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DOWNWARD SHIFT OF THE ACCELERATION/INJECTION REGION DURING SOLAR FLARES

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Simultaneous observations of impulsive hard x-rays and type III radio bursts associated with two recent solar flares have been analyzed in order to study the characteristic increase in the starting frequency of fast-drift type III bursts during the impulsive phase. The time variation of the starting frequency has been found to be similar to that of the 35 KeV x-rays, especially during the increasing phase. A similar variation has been observed for the low frequency cut-off of these bursts. The observations are consistent with a systematic downward shift of the electron acceleration/injection region during the impulsive

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phase of solar flares.

DOWNWARD SHIFT OF THE ACCELERATION/INJECTION REGION DURING SOLAR FLARES

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ABSTRACT

Simultaneous observations of impulsive hard x-rays and type III radio bursts associated with two recent solar flares have been analyzed in order to study the characteristic increase in the starting frequency of fast-drift type III bursts during the impulsive phase. The time variation of the starting frequency has been found to be similar to that of the ~35 keV x-rays, especially during the increasing phase. A similar variation has been observed for the low frequency cut-off of these bursts. The observations are consistent with a systematic downward shift of the electron acceleration/injection region during the impulsive phase of a solar flare.

I. INTRODUCTION

Although electrons are known to be accelerated in solar flares, very little information is presently available about the acceleration process itself, its location in the solar atmosphere and its evolution during the course of a flare. In view of the important role energetic electrons seem to play in solar flares, any new information on the characteristic of the electron acceleration process is of vital importance for an understanding of the flare process itself.

Simultaneous observations of impulsive hard x-rays and type III radio bursts provide an important means for studying the acceleration and propagation of energetic electrons in solar flares. In the earlier studies [*Kane*, 1972, 1981; *Kane and Lin*, 1972] the relationship between the impulsive x-ray and type III radio burst groups was found to have several important charac-

*Most of this work was completed while the author was a Visiting Astronomer at the Observatoire de Paris, Meudon, France teristics. The overall statistical correlation between these two types of bursts is ~ 20%. The overall correlation improves with the increase in the hardness of the x-ray spectrum, intensity and starting frequency of the type III radio burst groups, this correlation being often evident even during a single flare. The correlation also improves with the hardness and emission measure of $\gtrsim$ 20 keV electron spectrum inside the impulsive x-ray source [*Kane*, 1981]. In flares where both the impulsive x-ray and type III radio emission occur, the temporal relationship between them is very close, indicating a common origin of the energetic electrons responsible for the two types of emissions. The deduced ion density in the region of electron acceleration seems to vary from event to event and lies in the range 10^9 - 10^{11} cm^{-3}. In a later study, [*Kane, Pick and Raoult*, 1980] it was found that the electron acceleration region covers a wide range of magnetic field lines. Moreover, inside the acceleration region, the acceleration efficiency seemed to undergo both spatial and temporal variations.

In this paper, we present new substantially improved high time resolution observations of impulsive x-ray and type III radio bursts associated with two flares. Simultaneous spatially resolved measurements at 169 MHz help in reducing possible ambiguity in the interpretation. The present observations indicate that the electron acceleration region undergoes a systematic downward shift during the impulsive phase.

II. INSTRUMENTATION

The observations presented in this paper were made with three different instruments: x-ray spectrometer, radiospectrograph, and radioheliograph. The x-ray spectrometer aboard the International Sun Earth Explorer-3 (ISEE-3) has been described earlier [*Anderson et al.*, 1978; *Kane et al.*, 1979, 1981]. It measures the whole-sun (global) x-ray emission from 5 - 2630 keV in 18 energy channels. In this paper we are concerned primarily with 7 channels which cover approximately 26 - 350 keV range and have a time resolution of 0.5 sec.

Unlike the more common swept-frequency instruments, the radiospectrograph at Nancay, France consists of a large number of "single" frequency filters, the output of which is continuously recorded on a 35 mm photographic film. The instrument analyzes 115 channels of 1 MHz bandwidth chosen in the frequency range of 150 - 470 MHz. More information concerning this instrument can be found in Internal Report no. 203/Sectro 44 Despa-Meudon.

