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J. T. Karpen, C. J. Crannell and K. J. Frost

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SPECTRAL EVOLUTION OF MULTIPLY-IMPULSIVE SOLAR BURSTS

J. T. Karpen*, C. J. Crannell, and
K. J. Frost

Laboratory for Astronomy and Solar Physics
NASA-Goddard Space Flight Center
Greenbelt, Maryland 20771

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ABSTRACT

Hard X-ray and microwave observations of multiply-impulsive solar bursts, identified in the OSO-5 data, have been analyzed in a search for the physical basis of the multiplicity of spikes within these events. Spectra in both frequency ranges have been used to determine whether or not the source properties change from peak to peak within individual bursts. Two categories of microwave spectral behaviour have been identified: those events during which the microwave turnover frequency and spectral shape remain the same from peak to peak, and those during which the turnover frequency and spectral shape change significantly. These categories correspond to two classes of multiply-impulsive bursts: those for which the emission can be characterized by a constant magnetic field and therefore a single source region, in which case the multiplicity may be due to modulation of the emission process; and those in which groups of component spikes appear to originate in regions of different magnetic-field strengths, corresponding to separate source regions which flare sequentially. Examples of the latter type of events are presented, with a detailed analysis of the discrete flaring regions and estimates of their spatial separations.

I. INTRODUCTION

The impulsive phase provides the most direct evidence available for the role of energetic electrons in solar flares (Kane 1974). This phase is characterized by emission on rapid time scales at all wavelengths, occasionally accompanied by the ejection of high-energy electrons into interplanetary space (Lin 1974). The observed association and similar time-intensity profiles of hard X-ray and microwave emission during impulsive solar events (Kundu 1961, 1965), as well as their similar location $\gtrsim 10^4$ km above the photosphere (Frost and Dennis 1971; Kane 1974; Hudson 1978), reveal their common origin. Emissions such as H-alpha and soft X-rays are observed in association with the impulsive phase, but generally are characterized by longer time scales, dissimilar time-intensity profiles, and lower temperatures. These features indicate source conditions or emission mechanisms unlike those responsible for the impulsive hard X-ray and microwave emissions. Although these complex differences have been identified qualitatively, present solar-flare models are only beginning to provide quantitative relationships between the impulsive hard X-ray and microwave sources and the associated H-alpha and soft X-ray emission. This work is limited, therefore, to analysis of the impulsive hard X-ray and microwave observations.

The hard X-ray and microwave radiation are thought to be bremsstrahlung and gyrosynchrotron radiation, respectively, resulting from interactions of the electrons accelerated in the initial stages of the flare (Peterson and Winckler 1959; Kundu 1965; Brown 1976). In order to study these energetic electrons, and thereby the physical processes responsible for their acceleration, we require observations which determine both temporal and spatial features of the impulsive emissions. Of particular significance is the location of the sources with respect to the magnetic-field topology of the active region (Kane 1974). The different dependences of the hard X-ray and microwave emission on source properties such as electron density, magnetic-field strength, and temperature or spectral index enable us to follow the evolution of these source parameters throughout an impulsive event. Each set of source properties can be utilized to locate the emitting region in the solar atmosphere, by means of the extant models of density and magnetic-field strength as a function of height above photospheric active regions. The results of such an analysis provide information on the evolution of the spatial characteristics of the impulsive flare source, and further clues as to the basic mechanisms of the flare process. In the current absence of data from instrumentation capable of hard X-ray imaging, this is the only method by which an idea of the positioning of impulsive hard X-ray burst sources can be obtained.

In this paper, some results from the analysis of a set of multiply-impulsive hard X-ray and microwave bursts are presented. This work is part of an ongoing study of impulsive solar events observed with the OSO-5 hard X-ray spectrometer and several radio observatories. The good time resolution of the hard X-ray and the microwave observations, in the range 0.1 to 10 s, enables a determination of the source properties for each impulsive spike within an event.

We have found that the multiply-impulsive solar bursts do not comprise a homogeneous set of events. Rather, they fall into two categories according to their spectral charateristics: those events for which the measured values of the microwave turnover frequency and electron temperature yield the same magnetic-field strength for the source of each peak within a burst; and those events which demonstrate significant differences between the magnetic-field strengths of the sources of different peaks within a burst, as deduced from variations in turnover frequency and temperature. These two classes of spectral behaviour are interpreted as evidence for two types of spatial structure in impulsive bursts: events whose component spikes apparently originate in one location, and events in which groups of spikes appear to come from separate regions which flares sequentially. Although the concept of separate regions contributing to a complex flare has been discussed by many authors (e.g., Hagen and Neidig 1971; Zirin and Tanaka 1974; Alissandrakis and Kundu 1975; Vorpahl 1976), the present work is the first analysis showing both hard X-ray and microwave evidence for the existence of these discrete flaring "kernels" within the regions producing multiply-impulsive bursts.

The analysis of the selected set of multiple-spike bursts is described in Section II. In Section III, the division of these events into two classes according to the evolution of spectral properties and magnetic-field strength is discussed, and specific examples of each type are presented. The conclusions drawn from this research are presented in Section IV, and the results are discussed in the context of observations and current theoretical predictions.

II. ANALYSIS

A total of 66 multiply-impulsive solar flares have been identified in the OSO-5 hard X-ray spectrometer data. The properties of the instrument are described in detail by Frost, Dennis and Lencho (1971). These events were chosen for their apparent impulsive nature, according to the following morphological criteria:

(1) Maximum counting rate $\geq$ 280 counts/second.

