the finer structures repeat every 30-60 ms, (displaying an equivalent repetition rate of 16-20 s<sup>-1</sup>). The more slowly varying component with a time scale of about 1 second was identified in microwave and hard X-rays throughout the burst duration. Similarly to what has been found for mm-microwave burst emission, we suggest that X-ray fluxes might also be proportional to the repetition rate of basic units of energy injection (quasi-quantized). We estimate that one such injection produces a pulse of hard X-ray photons with about 4 x 10<sup>21</sup> erg, for ε &gt; 25 keV. We use this figure to estimate the relevant parameters of one primary energy release site both in the case where hard X-rays are produced primarily by thick-target bremsstrahlung, and when they are purely thermal, and also discuss the relation of this figure to global energy considerations. We find, in particular, that a thick-target interpretation only becomes possible if individual pulses have durations larger than 0.2s.</i>			
15. Remarks <i>Submitted to Solar Physics. Supported partially by FINEP. *NASA/GSFC, **CALTECH, ***Univ. Glasgow.</i>			

## MULTIPLE ENERGETIC INJECTIONS IN A STRONG SPIKE-LIKE SOLAR BURST

P. KAUFMANN, E. CORREIA and J.E.R. COSTA

*INPE: Instituto de Pesquisas Espaciais, CNPq, C.P. 515, 12200,  
São José dos Campos, SP, Brazil.*

B.R. DENNIS

*Laboratory of Astronomy and Solar Physics, Solar Activity Branch  
NASA-Goddard Space Flight Center, Greenbelt, MD 20771, USA*

G.H. HURFORD

*California Institute of Technology, Owens Valley Radio Observatory  
Pasadena, CA 91125, USA*

and

J.C. BROWN

*Department of Astronomy, The University, Glasgow G12 8QQ, U.K.*

**ABSTRACT** - An intense and fast spike-like solar burst was observed with high sensitivity in microwaves and hard X-rays, on December 18, 1980, at 19h 21m 20s U.T. It is shown that the burst was built up of short time scale structures superimposed on an underlying gradual emission, the time evolution of which showed remarkable proportionality between hard X-ray and microwave fluxes. The finer time structures were best defined at mm-microwaves. At the peak of the event the finer structures repeat every 30-60 ms, (displaying an equivalent repetition rate of 16-20 s<sup>-1</sup>). The more slowly varying component with a time scale of about 1 second was identified in microwaves and hard X-rays throughout the burst duration.

Similarly to what has been found for mm-microwave burst emission, we suggest that X-ray fluxes might also be proportional to the repetition rate of basic units of energy injection (quasi-quantized). We estimate that one such injection produces a pulse of hard X-ray photons with about  $4 \times 10^{21}$  erg, for  $\epsilon \gtrsim 25$  keV. We use this figure to estimate the relevant parameters of one primary energy release site both in the case where hard X-rays are produced primarily by thick-target bremsstrahlung, and when they are purely thermal, and also discuss the relation of this figure to global energy considerations. We find, in particular, that a thick-target interpretation only becomes possible if individual pulses have durations larger than 0.2s.

#### 1. OBSERVATIONS OF THE SOLAR BURST OF 18 DECEMBER 1980, 1921:20 UT.

An intense spike-like burst was observed on 18 December 1980, 1921:20 UT, at various energy ranges, by several space and ground-based observatories (NOAA, 1981). It corresponded to an SN optical flare that occurred in NOAA region 2840 at a location of N07 W11. Hard X-ray data with high sensitivity and time resolution were obtained by the Hard X-ray Burst Spectrometer (HXRBS) on the Solar Maximum Mission (SMM) satellite, (Orwig et al., 1980; Dennis et al., 1982). High sensitivity and time resolution mm-microwave data were obtained with the Itapetinga 14-m antenna, at 22 GHz and 44 GHz (Kaufmann et al., 1982a), and cm-microwave data were obtained with the Owens Valley interferometer, at 10.6 GHz (Zirin et al., 1978).

In Figure 1 we show the hard X-ray burst in five energy

ranges. In Figure 2 we show the same event at 44 GHz, 22 GHz and 10.6 GHz.

"Slow" time structures, with a time scale of about one second are observed throughout the burst duration. They are particularly well defined at 44 GHz and in the hard X-ray plot but they are smoothed out at lower microwave frequencies. A very similar burst was obtained by HXRBS on March 29, 1980 at 0918 UT (Dennis *et al.*, 1981). It presented a e-folding rise and fall time of  $\sim 2$ s, hard spectrum, and multiple time structures at the peak.

## 2. ULTRAFast TIME ANALYSIS AT MM-MICROWAVES

The 22 GHz and 44 GHz flux data have a  $3\sigma$  detection limit of about 0.03 s.f.u. and time resolution of about 1 ms (Kaufmann *et al.*, 1982a). The burst flux rise implies in a growth of the system noise, and therefore the minimum detection limit at the peak of the event becomes about 0.3 s.f.u. at 22 GHz, and of about, 0.05 s.f.u. at 44 GHz (Kaufmann *et al.*, 1982a). The time profiles shown in Figure 2 have been expanded for the major time structure at the peak of the burst (1921:19 - 1921:20UT), and are reproduced again in Figures 3 and 4. At the time of maximum flux, a "ripple" is observed with a peak-to-peak flux  $\Delta S$  of about 2.9 s.f.u. at 22 GHz, and 0.2 s.f.u. at 44 GHz. These values are very small compared to the total flux  $S$ , with  $\Delta S/S \sim 0.01$  both at 22 GHz and at 44GHz but they are, however sufficiently large to be measurable. The structures correlated at 22 GHz and 44 GHz are nearly "in phase", within about 10 ms.

Counting 10-12 spikes in the peak time duration of about 0.6 sec, implies in a repetition rate of about  $16-20 \text{ s}^{-1}$ . This rate at the peak would correspond to a 22 GHz flux  $\geq 100 \text{ s.f.u.}$ , according to the correlation flux vs. repetition rate established for various burst by Kaufmann et al., (1980). This value in fair agreement with observations taking into account the number of uncertainties involved in the determination of the absolute flux scale when using large antennas.

Instrumental or observational effects were considered, and they cannot account for the ultrafast time structures found in solar burst. The obtention of larger repetition rates for larger fluxes in a solar burst constitute a trend that cannot be explained as an experimental effect. The ultrafast time structures are not found when tracking the solar limb or active centers. Atmospheric turbulence may produce fluctuations in clear sky conditions in rare occasions. They have a much slower time scale ( $>$  seconds). Subsecond structures would imply in atmospheric inhomogeneities moving at supersonic speeds, which is unrealistic.

The tracking accuracy of the Itapetinga antenna (less than 2 arcsec, r.m.s.) can be determined by tracking the solar limb and more accurately by measuring the tachometers' loops during tracking. The time scale is again slower than the sub-second structures observed. The antenna structure has a mechanical resonant frequency of about 2 Hz. The main reflector cannot respond to subsecond vibrations. The Cassegrain subreflector may oscillate or vibrate at a higher rate. This, however, was not observed in laser beam experiment, which has shown a maximum

subreflector lateral displacement of 5mm from 10-75 degrees in elevation, in a smooth displacement with elevation. The effects of subreflector lateral displacement on gain were analysed by Predmore (1978) and Zarghamee (1982) for Cassegrain optics identical to Itapetinga antenna. Any gain change produced by lateral displacement of the subreflector must be 2-4 times larger at 44 GHz compared to 22 GHz, which is not observed in the sub-second structures. The estimates depend on how well the subreflector was aligned and the peak gain will change with elevation (Zarghamee, 1982). A peak gain change one percent (at a 70db level) would imply in a variation in elevation angle larger than 30 arcsec, which is unrealistic for the Itapetinga antenna. On the other hand, estimates of relative gain variation due to subreflector lateral displacement, derived by Predmore (1978), predict a 5mm displacement for one percent gain variation at 22 GHz, corresponding to four percent change of gain at 44 GHz. For obtaining a 5mm displacement of the subreflector, however, the antenna should move from elevations 10-75°. For a two arcsec movement (or oscillation) we might predict a subreflector displacement of about  $10^{-5}$  mm, which is beyond any possibility of measurement. If the antenna is mispointed to the burst source, the gain variations due to one of the causes indicated above, become more pronounced. But still the effects should be significantly larger at 44 GHz (which was not observed), and implying in amplitude of mechanical vibrations not attained by the system. We can therefore conclude that the observed sub-second time structures in solar bursts cannot be explained by observational effects.