The spatially resolved radio observations were obtained with the radioheliograph at Nancay, France. The instrument has also been described before [*Radioheliograph Group*, 1977]. At the time of the present observations it provided one dimensional (East-West) images at 169 MHz with an optimum spatial resolution of 1.15' and time resolution of 0.04 sec per image.

III. OBSERVATIONS

The general optical and radio characteristic of the flares on 11 April 1979 (~ 1345 UT) and 13 April 1979 (~ 1050 UT) are summarized in Table I. Both the flares were located in the Eastern hemisphere, the flare on /1 April being more intense than that on 13 April by about one order of magnitude.

(a) 13 April 1979 flare

Details of the x-ray and radio emission associated with the 13 April 1979 flare are shown in Figure 1. In this flare, significant increase in the hard x-ray flux was detected only in the 26 - 42 keV range. The observed x-ray enhancement consisted of four quasi-periodic pulses lasting ~ 10 sec, with possible sub-structure in each.

The radio spectrum show that the starting frequency of type III emission evolved during the event: initially the starting frequency was low (≈ 340 MHz), then increased to about 400 MHz, and reached 470 MHz at the end of the event. It can be noted that the low cut-off frequency followed roughly a similar evolution towards higher frequencies during the event.

The type III emission appears to be organized into subgroups: one subgroup with starting frequency ~ 340 MHz, followed by three subgroups whose starting frequency is ~ 400 MHz, then one with starting frequency ~ 470 MHz. It is important to note that the frequency drifts are not homogenous within subgroups; while some drifts exhibit changes in their slope, others are reversed.

At the 169 MHz level, the type III activity occurred at three stable and distinct E-W locations (7 arcmin E, 4 arcmin E, and 1 arcmin W) having essentially simultaneous emissions. The relative radiation intensities at the three locations varied during the event. The extreme separation of the locations (8 arcmin) and the variety of frequency drifts suggest that the event is occurring in a region of complex diverging field lines.

The first subgroup of type III bursts starting at $\sim$ 360 MHz is not associated with any detectable x-ray emission. Later, however, each x-ray major maximum correlates in time with a subgroup of type III bursts having a high starting frequency.

Inside each subgroup there is some indication of even finer peak-to-peak correlation with the x-ray emission. The temporal resolution and statistical accuracy of the x-ray data, however, are not sufficient to establish this firmly. In this connection, it is interesting to note that the first subgroup that correlates with x-rays has only one burst starting at 400 MHz, and is associated with the sharpest x-ray maximum. The width of the three following x-ray maxima is roughly proportional to the number of bursts starting at high frequencies in the corresponding type III burst subgroup.

Another aspect of the correlation with the 169 MHz activity is that the type III components that reach the 169 MHz activity from higher frequencies and maintain rapid frequency drift during the passage of the electron beam through the corona do have a good temporal correlation with the x-ray structures. But many of the the type III components that start at high frequencies either vanish before the 169 MHz level, or endure such frequency drifts that they are delayed by several seconds with respect to the relevant x-ray emission.

(b) 11 April 1979 flare

Figure 2 shows the hard X-ray and radio measurements during the 11 April 1979 flare. In microwave, hard X-ray, as well as optical emission, this flare was more intense than the 13 April 1979 flare by almost one order of magnitude. The 26 - 42 keV x-ray enhancement consisted of two principal maxima separated in time by $\sim$ 40 sec, the first maximum being larger than the second maxima by a factor of $\sim$2. Those two successive x-ray pulses are part of a much larger event. In the pre-heating phase, (not shown in the figure) only a few faint type III bursts could be observed.