(2) Successive peaks which are distinctly separable, with rapid rise to and fall from an intensity $\geq 3\sigma$ above noise.

(3) No apparent gradual component before, after or during the impulsive event, above 15% of the maximum flux.

Microwave data were collected for as many events as possible from Sagamore Hill, Bern, and other ground-based radio observatories.

Interest in these events was sparked by the resemblance of the component spikes to the simple impulsive "spike bursts" discussed by Crannell *et al*. (1978). The time-intensity profiles of the multiple-spike bursts appear to consist of groups of overlapping spikes; thus it seemed worthwhile to look more deeply for evidence of fundamental structures corresponding to the invidivual spikes within each event. For the simple spike bursts Crannell *et al*. (1978) found that the microwave and hard X-ray emissions during each time interval are consistent with a commmon origin in the same localized population of energetic electrons. Due to the apparent similarities between the single spike and the multiple-spike bursts, this result has been assumed throughout the present analysis.

Thirteen events were observed to have sufficiently intense hard X-ray emission and coincident microwave coverage with sufficiently good time resolution to allow a detailed study of the spectral evolution throughout each event. The major peaks of each burst were identified in the hard X-ray time-intensity profiles. Least-squares fits were performed for each spectrum, to both single power-law and isothermal forms. For a number of multiply-impulsive bursts, including those discussed in detail in Section III, the X-ray spectra of the major peaks are much better fit by single-temperature thermal distributions.

Microwave spectra were obtained for the times corresponding to the X-ray peaks within each burst. The turnover frequency, f_t, the frequency at which the spectrum changes from being optically thin to optically thick, was determined empirically according to $f_t = 0.7\ f_m$, where f_m is the frequency at which the maximum flux was observed. Then the following procedure for finding the ambient magnetic-field strengths from the properties of the microwave spectra was applied.

The magnetic-field strength corresponding to each peak within an event was calculated according to the following formula, taken from the work on gyrosynchrotron radiation from a thermal population of electrons by Mätzler (1978):

$$f_t = f_c\ (5.8 + 0.406T) \left\{ 0.25 \times 10^{-25}\ \frac{n_e z}{B} \right\}^{1/(\gamma-2)} \text{Hz} \qquad (1)$$

where $f_c = eB/mc$ = the local cyclotron frequency in Hz; T = the source electron temperature in keV, as derived from the X-ray spectrum; $n_e z$ = the column density in cm^{-2}; B = the ambient magnetic-field strength in Gauss; and γ = the high-frequency (very optically thin) slope of microwave spectrum. The value adopted for the column density, $n_e z = 4 \times 10^{17}\ cm^{-2}$, is typical of the relevant region of the solar atmosphere (Mätzler 1978). The microwave spectral slope, $\gamma = 8$, was taken from Mätzler (1978), but only after verification by inspection of several microwave spectra. The accuracy of these estimates is quite adequate because Equation 1 is only weakly dependent on both quantities.

For the parameter values given above, the magnetic-field strength depends on the electron temperature and the turnover frequency according to the following relationship:

$$B = 2.2 \times 10^{-8} \left[\frac{f_t}{5.8 + 0.406\ T} \right]^{8/7} \text{G}. \qquad (2)$$

It is crucial to note that, without the temperature derived from the hard X-ray spectra, it would be impossible to determine the magnetic-field strength for each peak. The microwave spectra alone are not sufficient to distinguish whether peak-to-peak changes in the observed turnover frequency indicate changes in the magnetic field, or simply reflect changes in the temperature of the source electrons.

III. RESULTS

On the basis of microwave spectral characteristics alone, the 13 events studied fall into two categories:

(1) Eight events in which the microwave spectra retain the same shape and turnover frequency from peak-to-peak, changing only in relative intensity (for example, see Figure 1); and

(2) Five events in which the microwave spectra change significantly from peak-to-peak, particularly in the location of the turnover frequency (for example, see Figures 2 and 4).

Work is in progress on the set of events with spectral shapes that do not change from peak-to-peak, and is not presented in this paper. Preliminary results indicate that the multiply-peaked nature of these bursts is consistent with modulated emission from a single source.

To illustrate the second class of bursts, those with obvious peak-to-peak spectral changes, we have chosen 2 of the 5 events: 1970 September 8, 1228 to 1233 UT, and 1969 May 29, 1938 to 1944 UT. These bursts contain the largest number of clearly-separated peaks, thus providing the largest number of reliable hard X-ray and microwave spectra. The parameters characterizing these two bursts are presented in Table 1, which lists for each peak within the bursts the time of the X-ray peak; the hard X-ray flux from 28 to 254 keV; the flux at the peak of the microwave spectrum; the turnover frequency, f_t; the best-fit temperature and emission measure of the hard X-ray spectrum and the reduced χ^2 of the fit; and the corresponding magnetic-field value, derived from f_t and T, as described in Section II.

The hard X-ray time-intensity profile in the 28 to 254 keV range for the September 8 event is shown in Figure 3. The different phases of microwave evolution, shown in Figure 2 a, b, and c, are denoted in Figure 3 by the sections labelled a, b, and c. In phase a, the turnover frequencies are close to or greater than the highest observed frequency, 15.4 GHz. In the next two phases (b and c), although the high-frequency portions of the spectra differ in slope, the turnover frequencies are approximately the same, about 4.5 GHz. The inferred magnetic-field strengths range from $\gtrsim$ 240 G in phase a to ~ 75 G in the later phases, as detailed in Table 1.