### 3. OVERALL BURST CHARACTERISTICS

Some other overall burst characteristics, which are relevant to the present study, are now described. These show the complexity of high sensitivity and high time resolution data in relation to the spike-like and smoothed out burst observed by other methods. The microwave radio spectrum at peak emission was derived using additional data from Sagamore Hill radio-observatory (NOAA, 1981; Cliver, 1981) and Huancayo Observatory (Ishitsuka, 1981) (Figure 5). The time resolution and absolute timing accuracy of these measurements obtained by patrol telescopes are poorer than about one second. The time profiles indicate a featureless spike and a rather typical spectrum, with a relatively high turnover frequency at about 15 GHz. At frequencies below 1.4 GHz the spectrum rises and the burst splits into major time structures of different morphology (Cliver, 1981). At dm- and longer wavelengths the radio emission arises higher in the corona and will not be discussed here.

The hard X-ray photon energy spectrum, obtained for the peak emission (1921:18.83 - 1921:19.98 UT) shows a rather hard spectrum, fitting either a power-law plot with  $\gamma \approx 3.2$  or a thermal curve with  $T \approx 6.1 \times 10^8 \text{K}$ .

The Owens Valley 10.6 GHz data, with a time resolution of about 100 ms and a detection limit of about 0.15 s.f.u., also provide information on circular polarization and on the burst source position. In Figure 6 we show the right- and left-handed circularly polarized output (in relative units) as well as the time variation of the

polarization degree. The 10.6 GHz interferometer phase data indicated that the burst source position remained fixed 1 arc second (one dimension), throughout the burst duration. The relatively slow decrease of polarization degree with the increase in flux is a quite well known trend (Kaufmann and Santos, 1973; Steffen, 1975; Kane et al., 1983). The still limited time resolution, however, prevents us from detecting very fast polarization changes of the type reported by Kaufmann et al., (1983b).

The high frequency microwave spectral index  $\alpha (S \propto f^\alpha)$  can be derived from the two highest microwave frequencies 22 GHz and 44 GHz, which are assumed to be both in the optically thin part of the gyrosynchrotron emission spectrum (Takakura, 1972; Dulk et al., 1979). From the data shown in Figures 2 and 5, we obtain a spectral index of about  $\alpha_{44-22} \sim -4.5$  at the peak of the event. From other data shown in Figure 5, this index can be  $< -4.5$  for 35 and 44 GHz.

The time variation of the underlying burst emission showed remarkable proportionality between microwaves (for  $f > 15$  GHz) and hard X-rays. This is illustrated in Figure 7, for the rise-and-fall phases of the event, at 22 GHz and hard X-rays ( $\epsilon \gtrsim 26$  keV). The half-width durations of the burst, however, display a marked reduction towards higher microwave frequencies (Figure 8). At frequencies larger than the turnover frequency ( $\sim 15$  GHz) the rise-and-fall spike half-width duration approaches 3-4 seconds comparable to the half-width duration in hard X-rays which is similar for all the various energy ranges, within the noise of the measurements.

#### 4. INTERPRETATION ON THE FAST FINE STRUCTURES

The overall characteristics of a relatively simple spike-like solar burst (traditionally classified as a "Simple 2" burst) can be more or less interpreted by means of existing models (Takakura, 1972; Crannell et al., 1978; Dulk et al., 1979; Mätzler et al., 1979). Analysis, however, becomes complicated with the evidence of superimposed rapid fluctuations in emission.

Brown et al (1980) have suggested that X-ray emission of an apparently featureless burst could be conceived as the convolution in time and space of the production of many short lived kernels, which were not resolved in time due to the limitations in instrumental time resolution. For any multikernel model, the emitted flux can be represented by an integral of the form (Brown et al., 1980).

$$I(\epsilon, t) = \int_K Q_K(t) U_K(\epsilon) dK \quad (1)$$

where  $U_K(\epsilon)$  is a pulse of emitted photons by one kernel,  $K$  is a set of kernel parameters, and  $Q_K$  is the rate of production of kernels per unit  $K$ . For a given kernel emission function  $U_K(\epsilon)$ , different kernel production function  $Q_K(t)$  can produce a wide variety of temporal and spectral forms in the time smoothed total emission  $I(\epsilon, t)$ .

Using this assumption, Brown et al., (1980) reconciled the suggested proportionality between emission measure and temperature in the thermal model (Crannell et al., 1978; Mätzler et al., 1979) with multiple emitting kernels, impulsively heated and cooled by anomalous conduction, according

to the mechanism suggested by Brown et al.; (1979). Brown et al., (1983) have given a similar interpretation of frequency dependent delays in microwave bursts.

We propose to identify the ultrafast time structures reported here with time resolved emission from such individual kernels. Such multiple energy release sites should be present, at various repetition rates, according to a variety of mechanisms for primary energy release in flares (eq. Gold and Hoyle, 1960; Fùth et al., 1963; Kuperus 1976). The apparent observation of distinct fast and ultrafast time scales might then be associated with a hierarchy of unstable scale sizes or wavelengths in such mechanisms. If this broad picture is correct then the overall mm-microwave flux level (so far called the "underlying" flux) could in fact have an important contribution from the kernels themselves which, in the short time scales involved, would lead to extremely high radio brightness temperature (Kaufmann et al., 1982b) for which there is some evidence - eg. values exceeding  $10^8$  K for cm-microwave bursts observed by interferometers (Kundu, 1980; Marsh et al., 1980). Then, the overall fluxes in microwaves and hard X-rays should be described as being approximately proportional to the convolution in space and time of multiple primary energetic injections.

According to Kaufmann et al. (1980), 22 GHz bursts are build up from discrete primary bursts (quasi-quantized), the energy content of each of which is roughly independent of the overall burst flux. The overall flux is then chiefly determined by the production rate of sources of such primary bursts, i.e., by the repetition rate R.

A similar conclusion was obtained independently from the statistical analysis of a large collection of soft X-ray bursts (Kaufmann et al., 1978). The overall flux vs R trend was also verified for several bursts observed at another microwave frequency, but at a larger time scale (Wiehl and Matzler, 1980), and in a burst observed simultaneously at hard X-rays, UV and 22 GHz (Tandberg-Hanssen et al., 1983). Ultra-fast time structures at hard X-rays were identified by several authors (Dennis et al., 1981; Charikov et al., 1981; Kiplinger et al., 1983). Charikov et al., (1981) indicate that the ultra-fast time structures at hard X-rays have similar characteristics of the structures found at mm-microwaves by Kaufmann et al., (1980). Simultaneous observations of ultra-fast time structures at mm-microwaves and hard X-rays were recently obtained (Takakura et al., 1983) suggesting a nearly one-to-one correspondence of the structures.

The fact that the index  $\gamma$  remained nearly constant during the fast rise and fall of the spike studied here (Figure 9) lends further support to the idea that the event comprises superposition of basic primary injections of similar nature, at various repetition rates.

Such a situation implies that, in the proposed model, all the kernels are described approximately by taking a Delta function distribution of K in Equation (1) and replacing

$$\int_K Q_K(t) dK = R(t) \quad (2)$$

Then the overall radio flux will be

$$S(f, t) \approx R(t) U_R(f) \quad (3)$$

The excellent correspondence found for ultrafast structures at hard X-rays and microwaves (Takakura et al., 1983) strongly suggest that both have a common origin and that we should therefore also write the hard X-rays overall fluxes as

$$I(\epsilon, t) \approx R(t) U_X(\epsilon) \quad (4)$$

where each kernel is characterized by a typical amount of photon emission  $U_R(f)$  in microwave and  $U_X(\epsilon)$  in X-rays with  $U_X = U_R$ .

In hard X-rays, the observed energy spectrum at maximum, for  $\epsilon \gtrsim 25$  keV, provides  $I(25) \sim 600$  photons  $\text{cm}^{-2} \text{s}^{-1}$  which, for a repetition rate of, say  $R(t) = 16 \text{ s}^{-1}$  implies  $U(25) \approx 33$  photons  $\text{cm}^{-2}$ . At the Sun the number of  $> 25$  keV photons emitted becomes  $n_X(25) \sim 10^{29}$  photons and the total energy in 25 keV photons is

$$E_X(25) = n_X(25) \times \epsilon \text{ (erg)} \sim 4 \times 10^{21} \text{ erg} \quad (5)$$

##### 5. PHYSICAL CONDITIONS IN ENERGY RELEASE SITES

Here we consider the implications for flare plasma parameters of interpreting the ultrafast structures reported above in terms of successive emissions from a rapid series of primary energy release events. We will use the hard X-ray flux to indicate the total

electron energy requirements and the microwave data to define the required time scales. Since the total electron energy needed to produce a specified number of photons by bremsstrahlung is strongly dependent on the degree of relaxation of the source (cf. Brown and Smith 1980), we will consider here two limiting cases of a purely thermal model and of a thick-target model. The former is essentially the model proposed by Brown et al. (1980) in which the energy release events result mainly in plasma heating. The latter corresponds to a case in which most of the hard X-rays come from a thick-target stream of electrons originating in a rapid series of energy release events resulting in electron acceleration.