All the observed type III bursts have starting frequencies higher than 470 MHz (except the first one that starts around 460 MHz) and exhibit very fast frequency drifts. The temporal evolution of the starting frequency of this type III group could not be studied from the Nancay radiospectrograph data because it lies beyond the range of the spectrograph. Complementary spectral data from Zurich [*Benz*, private communication] show, however, that the starting frequency exhibits increase towards higher frequencies during the rise of the first x-ray pulse. The systematic increase of the low frequency cut-off from 150 MHz to 360 MHz can be very clearly seen in this event.

The spectrum shows a broadband continuum emission, lasting about 10 sec, that starts during the decay of the first x-ray pulse and reaches a maximum at the time of the minimum between the two major x-ray maxima.

From radioheliograph observations, we know that the type III activity occurred in a unique source position located at 7 arcmin E and remained stable during the event. The polarization of this type III burst was $\sim$ 30%. At 169 MHz, the continuum emission is more intense than the type III emission and is located much higher in the corona (19 arcmin E).

In summary, all the type III bursts in this event had a starting frequency $\gtrsim$ 470 MHz. The x-ray-radio correlation was good right from the onset to the maximum of the first x-ray pulse. A single type III burst was associated with the onset of the second x-ray pulse. This was followed by a group of type III bursts at the time of the second x-ray maximum. The last group of type III bursts was associated with a relatively small third maximum in the x-ray flux.

As in the case of the 13 April 1979 event, there was a good correlation between x-ray intensity structures lasting more than 10 sec and subgroups of type III bursts. It is tempting to look for peak-to-peak correlations between the quasi-periodic type III activity and the x-ray spikes superimposed on the first slowly varying x-ray pulse. While both the rise and decay portions of this x-ray pulse exhibit many fluctuations, type III bursts were observed during the rise portion only. Therefore any finer peak-to-peak correlation in this event could be fortuitous.

IV. DISCUSSION

The most significant result of the present study is the observed systematic increase in the starting frequency (f_s) of the type III emission during the impulsive phase. The time variation of f_s seems to follow closely the variation of the ~ 35 keV x-ray flux, especially during the increasing phase. In addition, the low-frequency limit f_l of the fast-drift type III bursts also seems to increase during the impulsive phase.

Earlier studies indicated that the electron acceleration/injection region is located in the lower corona [*Kane*, 1981]. In models similar to that proposed by *de Jager and Kundu* [1961] electrons moving downwards towards the chromosphere enter the higher ion density regions and produce x-rays through the bremsstrahlung process. Those electrons which move outwards through the corona produce type III emission through a plasma process (cf. *Sturrock*, 1964).

In general, the x-ray emission from a given region depends on the ambient ion density and the spectrum of the accelerated electrons. If the increase of the x-ray emission is due to an increase in the number of associated electrons, it is likely that the intensity of the successive type III bursts will also be enhanced, at least in the case of "small turbulence." Due to the detection limit of the radiospectrograph, the emission could be detected at higher and higher frequencies, as the intensity of type III emission increases. As a consequence, one should see a systematic increase in the intensity of successive type III bursts seen at a fixed frequency, which is not observed in the present events. Therefore this explanation, as well as any other process which can systematically enhance the type III emission during the impulsive phase, does not seen adequate to explain the present observations.

A more likely explanation would involve a dynamical process related to the temporal evolution of the acceleration/injection of electrons and/or the magnetic field structure in which electrons can escape. In a simple interpretation, the starting frequency $f_s \approx f_{po}$, where f_{po} is the electron plasma frequency at the level just above the region where energetic electrons are accelerated/injected. If n_e be the number density of the ambient electrons, then $f_p \approx 9 \times 10^{-3}\, n_e^{1/2}$ MHz. Hence, if N_{eo} be the ambient electron density just above the region of electron injection, then $f_s \approx 9 \times 10^{-3}\, n_{eo}^{1/2}$ MHz.

The present observations indicate that f_s increased by a factor of ~ 1.4 during a period of ~ 45 sec. This corresponds to an increase of n_{eo} by a factor of ~ 2. We now consider two relatively simple explanations of this increase in n_{eo}.