The event of 1969 May 29 exhibits spectral changes which differ quantitatively from those of the September 8 event, but leads to similar conclusions. The time study of this burst, shown in Figure 5, is divided into phases a, b, and c corresponding to the microwave spectra shown in Figure 4 a, b, and c. During phase a, the turnover frequencies are approximately 4.5 GHz. In the next phase, however, a "double-humped" structure appears in each of the microwave spectra, for which two turnover frequencies can be found: 4.5 to 6 GHz, and 12 to 15 GHz. The existence of two turnover frequencies for each peak in this phase is equally consistent with source parameters of two magnetic fields or two temperatures, or both. Since a two-temperature distribution can neither be ruled out nor verified on the basis of the available hard X-ray spectra, the peaks in phase b are assumed to be characterized by the best-fit single temperature listed in Table 1. The corresponding magnetic-field values are, on the average, 50 G in phase a, and 65 and 200 G in phase b.

Finally, in phase c, the microwave spectrum resumes a single C-type shape with a turnover at approximately 12 GHz. No X-ray coverage exists for this phase, which includes a single microwave peak at 1943.1 UT. If the source of this peak were at a temperature in the range 34 to 64 keV, as is typical of phases a and b, then the turnover frequency of 12 GHz yields a magnetic-field strength in the range 130 to 230 G. This is consistent with the higher of the fields appearing in phase b.

IV. DISCUSSION AND CONCLUSIONS

We have shown that some multiply-impulsive bursts can exhibit widely-different magnetic-field strengths at different times in their duration. The question which then arises is, do these different magnetic fields appear in the same burst location, or are they features of separate flaring regions?

According to the Solar-Geophysical Data Prompt and Comprehensive Reports (1969 through 1972), each impulsive burst correlates in time with only one H-alpha flare in a specific active region. This fact, in conjunction with the short time scales between the consecutive phases of magnetic-field evolution, implies that if there were separate sources within one burst, they must be located within the same active region.

Observational evidence on flare-associated magnetic-field changes is ambiguous at best, and often contradictory (Rust 1976a, b). Although extensive observations of the photospheric field have been obtained over the past 20 years (e.g., Howard and Babcock 1960; Howard and Severny 1962; Severny 1969; Michard 1971; Harvey and Harvey 1976), almost no information has been obtained on the temporal evolution and spatial structure of the fields in the chromosphere and corona, where most hard X-ray and microwave bursts occur. The available evidence, mostly indirect, leads to the conclusion that the magnetic field in a single location does not change during flares by factors of 2 to 3, as would be required to fit the present observations. The existence of homologous flares, which are nearly identical events occurring within hours of each other, strongly suggests that the magnetic features of a flaring region are not destroyed, even during large events (de Feiter 1974; Švestka 1976; Zirin 1978). The persistence of magnetic structures above active regions is implied also by the existence of "elementary burst structures" both in hard X-ray and [illegible] microwave events (van Beek, de Feiter and de Jager 1974; de Jager and de Jonge 1978; Wiehl 1978). Magnetic reconnection processes, which are thought to provide the energy for the impulsive phase, convert at most 5% of the ambient magnetic-field energy into heating and particle acceleration (Baum and Bratenahl 1976; Schnack and Killeen 1976, quoted by Spicer 1978). Furthermore, the May 29 burst exhibits an <u>increase</u> in magnetic-field strength, which is contrary to the theoretical expectations of magnetic-energy release during flares.

We are, therefore, led to conclude that the different magnetic-field strengths belong to separate regions in the flare area. The idea that complex, impulsive structures in flares originate in different areas has been proposed by many authors (e.g., Beigman <u>et al</u>. 1969; Hagen and Neidig 1971; Anderson and Mahoney 1974; Vorpahl 1976; Zirin 1978). This suggestion has been supported primarily by evidence of an indirect nature. Zirin and Tanaka (1973) observed good temporal correlations between hard X-ray spikes and H-alpha brightenings during the 1972 August 2 flare. Alissandrakis and Kundu (1975) and Hobbs <u>et al</u>. (1973) observed impulsive microwave bursts with the NRAO interferometer at 3.7 and 11.1 cm. They found evidence for discrete small-scale features within the bursts, with sizes of a few arc seconds. Using the VLA interferometer at 4.9 GHz, Marsh, Zirin and Hurford (1978) observed microwave events with impulsive components clearly located in regions a few seconds of arc apart, but with no hard X-ray coverage. All of these observations are consistent with the existence of small-scale spatial features within impulsive flares.

Estimates of the distance between the sources within a multiply-impulsive burst can be made in two independent ways. One method utilizes the hypothesis that the time between successive phases of microwave spectral evolution, Δt, defined as the time between the last hard X-ray peak in one phase and the first peak in the following phase, equals the time requested for some initiating disturbance to travel between these regions. If these component sources are connected by common magnetic field lines, then a shock wave or other plasma-wave disturbance would propagate between the regions at or near the local Alfven speed, V_A. Assuming that this speed remains approximately constant over the distance traversed, we can express the distance, D, between the individual sources as follows:

$$D = V_A \cdot \Delta t \approx (2.2 \times 10^6 \ B \ n_e^{-1/2}) \ \Delta t \quad \text{km} \ , \tag{3}$$

where n_e = local electron density in cm^{-3}, B is the local magnetic-field strength in Gauss, and Δt is in seconds.