We have already noted that to produce the observed mean hard X-ray flux ultrafast structures with a repetition time  $\tau \approx 60\text{ms}$  requires the emission of about  $10^{29}$  photons above 25 keV from each energy release site. Since the relative amplitude of the ultrafast 'ripple' is only  $\Delta \approx 10^{-2}$ , the lifetime  $T$  of each site must be substantially longer than  $\tau$ . The exact relationship between  $T$ ,  $\tau$  and  $\Delta$  depends somewhat on the time profile of an individual burst. We have considered in detail the case of superposition of a long series of symmetric pulses with triangular time profiles of base length  $T$  and regular  $\tau$  and find that for  $T/\tau \gg 1$ , the resulting ripple of spacing  $\tau$  has relative amplitude  $\Delta \approx \tau^2/2T^2$ . A roughly similar result is to be expected from addition of pulses of different shape (e.g. gaussian) but the same half-width (cf.(c) below). For triangular pulses to reproduce the observed case of  $\Delta \approx 10^{-2}$  with  $\tau \approx 60\text{ ms}$  implies  $T = 400\text{ ms}$  or a half width for each emission process of  $t_0 \approx T/2 = 200\text{ ms}$ .

Together with the X-ray flux and spectrum,  $t_0$  enables us to place useful constraints on plasma parameters required for both the thick-target and thermal cases. In each we characterize the energy release site by a size  $L = 10^8 L_8$  cm, a density  $n = 10^{10} n_{10}$  cm<sup>-3</sup>, and a magnetic field  $B = 10^2 B_2$  gauss.

(a) Thick-Target Case

We assume that only collisional losses from the non-thermal electrons are important, neglecting return current losses (cf. Emslie, 1979; Brown and Hayward 1982) and wave generation (cf. Hoyng et al., 1978; Smith and Emslie, 1983). Inclusion of these would only enhance the conclusions we reach below. The emission of  $n_{25}$  photons of  $\epsilon > 25$  keV with power-law flux spectrum of index  $\gamma$  is then attributed to the collisional thick-target emission from injection of a pulse of  $N_{25}$  electrons with spectral index  $\delta = \gamma + 1/2$ . These are related by integrating along the electron path in a fashion similar to that used by Brown et al (1980) (their equations (25) - (37) for an injected Maxwellian tail). With Kramer's cross-section, the present case gives

$$n_{25} \approx 10^{-5} N_{25} / \gamma^2 (\gamma - 1)^2 \quad (6)$$

From the observed X-ray flux we found  $n_{25} = 10^{29}$  and from the spectrum  $\gamma = 3.2$ , so (6) implies  $N_{25} = 5 \times 10^{35}$  electrons, or a total energy  $E_{25} = 2 \times 10^{28}$  ergs in one pulse.

To supply this much energy by magnetic field annihilation requires at the very least that  $B^2 L^3 / 8\pi > E_{25}$  or

ORIGINAL PAGE IS  
OF POOR QUALITY

$$B_2 \cdot L_8^{3/2} > 7$$

(7)

(even if most of the field is annihilated and most of the energy goes into accelerated electrons).

Secondly, in order that this energy be release fast enough to be consistent with the observed characteristic lifetime  $t_0$  of a single ultrafast structure demands at the least that  $L/V_A < t_0$ , where  $V_A$  is the Alfvén speed, or

$$\frac{B_2}{n_{10}^{1/2} L_8} > 2.3 \quad (8)$$

for the  $t_0 = 200$  ms obtained above for triangular pulses.

Thirdly, to provide a sufficient supply of beam electrons we must impose the requirement that the neutralizing return current established in the ambient plasma should be stable (cf. Hoynig et al., 1976; Brown and Melrose, 1977). This means that the beam flux  $= N_{25}/L^2 t_0$  should not exceed the ambient density times a multiple  $\leq 10$  times the ion-speed  $(kT_e/mp)^{1/2}$ . Taking  $T_e = 10^7$  K as a maximum plausible temperature in the ambient plasma, we find with the above  $N_{25}$  and  $t_0$  that stability requires

$$n_{10}^{1/2} L_8 \geq 9 \quad (9)$$

Together with (8) this would imply  $B_2 > 21$  or fields exceeding 2000 gauss which is unacceptably high even for the most optimistic case of inequality (8). The further requirement that  $L_8 < 1$  in order to keep the total

volume of the many dissipation sites within reasonable limits also demands high fields by (7) but this requirement is the less severe of the two.

It appears then that a thick-target model in which the ultrafast structures we observe are associated directly with electron acceleration events by field annihilation can be excluded at least for triangular pulses (cf.(c)below). Physically this is because the required smallness of the Alfvén travel time is incompatible with an annihilation site large or dense enough for return current stability. (The present analysis does not, however, exclude alternative thick-target interpretations in which electrons are accelerated over larger volumes and times but are dumped into a thick-target region by some process such as loss cone instability in times associated with our ultrafast structures).

(b) Thermal Model

Brown and Hayward (1981) have pointed out that if Maxwellian tail electrons escape continuously from a very hot thermal hard X-ray source, the thermal model is energetically equivalent to a thick-target model with acceleration, and so would be unacceptable here for the same reasons as in (a). If, however, the tail never forms or is somehow prevented from escaping, or is lost immediately, the thermal model can emit mainly by thermal bremsstrahlung and have a cooling rate determined only by extension at the ion sound speed by anomalous conduction. We therefore consider here only this most efficient limiting case.

If we suppose that annihilated field energy in one event goes entirely into thermal energy of the plasma, the temperature  $T_{\max}$  attained will be

$$T_{\max} \approx B^2 / 8\pi n k \quad (10)$$

It follows from (10) that the ion-sound speed after the heating will be comparable to the Alfvén speed during the heating. Thus to ensure that the heated region has both heating and cooling time of the same order as the characteristic time  $t_0$  of a dissipation region inferred above from the observations, it is sufficient to impose the same condition (8) as in the thick-target case. To obtain a temperature high enough ( $> 3 \times 10^8 \text{K}$ ) to fit the X-ray spectrum, however, (10) imposes the further condition that

$$\frac{B_2}{n_{10}^{1/2}} \geq 1 \quad (11)$$

Next, we find by integrating Equation (33) of Brown et al. (1980) over  $\epsilon > 25 \text{ keV}$  that to emit  $n_{25} \approx 10^{29}$  photons during its lifetime with peak temperature as above, the thermal source parameters must satisfy

$$n_{10}^{1/2} L_8 \approx 1.5 \quad (12)$$

The combination of conditions (8) and (12) then give

$$B_2 \approx 3.5 \quad \text{or} \quad B \approx 350 \text{ gauss}$$

which is quite plausible. If, for example, we take  $B \sim 500$  gauss then (11) would imply  $n < 2.5 \times 10 \text{ cm}^{-3}$  and (12) that  $L \geq 300$  km which are physically plausible, consistent with the presence of many dissipation sites within a reasonable total volume, and comparable with parameters in flare models such as that of Spicer (1977) (cf. Section 6).

(c) Effect of varying pulse shape

We must emphasize that simulation of the ultrafast "ripple" by addition of pulses of shape other than triangular can lead to a different estimate of  $t_0$ . In particular a sharper pulse shape like  $\exp[-a|t|^b]$  can give  $\Delta = 10^{-2}$  for half width  $t_0$  of order 1 second (Correia, 1983). Then for the thick-target interpretation we get  $B \geq 450$  gauss and for the thermal model,  $B \geq 75$  gauss. Either of these is physically possible through the thick-target requirement is much more severe.

6. CRITICAL MACROSCOPIC PRIMARY ENERGY RELEASE CONDITION

It is not appropriate here to enter into details of how the multiple energy release sites arise in terms of basic plasma physics. However we note that formation of smaller scale explosive magnetic islands, as a consequence of larger scale tearing mode phenomena, has been discussed (Samain 1976; Spicer 1977; 1981). The mechanism, based on magnetohydrodynamic conditions described by Fürth et al., (1963), was recently analysed by Spicer (1981). Initial reconnections can generate primary magnetic islands. Mode coupling

between islands may cause other perturbation vectors which, in turn, generate secondary islands. There is then an increase in the number of magnetic neutral points; and an increase in the number of resulting explosions, in time scales fast enough to be comparable to results found in the present paper. We may suggest qualitatively that the repetition rates of the observed ultrafast time structures would depend, for example, on the spectrum of tearing modes and on the effectiveness of mode coupling set in at a given magnetic topology, peculiar to a given active region where the solar burst occurs. It remains to be seen, however, whether certain critical conditions needed to produce a transient burst might be nearly independent of the particular magnetic topology, which would be required to account for the apparently nearly constant energy content of each primary injection (i.e., quasi-quantization).