1. The region of acceleration/injection was located at a constant altitude h_o, where the ambient electron density is n_{eo}. During the impulsive phase, the ambient electron density n_e at heights $h > h_o$ increased by a factor of 2.

2. Initially the region of acceleration/injection was located at an altitude h_o, where the ambient electron density is n_{eo}. During the impulsive phase, the effective region of acceleration/injection moved gradually to altitudes $h < h_o$ where the ambient electron density is $n_e > n_{eo}$.

Explanation 1 requires a rather rapid increase in the ambient electron density n_e. The relatively smooth appearance of the type III bursts requires that the increase in n_e should occur over an extended region in the corona. Such a rapid "coronal condensation" could, in principle, result from a compression of the surrounding magnetic field. This would inhibit, however, the escape of the energetic electron beam, which requires a relatively open field structure. Another way the ambient electron density, n_e, could increase at coronal altitudes is if the additional plasma is obtained from the chromosphere. In "thick target" models of impulsive phase (cf. *Brown*, 1979, *Hudson*, 1972), energetic electrons moving downward towards the chromosphere deposit a large amount of energy, which results in "chromospheric evaporation." It is possible that some of this evaporated material reaches coronal altitudes and increases the ambient electron density [*Somov et al.*, 1980]. In order to produce significant effects at coronal altitudes within a few seconds, however, chromospheric material must move upwards with a speed of $\sim 10^4$ km/sec, a speed much greater than the Alfvén velocity. In addition, a rapid increase in coronal density would induce a shift of the 169 MHz plasma level. No source movement has been detected in the present observations. Therefore, density enhancement, if present, must have been restricted to altitudes much smaller than that for the 169 MHz level.

Explanation 2 requires that the region where conditions are favorable to electron acceleration/injection varies with time. During the impulsive phase, the required conditions are satisfied at lower altitudes, and, hence, the acceleration/injection region effectively moves to lower altitudes. Since the time variation effect results from variations in the inter-relationship between magnetic field and plasma parameters rather than the bulk motion of material itself, speeds of the order of the Alfvén velocity can be invoked. Consider, for example, the motion of the acceleration/injection region from 360 MHz level to 470 MHz level during a period of 45 s. Those levels correspond, respectively, to $n_e \approx 1.4 \times 10^9$ cm^{-3} and $n_e \approx 2.7 \times 10^9$ cm^{-3} if the emission is produced at the fundamental level, and to $n_e \approx 3.6 \times 10^8$ cm^{-3} and $n_e \approx 6.8 \times 10^8$ cm^{-3} respectively, if the emission is assumed to be produced at the second harmonic. The spatial separation between these two levels has been estimated from the Saito model for the mean quiet corona [*Saito*, 1972] multiplied by factors from 5 to 10 which are generally accepted for coronal structures in which type III bursts are produced (cf. *Pick et al.*, 1979). This leads to speeds ranging from 850 km/sec to 1050 km/sec in the fundamental emission hypothesis and from 1300 km/sec to 1700 km/sec in the harmonic emission hypothesis. Computing the Alfvén velocity in the corresponding density structures in order to be consistent with the Alfvén speed, it is found that the above propagation speeds need magnetic fields from 18 G to 21 G in the fundamental hypothesis and from 13 G to 18 G in the harmonic hypothesis. The generally accepted values of B in the corona range from 1 G to 10 G, but values twice as large cannot be excluded in narrow structures. In addition, if the type III emission is not produced just above the acceleration/injection region, the required values for the magnetic field would be smaller.

Thus, although explanation 1 cannot be completely ruled out, explanation 2 seems to be more plausible. As far as the low frequency cut-off of the fast drift type III burst is concerned, it is probably related to the region in the corona where the outward moving electron beam becomes relatively diffused and ceases to excite significant plasma emission. The present observations indicate that this "scattering" region is also shifted downward during the impulsive phase.