An alternative distance estimate is obtained by relating the derived magnetic-field values for the different sources to their height in the solar atmosphere, then finding the distance between the respective heights. This method obviously underestimates the true distance, since it does not account for any horizontal separation. The magnetic-dipole model of the field above a sunspot, developed by Takakura and Scalise (1970), was used, which describes the field strength as a function of height as

$$B = B_o \left[\frac{d}{d + h}\right]^3 \ G, \tag{4}$$

where B_o = the sunspot's photospheric field value in Gauss; d = distance of the vertical magnetic dipole below the photosphere, defined to be 3.5×10^4 km in the model; and h = the height of the burst above the photosphere in km.

Taking B_o = 2800 G after Castelli *et al*. (1974), we find

$$h = (1.2 \times 10^{17}/B)^{1/3} - 3.5 \times 10^4 \ \text{km} \tag{5}$$

and therefore the vertical distance between the sources is

$$\Delta h = (1.2 \times 10^{17}/B_1)^{1/3} - (1.2 \times 10^{17}/B_2)^{1/3} \text{ km.} \quad (6)$$

For the September 8 event, the local Alfven speed is $\sim 3.5 \times 10^3$ km s^{-1} and the temporal separation between phases a and b is $\sim$ 12 s; substitution of these values for V_A and Δt into Equation 3 yields a source separation of about 4.2×10^4 km. According to Equation 6, the magnetic-field strengths of $\geq$ 240 and $\sim$ 75 G found for the sources in phases a and b imply a vertical source separation of $\Delta h \geq 3.7 \times 10^4$ km, which is comparable to the first estimate.

For the May 29 event, it is difficult to judge when the actual change in spectral phase occurs; both the hard X-ray and the microwave fluxes are too low to determine the spectrum between 1939.1 and 1941.7 UT, and there is no hard X-ray coverage during phase c. Also, the existence of the "double-humped" spectra in phase b imply a more complicated situation than for the September 8 burst. If we estimate the time difference between phases b and c to be no more than 30 s, according to the microwave records, then the maximum distance between sources is $\sim 8.1 \times 10^4$ km for the local Alfven speed of $\sim 2.7 \times 10^3$ km s^{-1}. Using Equation 6, a vertical separation of $\Delta h \gtrsim 3.8 \times 10^4$ km is found for the two regions, whose magnetic-field strengths are $\sim$ 65 G and $\sim$ 200 G. This is over twice the estimate of the vertical separation between the two regions, which may indicate that the sources have a significant horizontal separation.

In conclusion, our analysis of hard X-ray and microwave bursts has identified a class of multiply-impulsive solar events which consist of basic impulsive spikes, groups of which originate in localized flaring regions. For the events discussed, the estimated separation between these regions ranges from roughly 3.8 to 8.1 x 10^4 km (50 to 110 arc seconds). Further investigation of the fine structure within regions producing complex flares will benefit greatly from the use of observational equipment with good temporal and spatial resolution. Coincident observations with hard X-ray imaging instruments and interferometers operating in the microwave range are needed particularly to resolve the basic impulsive elements in these bursts, thereby increasing our understanding of the underlying physical processes.

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Table 1. Observed and Derived X-Ray and Microwave Parameters

X-RAY PEAK TIME in UT	X-RAY FLUX 28-254 keV in photons cm^{-2} s^{-1} keV^{-1}	MICROWAVE FLUX DENSITY at f_m in 10^{-22} W m^{-2} Hz^{-1}	f_t in GHz	T in keV	EM in 10^{-45} cm^{-3}	reduced χ^2	B in Gauss
1970 SEP 8							
$12^{h}29^{m}08.^{s}88$	0.028	≥40	≥11	*	*	*	*
12 29 22.64	0.109	≥90	≥14	63.1 + 12.8	0.21 + 0.04	0.45	≥160
12 29 30.64	0.097	≥115	≥12	44.0 + 4.2	0.25 + 0.03	0.99	≥186
12 29 40.24	0.106	≥125	≥15.4	45.8 + 4.2	0.26 + 0.03	0.54	≥239
12 29 55.92	0.043	58	~7	*	*	*	*
12 30 48.72	0.055	68	4.6	39.3 + 5.6	0.16 + 0.04	0.34	69
12 31 21.98	0.053	161	4.0	*	*	*	*
12 31 35.74	0.117	156	4.5	31.0 + 2.7	0.45 + 0.05	1.83	81
12 31 43.42	0.095	140	~4	26.9 + 2.8	0.45 + 0.05	1.35	~80
1969 MAY 29							
$19^{h}38^{m}35.^{s}25$	0.089	94	4.3	50.2 + 7.2	0.20 + 0.03	1.53	52
19 38 53.19	0.094	130	4.6	56.0 + 8.0	0.19 + 0.02	1.47	50
19 41 56.19 [a]	0.289	290 ; 390	6 ; 14	52.3 + 5.1	0.62 + 0.06	1.14	72 ; 188
19 41 59.75 [a]	0.320			53.1 + 5.0	0.68 + 0.06	1.23	
19 42 08.69	0.351	380 ; 530	6 ; 15	64.2 + 6.3	0.64 + 0.04	0.59	60 ; 171
19 42 24.03	0.166	240 ; 310	4.6 ; 12	34.2 + 2.4	0.55 + 0.06	0.28	75 ; 229
19 42 30.44	0.192	170 ; 390	4.5 ; 13	45.6 + 4.3	0.47 + 0.04	0.76	60 ; 198
~19 43 06 [b]	-	700	12	(34 - 64)	-	-	(130 - 230)

* X-ray flux is too low for determination of these quantities.

a These two peaks correspond to a single peak in the microwave records.

b No X-ray coverage at this time.