On the other hand, it has been recently investigated by Sturrock et al., (1982) that the multiple structures found in the impulsive phase of bursts may arise from explosions of an aggregation of filaments or "fluxules" which could be quasi-quantized in magnetic flux. We might take a macroscopic description of a magnetic loop instability, in relation to the results obtained in this study. For example it has been shown that the free magnetic energy developed in a loop twisted at the magnetic spots, can be represented by (Sturrock and Uchida 1981):

$$\Delta' = \frac{\Phi (\Delta\chi)^2}{16\pi^2 L} \quad (11)$$

where  $\Phi$  is the magnetic flux,  $L$  is the loop length and  $\Delta\chi$  the amount of differential twist. It has been shown that the tube becomes unstable

for a differential rotation  $\Delta\alpha$  exceeding  $\pi$  rad (Barnes and Sturrock 1972).

The magnetic flux is  $\Phi = B \times \pi \ell^2$ , where B is the magnetic field; and  $\ell$  is the loop radius. The total loop volume is approximately  $V_t \approx \pi \ell^2 L$ . The free magnetic energy available for a tube submitted to a critical differential twist  $\Delta\alpha \approx \pi$  rad becomes

$$\Delta' \approx \frac{B^2 V_t}{16} \left(\frac{\ell}{L}\right)^2 \quad (12)$$

The total energy which can be released by a single loop in a flare can be represented by

$$\Delta \Delta' \approx \frac{\epsilon_f B^2 V_t}{8} \left(\frac{\ell}{L}\right)^2 \quad (13)$$

where  $\epsilon_f = \Delta B/B$ , is the fraction of the field which is annihilated. Assuming  $\epsilon_f \sim 0.2$ ,  $\ell/L \sim 0.1$ , a typical field B  $\sim 500$  gauss and loop length L  $\sim 5 \times 10^9$  cm, we obtain  $\Delta \Delta' \sim 2.4 \times 10^{29}$  erg, which is about 10 times larger than the single injection energy content estimated in the previous section,  $E(25) \sim 2 \times 10^{28}$  erg, if most of the primary energy released is transferred to the heating of electrons to hard X-ray temperatures. This may be an indication that a single loop may release its energy in a number of cells, namely 10 for the numerical values involved here which is comparable to the total number of ultrafast structures observed at the maximum of the event investigated here,  $\sim 12$  (Figure 4), through there are admittedly several uncertain parameter involved.

The successive larger time scale burst structures (of about one second) may be associated with elementary flare burst time scales, produced by interaction between adjacent loops, according to a suggestion made by Emslie (1981) or by longer wavelength modes in a tearing loop. Each loop may contain several exploding cells, depending on its geometry and physical characteristics. Emslie's (1981) mechanism does not seem to work well for the ultrafast time structures at the peak of the event, since it would imply an unrealistically small separation between loops, and too small a release of energy. It does work however, for time scales larger of about 1 second, providing plausible numerical results for elementary flare burst time scales and energy releases.

## 7: FINAL REMARKS

The strong spike-like solar burst of 18 Dec. 1980, 1921:20 UT, analysed with high sensitivity and time resolution, provided an excellent opportunity to test a number of recently suggested ideas on the discrete nature of mechanisms initiating the burst phenomena. Attempts were made to reconcile the concept of elementary flare bursts (Frost, 1969; van Beek et al., 1974; de Jager and de Jonge, 1978) with the concept of multikernel emission convoluted in space and time in a single elementary flare burst (Brown et al., 1980) and with quasi-quantization of primary injected energy with repetition rates proportional to flux levels both at microwaves and hard X-rays (Kaufmann et al., 1978; 1980). The results seem quite reasonable.

In a suggested general macroscopic picture, we find that elementary flare bursts might be associated with single loop bursting into a number of discrete explosions, according to a multiple tearing mode primary mechanism (Kuperus, 1976; Spicer, 1981). Every discrete injection has a nearly typical energy content. Loop interactions (Emslie 1981), could account for the superposition of elementary flare bursts.

In a simplified picture (Figure 10) the time scales between elementary flare bursts would be regulated by the separation between loops,  $D$ , such as  $\tau_D \sim D/V_A$ , (Emslie, 1981). The time scale expressing the duration of one elementary burst, containing  $N$  exploding cells, would be related to the speed the triggering agent will travel across the loop, of length  $L$ . Assuming this speed to be also  $V_A$ , we have, for each primary explosion time scale  $\tau_p \sim (L/N)V_A \sim 1/R(t)$ , and for an elementary flare burst duration  $\tau_{\text{EFB}} \sim N \times \tau_p$ .

In general, we might expect that larger and complex solar bursts arise from larger and magnetically more complex active centers, which is a very well known qualitative trend for solar flares. The total energy produced in a flare, involving  $M$  interacting loops, each one with  $N \geq 1$  exploding cells, will be

$$E_t \sim U \sum_i^M N_i \quad (18)$$

Large and small flares would differ from each other by the number of interacting loops, and the number of exploding cells each one contain. In general, there is no reason to expect any coherent time sequence for

the explosions and interactions. Not only could a typical energy content be assigned to every primary cell explosion but also the primary energy release rates would be expected to be comparable for large or small events, as has been suggested in a separate study of small complex bursts (Kaufmann et al., 1983).

This picture raises the need to quite a number of subsequent investigations, both experimental and theoretical. Higher time resolution/sensitivity measurements on burst emission are very much needed for more precise description of the associated discrete phenomena. At lower frequencies, dm-microwaves, metric wavelengths, fast time structures in events occurring higher in the corona might be associated to primary accelerating mechanisms (Dröge, 1977, Slottje, 1978) and should be further investigated in correspondence to mm-microwaves and hard X-rays finer time structures. Acquisition of these measurements is particularly important at higher X-ray energy ranges and higher microwave frequencies - which implies the use of detectors/antennas with areas substantially larger than the best available for the time being.

ACKNOWLEDGEMENTS. We are grateful for the useful discussions concerning this paper by H.S.Sawant and A.M.Zodi. This research was partially supported by Brazilian research agency FINEP. INPE operates CRAAM and Itapetinga Radio Observatory.

R E F E R E N C E S

- Barnes, C.W., and Sturrock, P.A.: 1972, Ap.J., 174, 659.
- Brown, J.C.: 1971, Solar Phys., 18, 489.
- Brown, J.C., and Melrose, D.B.: 1977, Solar Phys., 52, 117.
- Brown, J.C., Craig, J.D., and Karpen, J.T.: 1980, Solar Phys., 67, 143.
- Brown, J.C., and Smith, D.F.: 1980, Rep. Progr. Phys., 43, 125.
- Brown, J.C., and Hayward, J.: 1981, Solar Phys., 73, 121.
- Brown, J.C., and Hayward, J.: 1982, Solar Phys., 80, 129.
- Brown, J.C., MacKinnon, A.L., Zodi, A.M., and Kaufmann, P.: 1983, Astron. Astrophys., 123, 10.
- Charikov, Y.E., Kocharov, G.E., and Lazutkov, V.P.: 1981, 17th. Int. Cosmic Ray Conf., Paris, 13-25 July.
- Cliver, E.W.: 1981, private communication.
- Correia, E.: 1983, MS thesis, INPE, Brazil.
- Crannell, C.J., Frost, K.J., Mätzler, C., Ohki, K., and Saba, J.L.: 1978, Ap. J., 223, 620.
- de Jager, C., and de Jonge, G.: 1978, Solar Phys., 58, 127.
- Dennis, B.R., Frost, K.J., and Orwig, L.E.: 1981, Ap.J., 244, L169.
- Dennis, B.R., Frost, K.J., Orwig, L.E., Kiplinger, A., Chawning, T.O., Dennis, H.E., Gibson, B.R., Kennerd, G.S., and Tobert, A.K.: 1982, NASA Technical Memorandum, n° 83925, NASA/GSFC, Greenbelt, MD, USA.

Dröge, F.: 1977, Astron.Astrophys., 57, 285.

Dulk, G.A., Melrose, D.B., and White, S.M.: 1979, Ap.J., 234, 1137.

Emslie, A.G.: 1979; Astrophys.J., 235, 1055.

Emslie, A.G.: 1981, Astrophys.Lett., 171.

Frost, K.J.: 1969, Ap.J., 158, L159.

Fürth, H.P., Killeen, J., and Rosenbluth, M.N.: 1963, Phys.Fluids, 6, 459.