In large flares, shocks may be produced very early in the event as suggested, for example, by the open coronal MHD model of *Wu et al.* [1978]. Such shocks may give rise to density enhancements in the corona. In the above discussion it has been assumed that no such shock waves were produced. The relatively small magnitudes of the present optical flares and hard X-ray bursts as well as the absence of detectable type II radio bursts support that assumption. It is possible, however, that non-linear high amplitude MHD waves were produced during the impulsive energy release at the flare site $\sim 0.1 R_{\oplus}$ above the photosphere (*M. Dryer*, private communication). The upward, downward or bidirectional propagation of these waves could produce alternate density compressions and rarefactions. It may be argued that such an alternating pattern of density compressions and rarefactions is suggested by the quasi-periodic nature of the x-ray response in Figures 1 and 2. If, however, the impulsive x-rays are produced in a thick-target source, as is generally assumed, the variations in the x-ray emission are caused primarily by the variations in the electron injection spectrum. Any changes in the ambient density alone are not expected to produce significant variations in the observed hard x-ray emission. Thus, although the presence of non-linear large amplitude MHD waves in the present flares cannot be ruled out, there is no direct observational evidence to support the density enhancements caused by these waves.

To summarize, the present observations of hard x-ray and type III radio bursts show that the acceleration/injection of particles in solar flares is a dynamical process where the characteristic plasma and magnetic field parameters most favourable for acceleration/injection vary with time. Specifically, the observations indicate that the region of electron acceleration/injection undergoes a systematic downward shift during the impulsive phase with an apparent velocity of $\sim 10^3$ km sec^{-1}.

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FIGURE CAPTIONS

Figure 1. X-ray and radio measurements during the 13 April 1979 flare made with the Nancay Radiospectrograph (top), ISEE-3 x-ray Spectrometer (center), and Nancay Radioheliograph (bottom). The three curves (solid, dashed and dotted lines) in the radioheliograph observations refer to emissions from three spatially-resolved components of the radio source. The groups of fast-drift type III bursts are in good time coincidence with the x-ray maxima. Note that the starting frequency of the type III bursts increased systematically with time.

Figure 2. Similar to Fig. 1, but for the 11 April 1979 flare. The two curves (solid and dashed lines) in the radioheliograph observations refer to two spatially-resolved component sources. The starting frequency of the type III bursts was mostly above 450 MHz and hence outside the range of the Nancay Radiospectrograph. The low frequency cut-off, however, was very evident. It increased from the onset to the maximum of the x-ray flux. The source of the type V emission (~ 1339:25 UT) was quite distinct from the source of the type III emission.

Table I. Optical and microwave characteristics of the two flares

DATE (1979)	11 April	13 April
Hα EMISSION		
START (UT)	1344	< 1050
MAX. (UT)	~ 1345	1050
END (UT)	1356	1100
IMPORTANCE	1B	SB
LOCATION	N04, E53	N04, E16
McMATH REGION	15937	
MICROWAVE EMISSION		
MAX (UT)	~ 1339.2	~ 1050.3
PEAK FLUX (SFU)		
15.4 GHz	180	
10.7 GHz	170	14
8.8 GHz	347	17
5.0 GHz	299	
2.7 GHz	234	7