Figure Captions

Figure 1. Microwave spectra at the times of peak intensity during the multiple-spike burst of 1970 December 12. Note the consistency of spectral shape and turnover frequency.

Figure 2. Microwave spectra at the times of peak intensity during the multiple-spike burst of 1970 September 8. The spectra are divided into phases a, b, and c according to spectral morphology.

Figure 3. Time-intensity profile of the multiple-spike burst of 8 September 1970. Portions labelled a, b and c correspond to the phases of microwave spectral evolution shown in Figure 2 a, b, and c, respectively.

Figure 4. Microwave spectra at the times of peak intensity during the multiple-spike burst of 1969 May 29. The spectra are divided into phases a, b and c according to spectral morphology.

Figure 5. Time-intensity profile of the multiple-spike burst of 1969 May 29. Portions labelled a, b and c correspond to Figure 4 a, b, and c respectively.

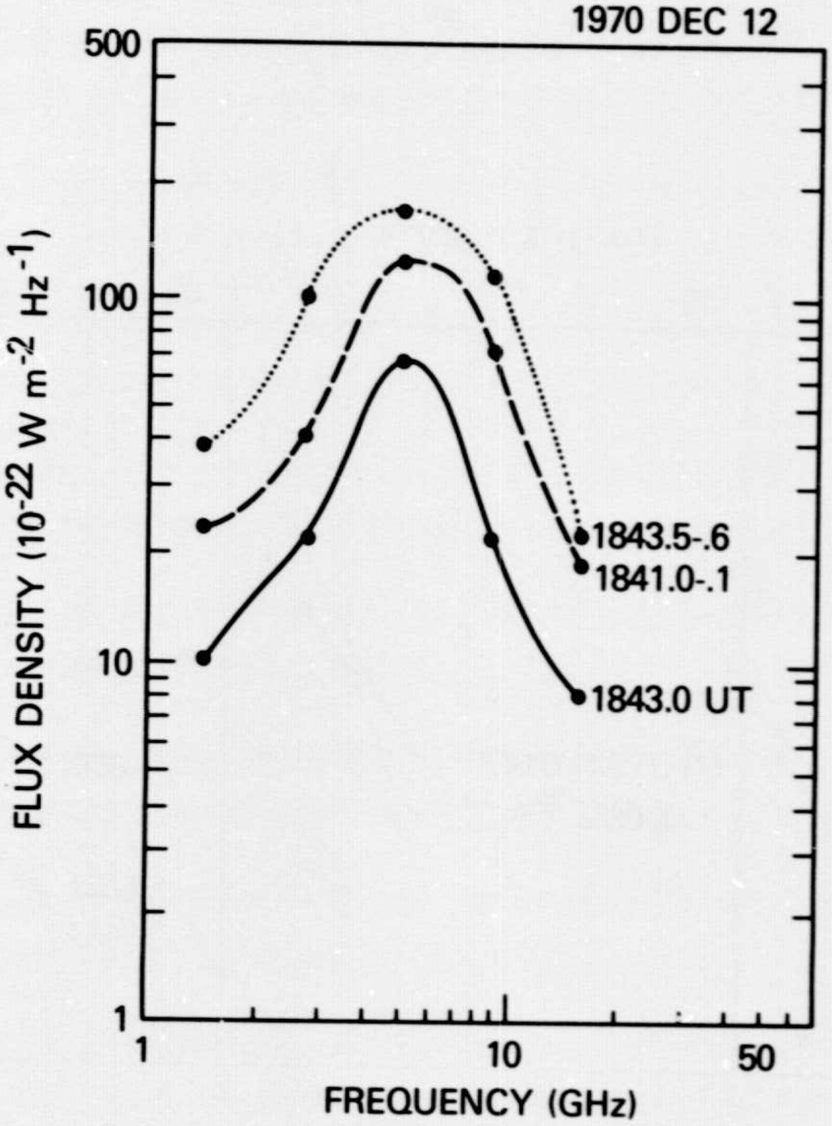

1970 DEC 12
500
100
10
1
1
10
50
FREQUENCY (GHz)
FLUX DENSITY (10^{-22} W m^{-2} Hz^{-1})
1843.5-.6
1841.0-.1
1843.0 UT

Figure 1

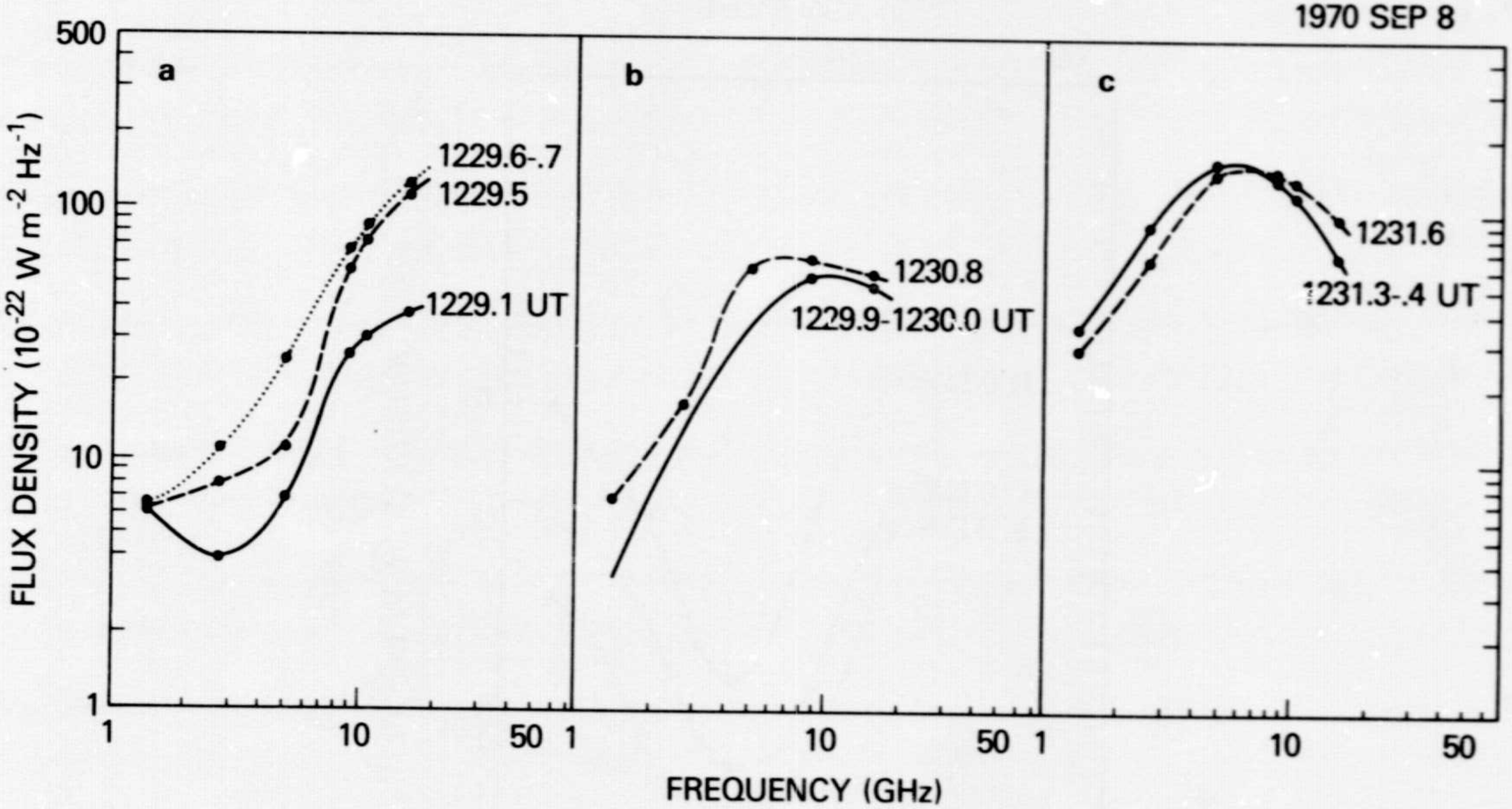

1970 SEP 8
a
b
c
FLUX DENSITY (10^-22 W m^-2 Hz^-1)
FREQUENCY (GHz)
500
100
10
1
1
10
50
1229.6-.7
1229.5
1229.1 UT
1230.8
1229.9-1230.0 UT
1231.6
1231.3-.4 UT