Gold, T., and Hoyle, F.: 1960, Mon.Not.Roy.Astron.Soc., 120, 89.

Hoyng, P., Brown, J.C., and van Beek, H.F.: 1976, Solar Phys., 48, 197.

Hoyng, P., Melrose, D.B., and Adams, J.C.: 1978, Astrophys.J., 230, 950.

Ishitsuka, M.: 1981, private communication.

Kane, S.R., Kai, K., Kosugi, T., Enomē, S., Landecker, P.B., and McKenzie, D.L.:  
1983, Astrophys. J., in press.

Kaufmann, P., and Santos, P.M.: 1973, Astron.Astrophys., 34, 197.

Kaufmann, P., Rizzo Piazza, L., Schaal, R.E., Iacomo Jr., P.: 1978, Ann.  
Geophys., 34, 105.

Kaufmann, P., Strauss, F.M., Opher, R., and Laporte, C.: 1980, Astron.Astrophys.,  
87, 58.

Kaufmann, P., Strauss, F.M., Schaal, R.E., and Laporte, C.: 1982a, Solar Phys.,  
78, 389.

Kaufmann, P., Costa, J.E.R., and Strauss, F.M.: 1982b, Solar Phys., 81, 159.

Kaufmann, P., Strauss, F.M., Costa, J.E.R., and Dennis, B.R., 1983, submitted to Ap.J., Abstract in: 1981; BAAS, 13.

Kiplinger, A.L., Dennis, B.R., Emslie, A.G., Frost, K.J., and Orwig, L.E.: 1983, Ap.J.; 265, L99.

Kundu, M.R.: 1980, in "Radio Physics of the Sun" (ed. by M.R. Kundu and T.E. Gergely), D.Reidel Publ.Co., Dordrecht, NL, 157.

Kuperus, M.: 1976, Solar Phys., 47, 79.

Marsh, K.A., Hurford, G.J., Zirin, H., and Hjellming, R.M.: 1980, Ap.J., 242, 352.

Mätzler, C., Bai, T., Crannell, C.J., and Frost, K.J.: 1979, Ap.J., 223, 1058.

NOAA 1981; Solar-Geophysical Data, Part 1, NQ 437, Boulder, CO, USA.

Orwig, L.E., Frost, K.J., and Dennis, B.R.: 1980, Solar Phys., 65, 25.

Predmore, R.: 1978, "FCRAO Millimetre Antenna: Cassegrain Optics, Alignment Criteria, and Subreflector Control and Antenna Efficiency Measurements, FCRAO Rept. #111, Univ. Massachusetts, Amherst, MA, USA.

Samain, A.: 1976; Plasma Phys., 18, 551.

Slottje, C.: 1978, Nature, 275, 520.

Smith, D.F. and Emslie, A.G.: 1983, preprint.

Spicer, D.S.: 1977, Solar Phys., 53, 305.

Spicer, D.S.: 1981, Solar Phys., 70, 149.

Steffen, P.: 1975, Solar Phys., 44, 149.

Sturrock, P.A., and Uchida, Y.: 1981, Ap.J., 246, 331.

Sturrock, P.A., Kaufmann, P., and Smith, D.F.: 1982, SUIPR Report n° 933.  
Stanford University, Stanford, CA, USA.

Takakura, T.: 1972, Solar Phys., 26, 151.

Takakura, T., Kaufmann, P., Costa, J.E.R., Degaonkar, S.S., Ohki, K., and  
Nitta, N.: 1983, Nature, 302, 317.

Tandberg-Hanssen, E., Kaufmann, P., Reichmann, E.J., Teuber, D.L., Moore, R.O.,  
Orwig, L.E., and Zirin, H.: 1982, in preparation.

van Beek, H.F., de Feiter, L., and de Jager, C.: 1974, Space Res., XIV, 447.

Wiehl, H.J., and Mätzler, C.: 1980, Astron. Astrophys., 82, 93.

Zarghamee, M.S.: 1982, IEEE Trans. Antennas Propag., AP-30, 1228.

Zirin, H., Hurford, G.J., and Marsh, K.A.: 1978, Astrophys. J., 224, 1043.

## CAPTIONS TO THE FIGURES

Fig. 1 - The 18 December 1980, 1921:20 UT solar burst, observed in five energy ranges of the HXRBS experiment on board of SMM satellite. Finer time structures are suggested. They become relatively more important for higher energies.

Fig. 2 - The 18 December 1980, 1921:20 UT spike-like burst, as observed at 44 GHz, 22 GHz and 10.6 GHz. Slower time structures are evident, specially at 44 GHz. The peak structure was expanded in Figures 3 and 5.

Fig. 3 - The peak time structure of the burst shown in Figure 2, in a second time expansion. Correlated ultrafast time structures are observed at both frequencies, repeating every 30-60 ms. Nearly 10-12 structures can be counted across the maximum duration of nearly 0.6 seconds (a).

Fig. 4 - Further time expansion (200 ms) at the maximum of the event at 22 GHz and 44 GHz (Figure 2,3). Label numbers are the same as in Figure 3.

Fig. 5 - The microwave burst spectrum at the peak emission of the burst.

Fig. 6 - 10.6 GHz polarization burst data from Owens Valley Observatory, indicate a slow reduction of the polarization degree with the growth of the flux.

Fig. 7 - The proportionality of the burst underlying flux levels at hard X-rays and mm-microwaves was remarkable, and is shown for I ( $\approx 26$  keV) vs. S (22 GHz).

Fig. 8 - The half-width durations of the spike - like underlying emission. Ordinates at left are for microwaves, in GHz. Ordinates at right, are for hard X-rays, in keV. The reduction of half-width duration is evident for higher microwave frequencies, approaching 3-4 sec at 44 GHz. At hard X-rays, the half-width duration does not seem to depend so much on the energy range with the half-width duration within 3-4 sec, with a slight reduction towards higher energies.

Fig. 9 - Time evolution of the power law parameters for the hard X-ray burst emission. It correspond to  $I(\epsilon, t) \approx a(t) (\epsilon/\epsilon_0)^{-\gamma}$ . Figure (a) describes  $a(t)$ , and Figure (b) describes  $\gamma(t)$ .

Fig.10 - A simplified conception of loops in an active region, each one releasing burst emission components from N exploding cells and constituting elementary flare burst. The interaction between loops would account for the clustering of elementary burst, each one consisting of  $N \approx 1$  primary releases.