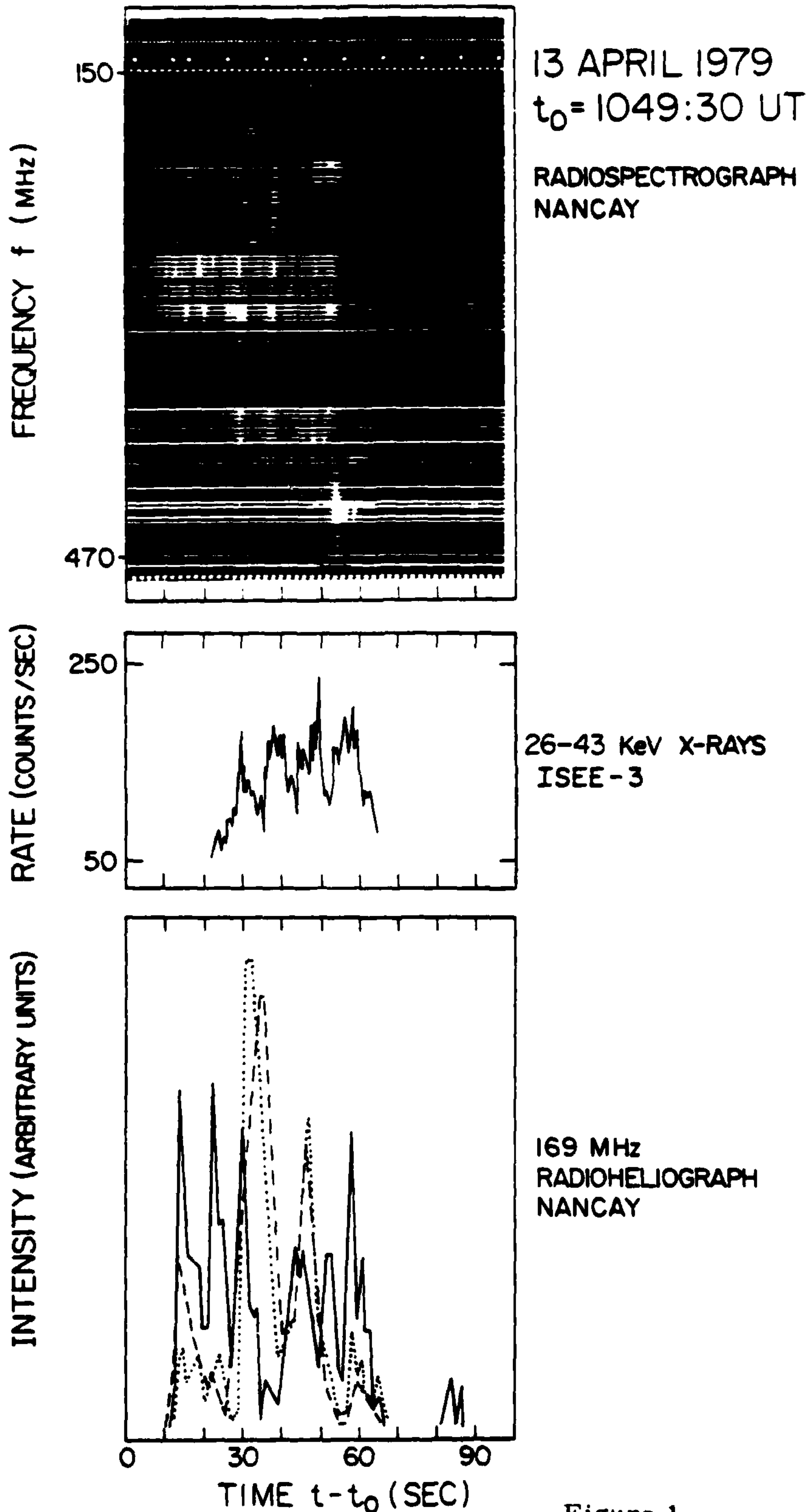
13 APRIL 1979
t_0= 1049:30 UT
RADIOSPECTROGRAPH
NANCAY
FREQUENCY f (MHz)
150
470
RATE (COUNTS/SEC)
250
50
26-43 KeV X-RAYS
ISEE-3
INTENSITY (ARBITRARY UNITS)
169 MHz
RADIOHELIOGRAPH
NANCAY
0
30
60
90
TIME $t-t_0$ (SEC)