Figure 2

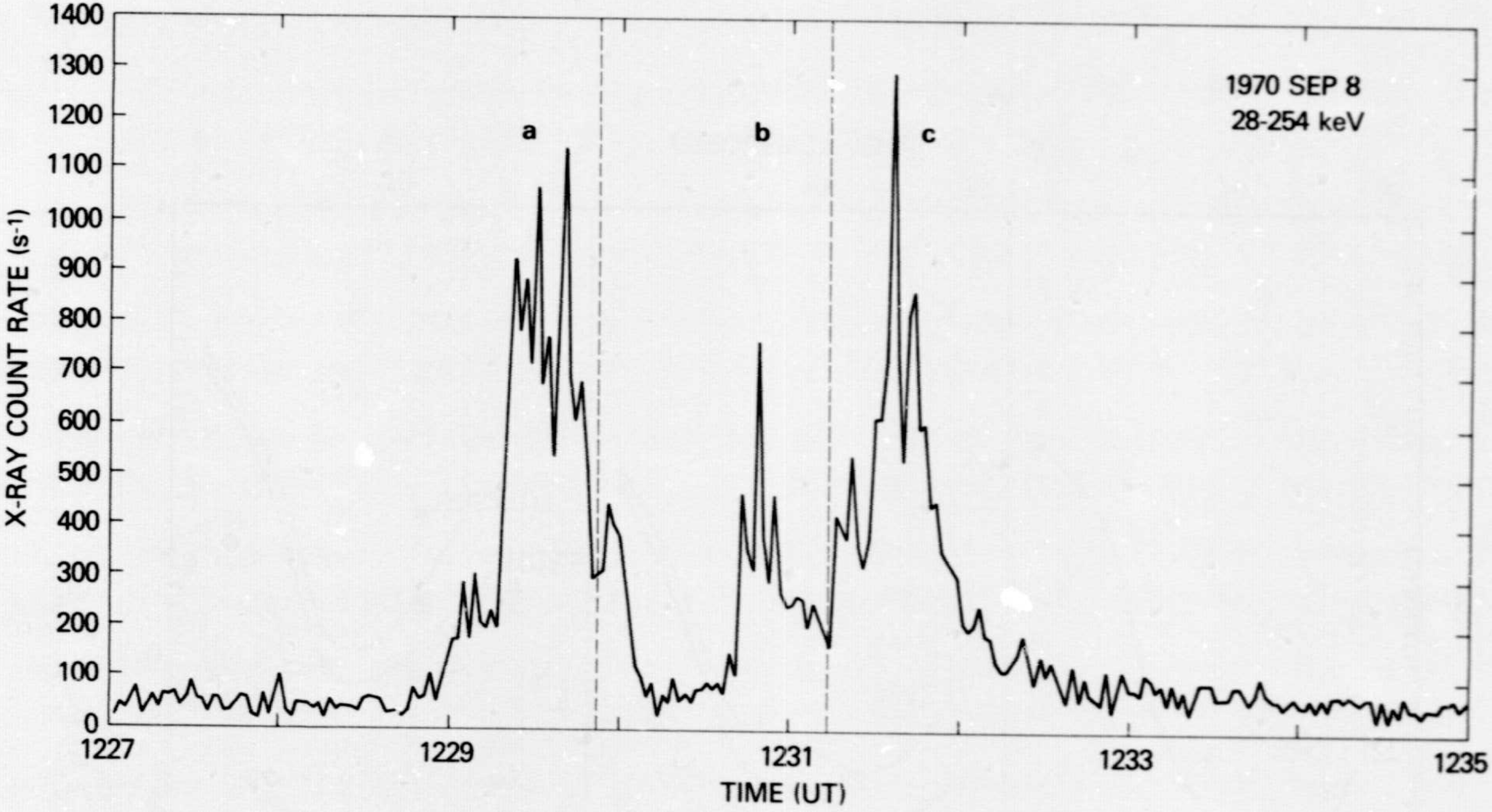

1970 SEP 8
28-254 keV
a
b
c
X-RAY COUNT RATE (s-1)
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1227
1229
1231
1233
1235
TIME (UT)