ORIGINAL PAGE IS  
OF POOR QUALITY

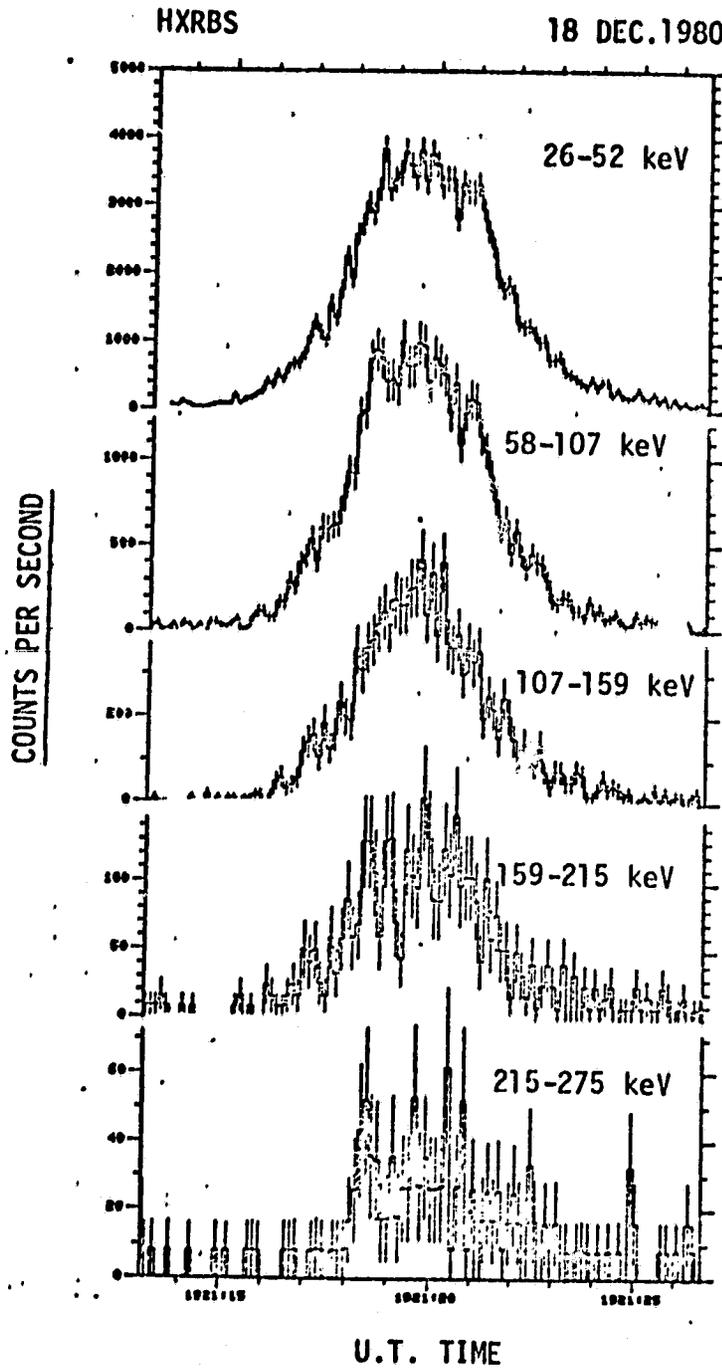
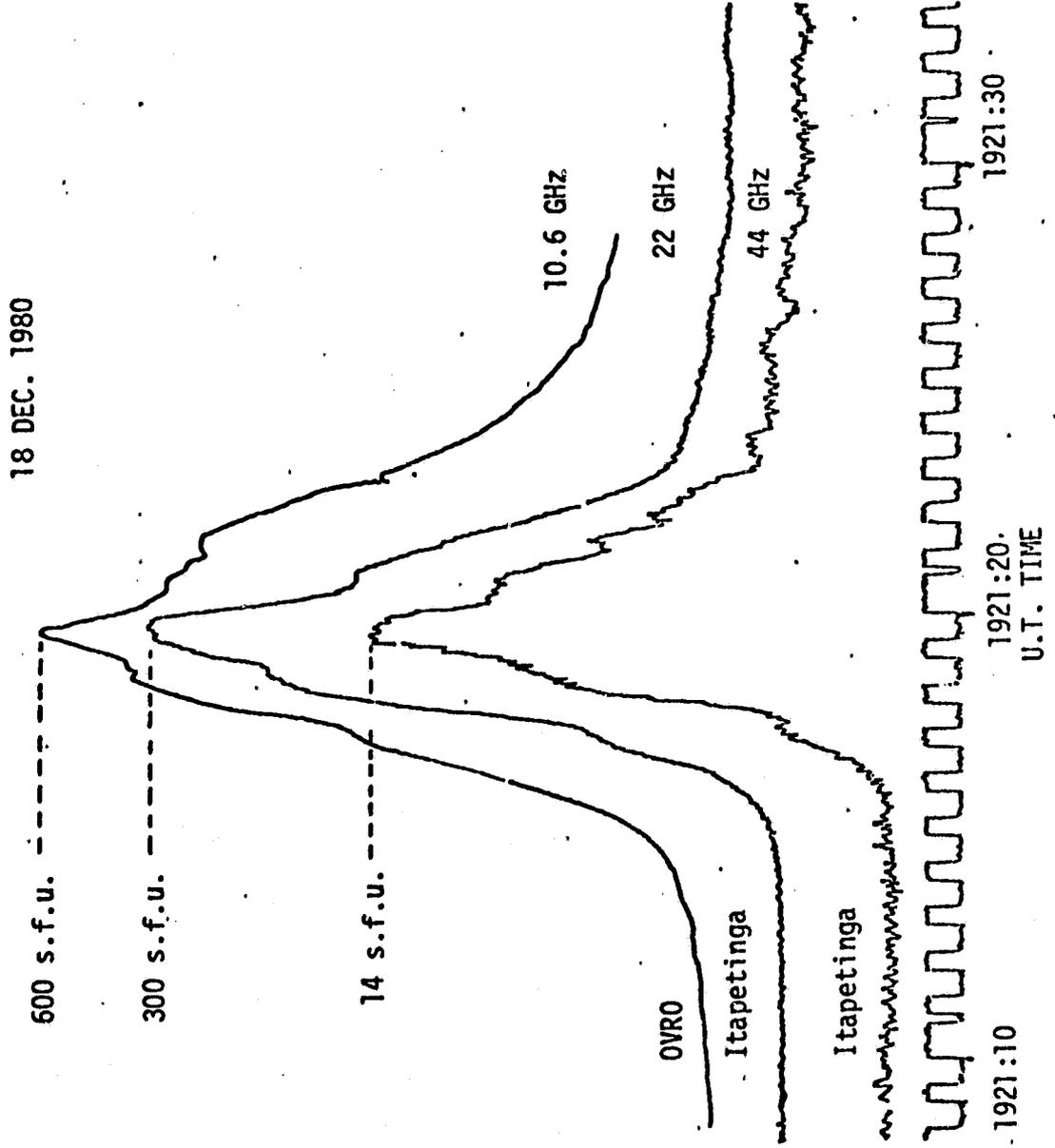