Figure 1

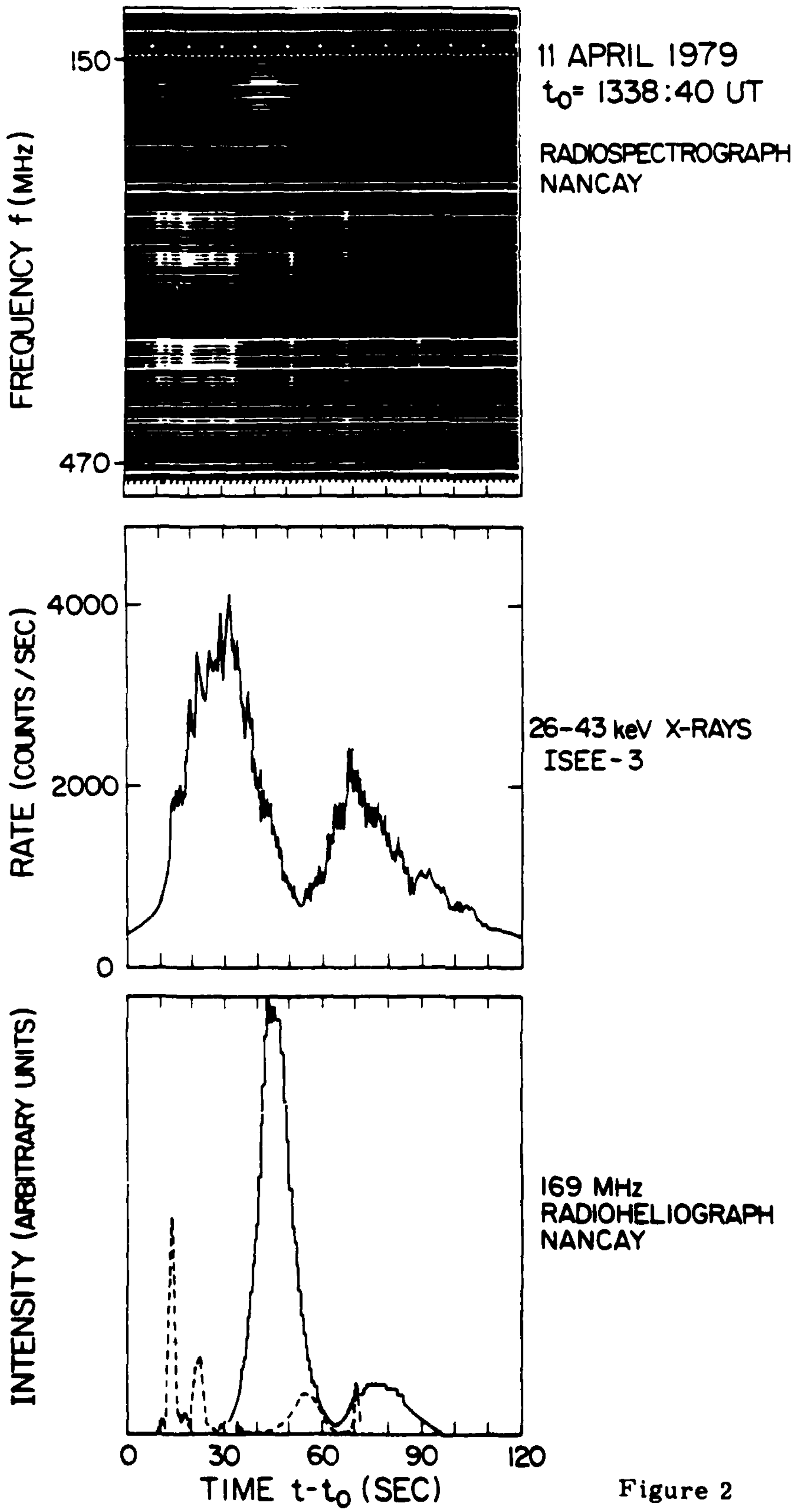
11 APRIL 1979
t_0= 1338:40 UT
RADIOSPECTROGRAPH
NANCAY
FREQUENCY f (MHz)
150
470
26-43 keV X-RAYS
ISEE-3
RATE (COUNTS/SEC)
4000
2000
0
169 MHz
RADIOHELIOGRAPH
NANCAY
INTENSITY (ARBITRARY UNITS)
0
30
60
90
120
TIME t-t_0 (SEC)

Figure 2