Figure 3

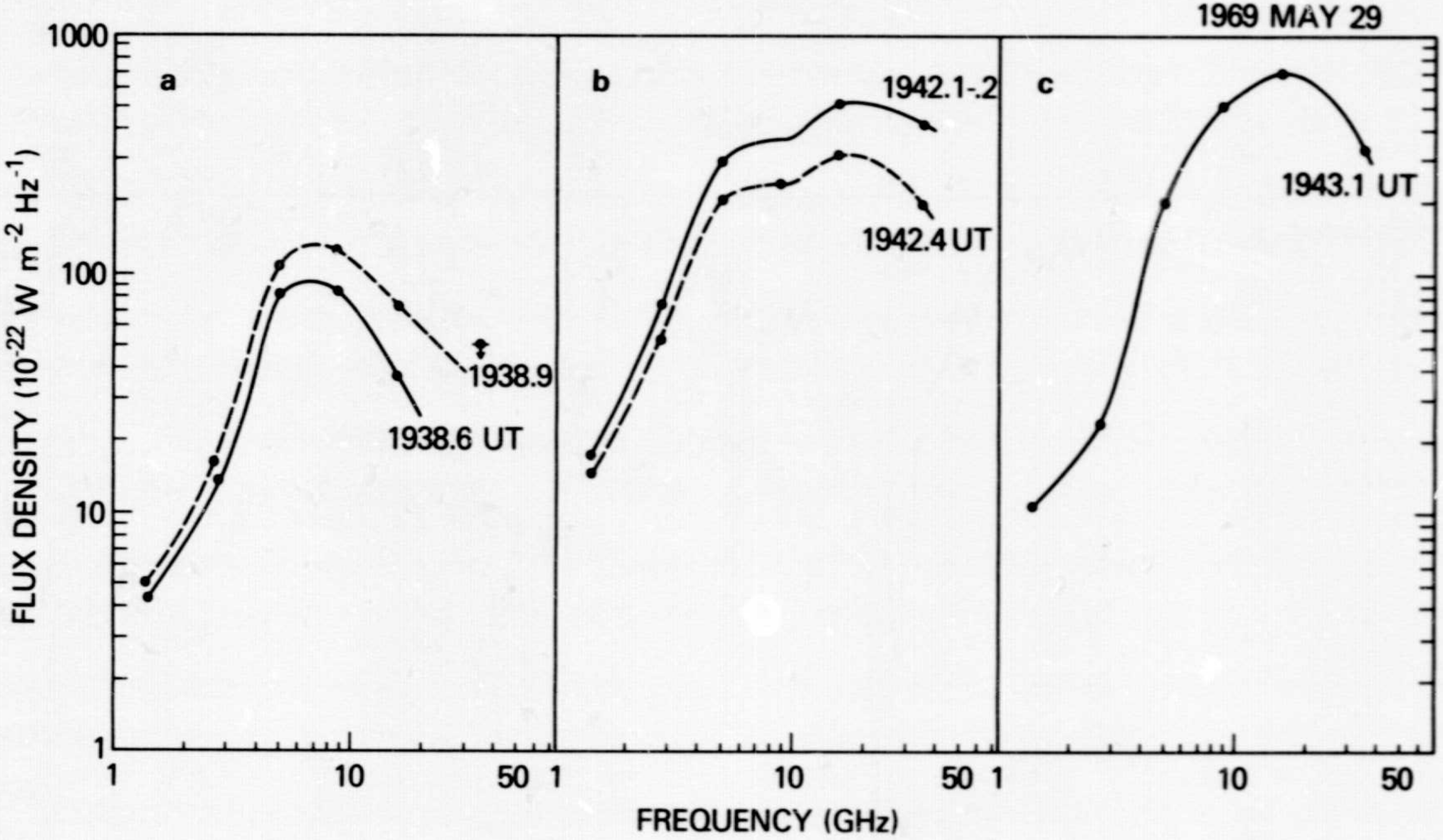
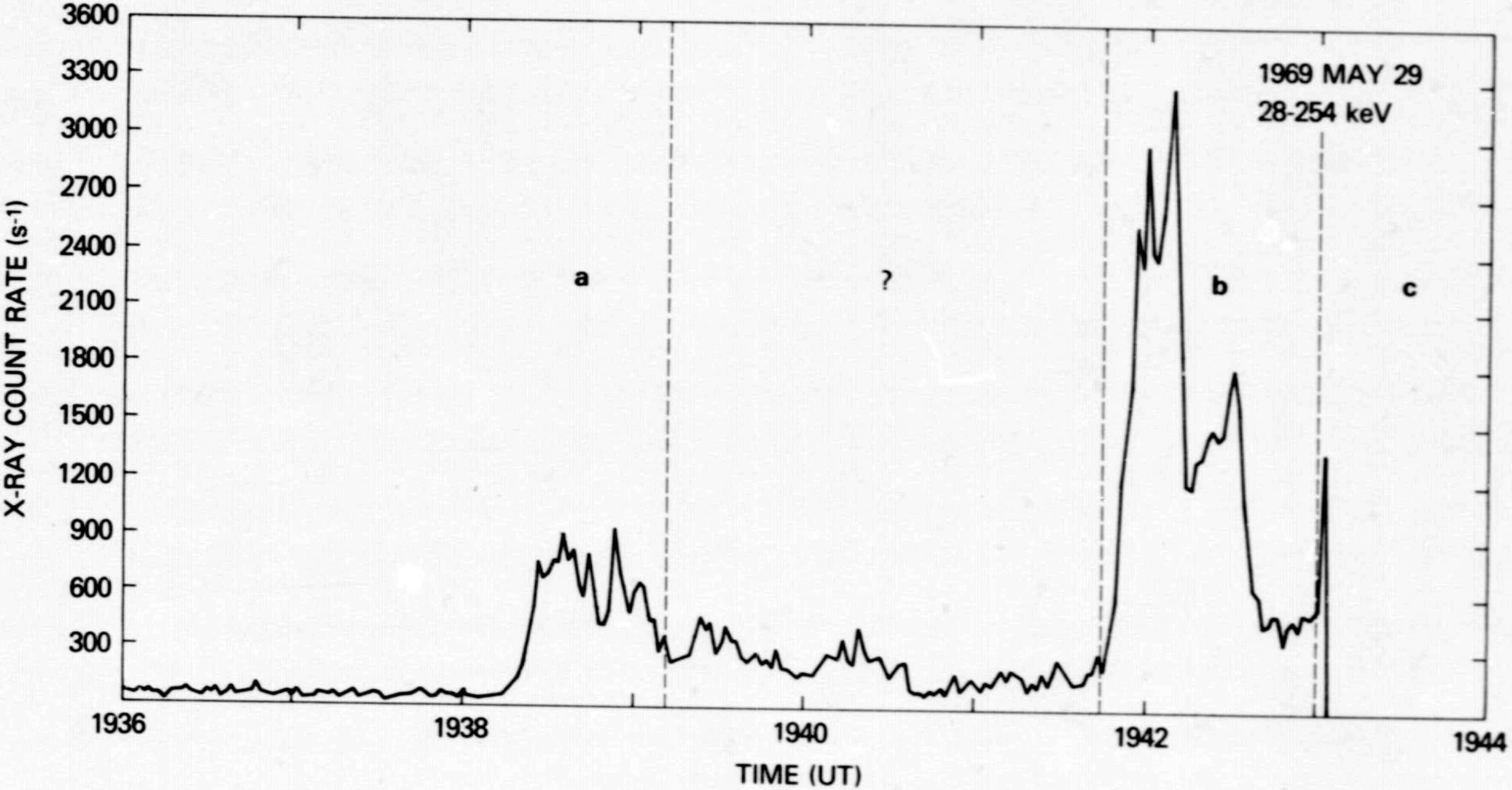

1969 MAY 29
a
b
c
1938.9
1938.6 UT
1942.1-.2
1942.4 UT
1943.1 UT
FLUX DENSITY (10^{-22} W m^{-2} Hz^{-1})
1000
100
10
1
1
10
50
FREQUENCY (GHz)

Figure 4



3600
3300
3000
2700
2400
2100
1800
1500
1200
900
600
300
X-RAY COUNT RATE (s-1)
1936
1938
1940
1942
1944
TIME (UT)
1969 MAY 29
28-254 keV
a
?
b
c

Figure 5