FIG. 1

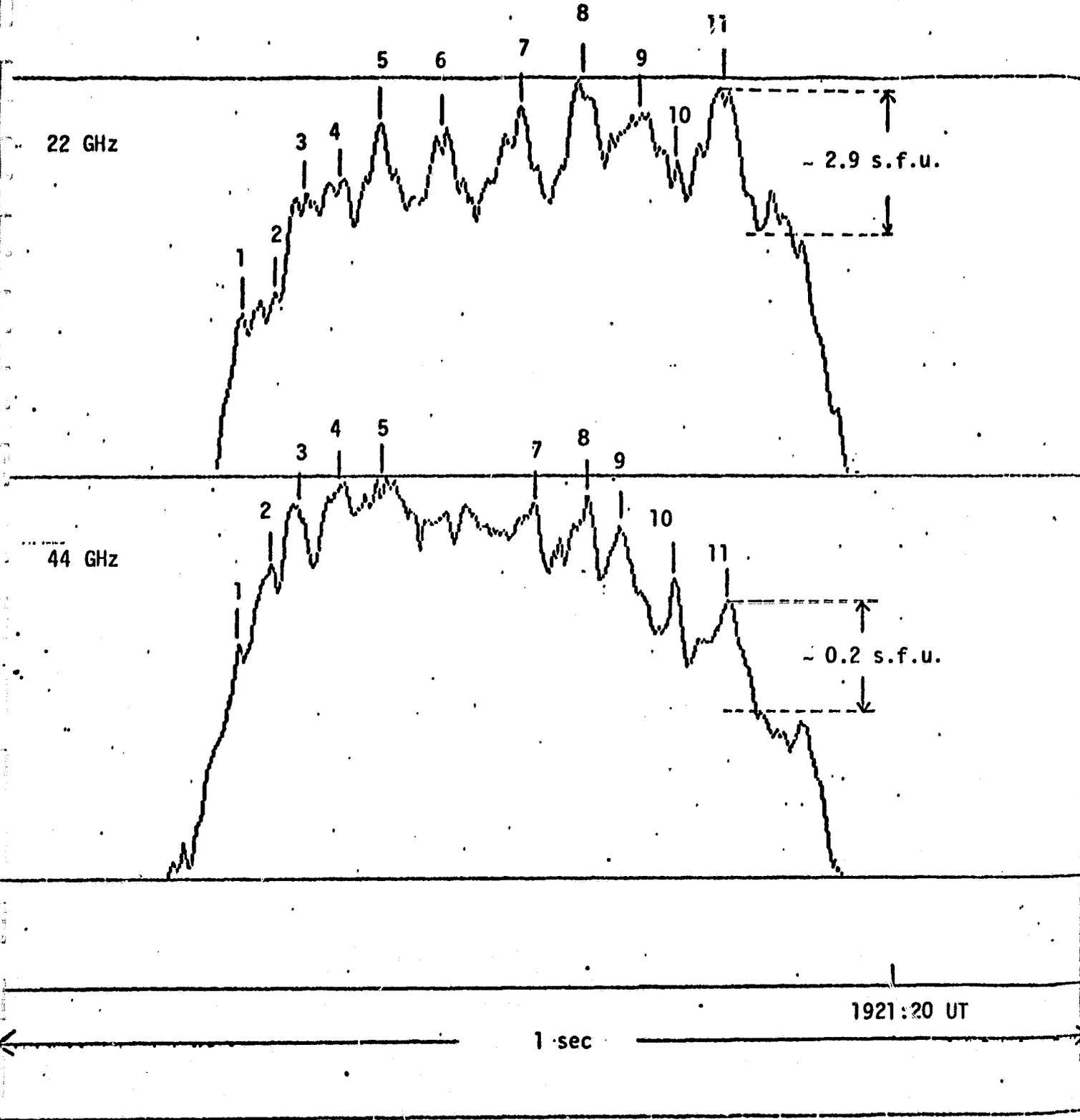
ORIGINAL PAGE IS  
OF POOR QUALITY



*Handwritten signature*

FIG. 2

ORIGINAL COPY IS  
OF POOR QUALITY



**FIG. 3**

*Kauffman*

ORIGINAL PAGE IS  
OF POOR QUALITY

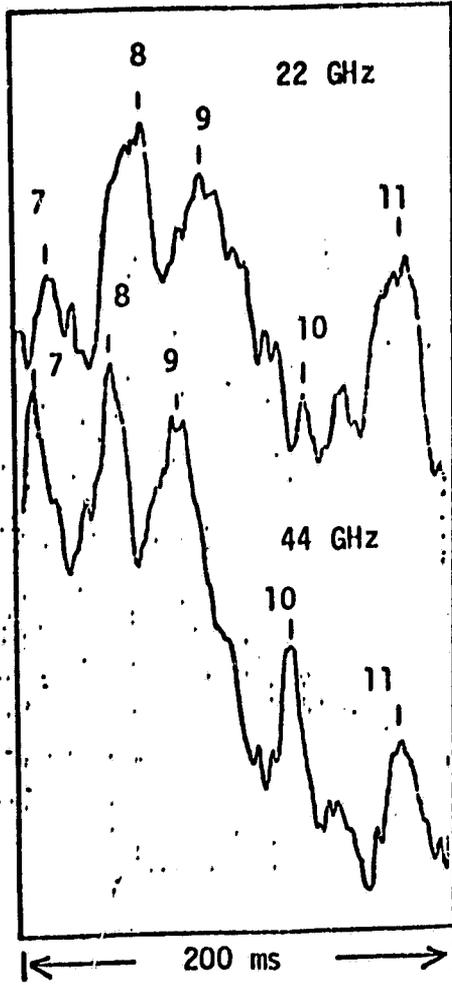


FIG. 4

*Keating, ... (1972)*

ORIGINAL COPY IS  
OF POOR QUALITY

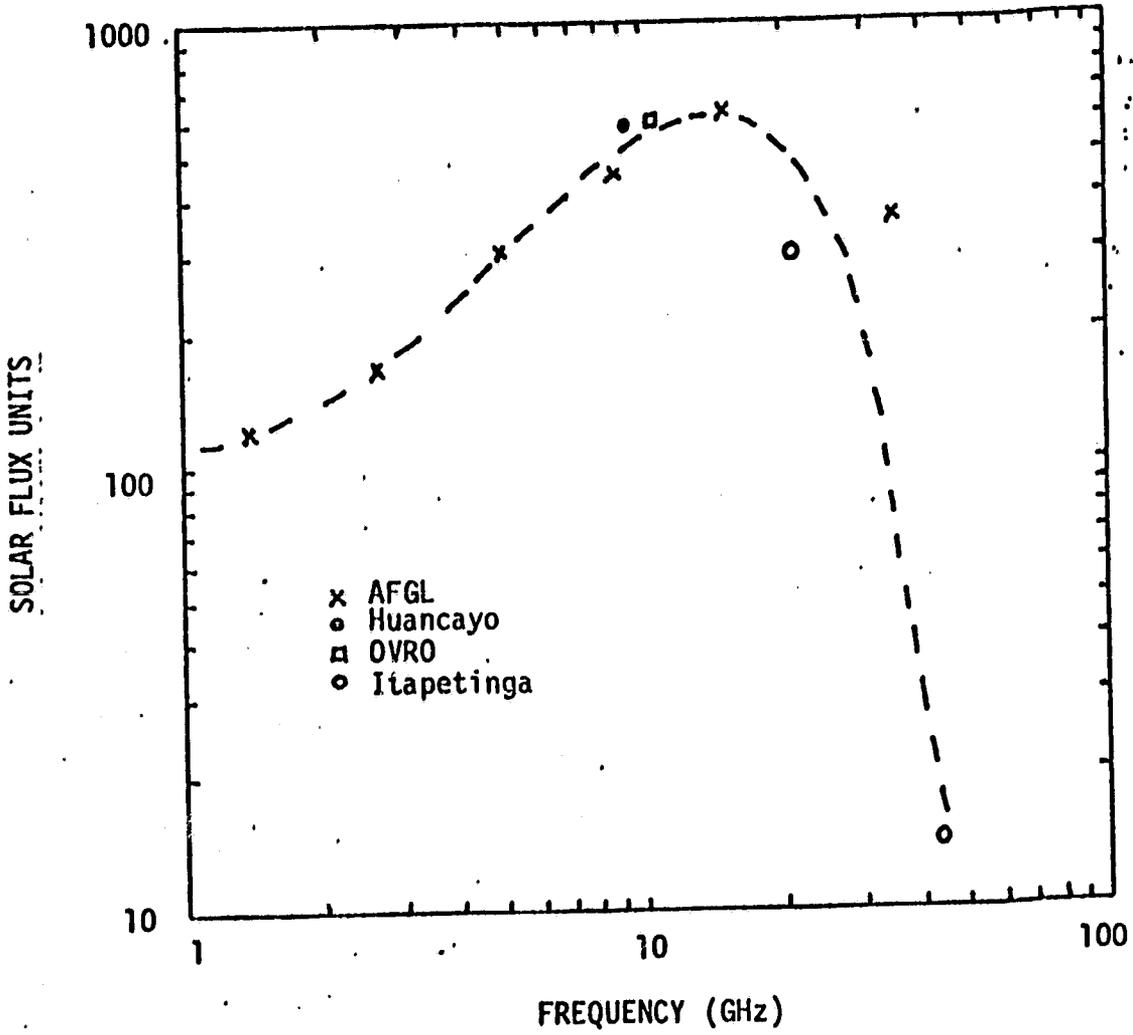


FIG. 5

*Ken fusuma 2/28*

ORIGINAL PAGE IS  
OF POOR QUALITY

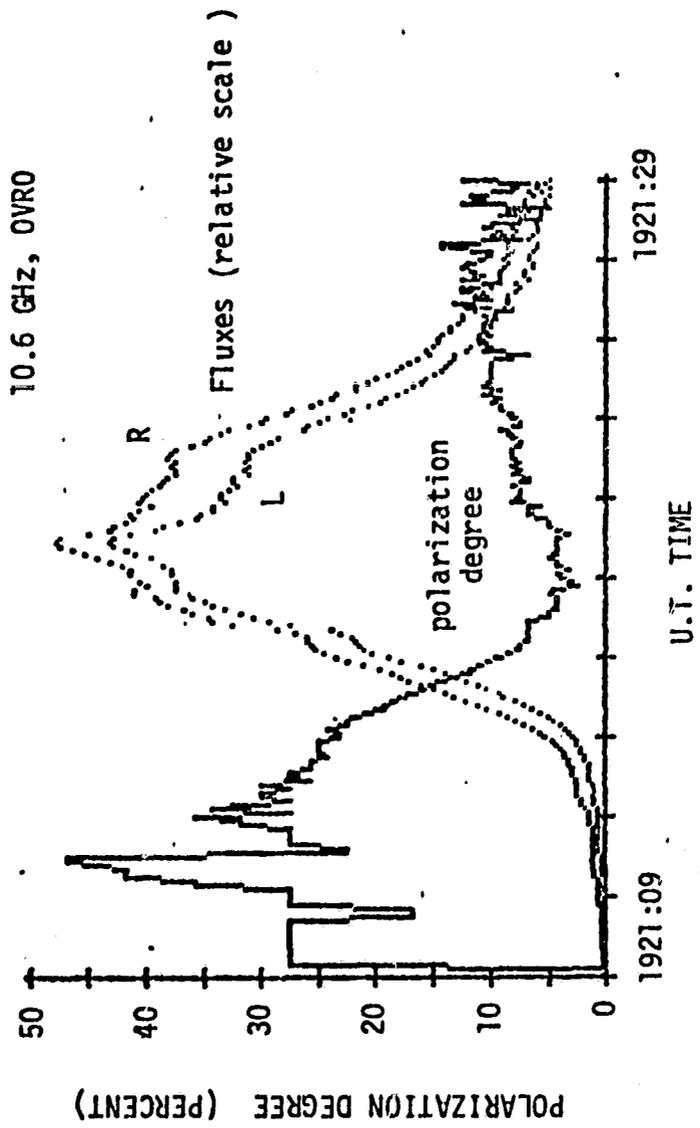


FIG. 6

ORIGINAL VALUES  
OF POOR QUALITY

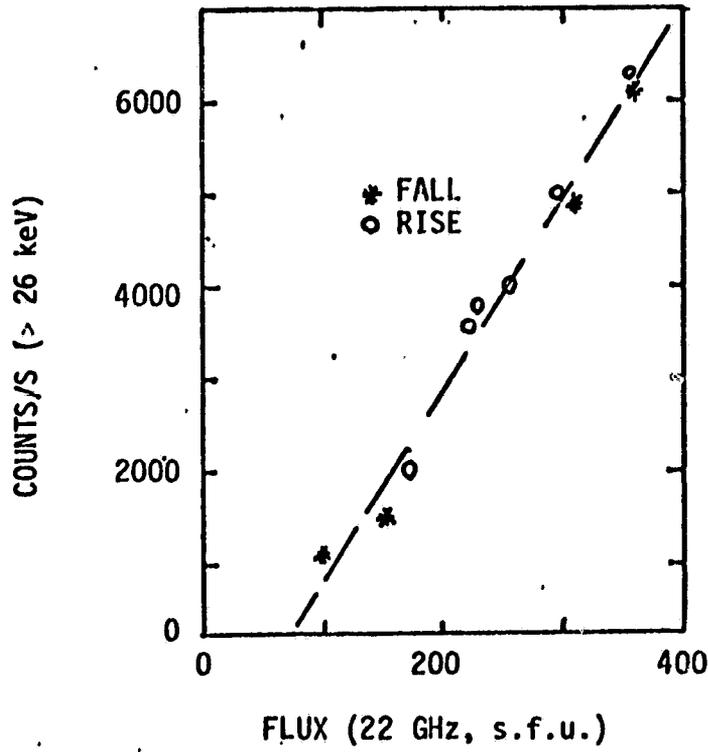


FIG. 7

*Handwritten note:* Handwritten at 2

ORIGINAL PAGE IS  
OF POOR QUALITY

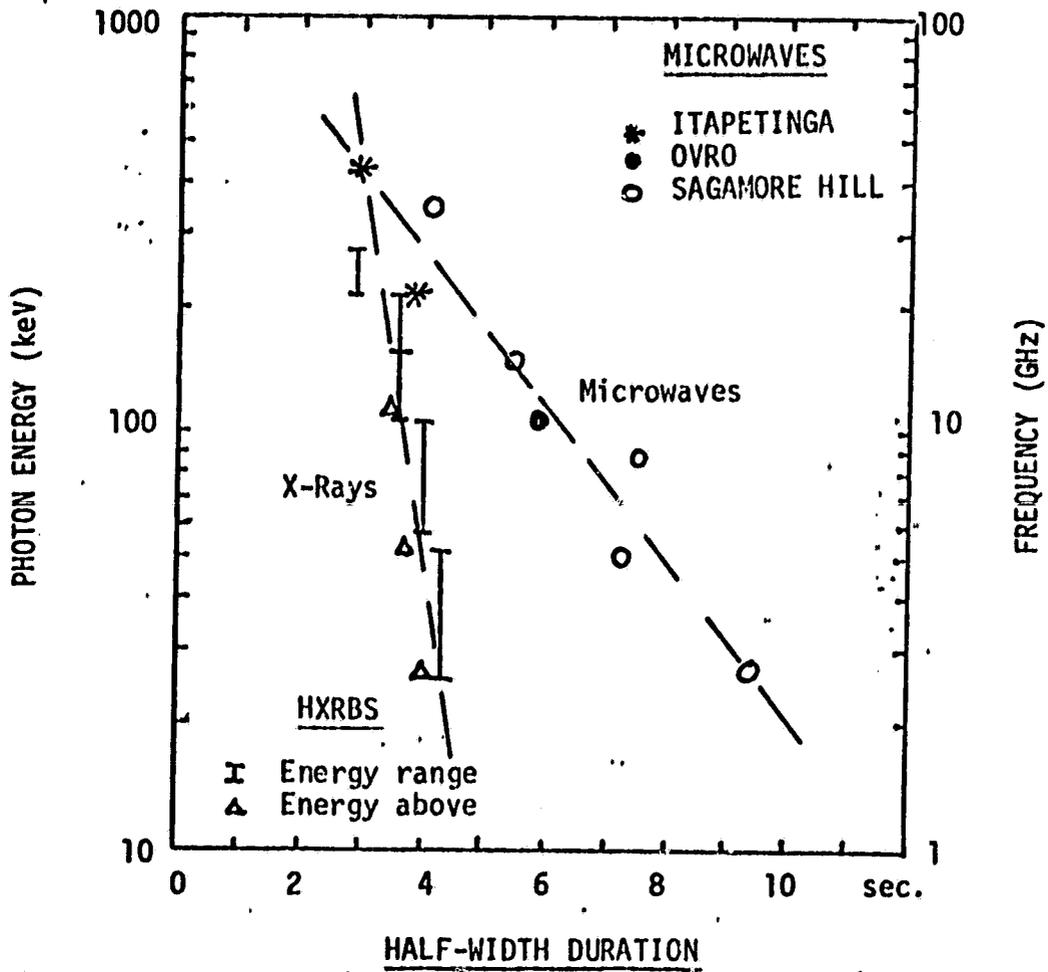


FIG. 8

*Kaufmann et al. (1977)*

CHARACTERISTICS  
OF POOR QUALITY

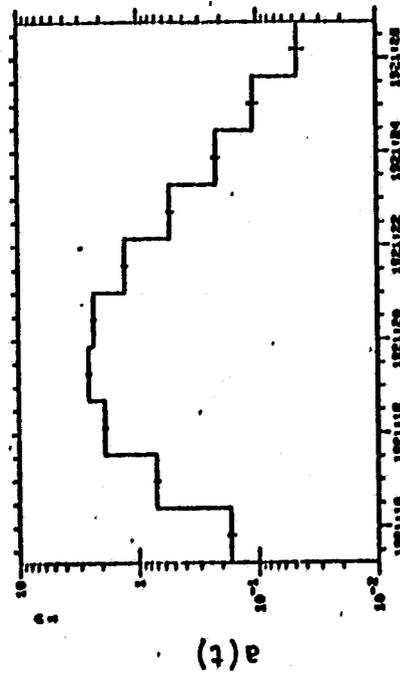
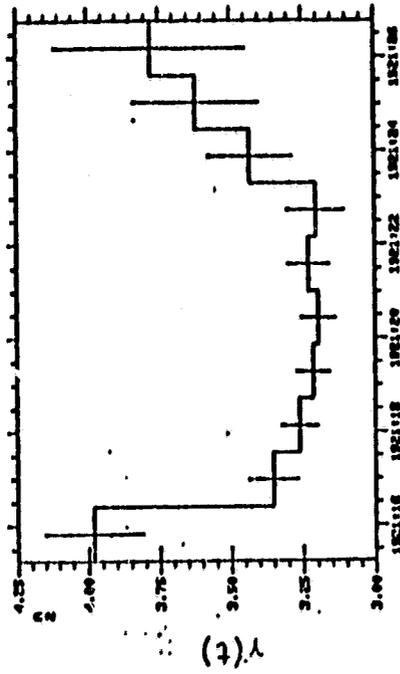


FIG. 9

ORIGINAL PAGE IS  
OF POOR QUALITY

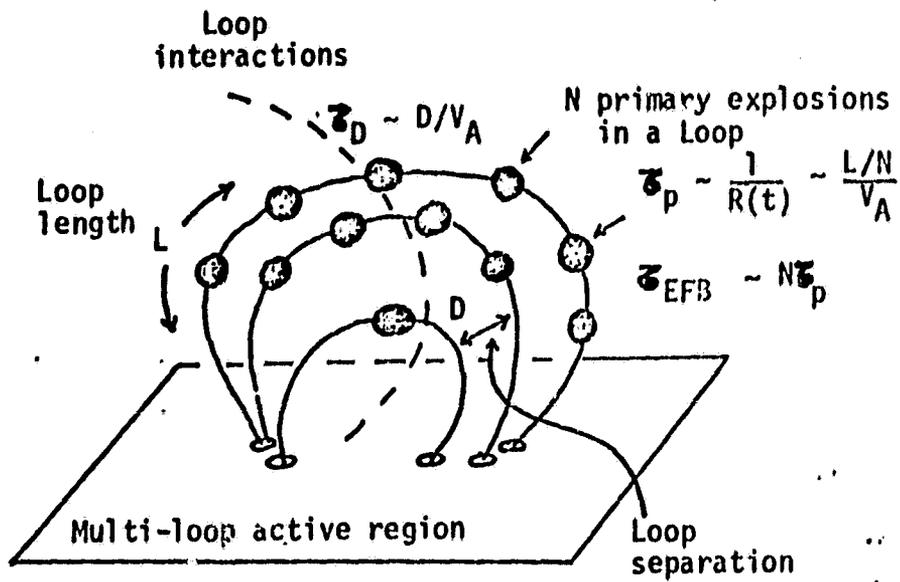


FIG. 10