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Evidence for Inhomogeneous Thermal Sources Of Two Similar Solar Spike Events of 1978 May 5 and December 4

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Abstract

Two short-duration single-spike solar events of 1978 May 5 and December 4 exhibit similar time profiles in the microwave and hard X-ray ranges, indicating emission from compact sources. Microwave spectral observations exhibit inhomogenieties present in the source parameters. The existence of fine time structures in the microwave time profiles at 10.4 GHz from Berne are interpreted as a signature of the dynamics of a disturbance travelling through the source at the ion-sound speed. Stereoscopic observations with the hard X-ray detector on the solar orbiter, Helios-2, and the Berne microwave antennae do not indicate any time lag or differences in the time profiles during the impulsive phase. This is taken as evidence for the absence of directionality of emission making beam models unlikely for short duration single spike events.

Subject Headings: Sun: flares - Sun: radio radiation - Sun: X-rays

1. Introduction

Solar flares are an exceedingly complex phenomenon. Some progress in understanding them has been achieved recently by investigating short-duration, simple, single-spike events in both microwave and hard X-rays. Statistical studies as well as case studies of such events have yielded some information about the dimensional extent of the flare region and the energetics involved. It is now becoming apparent that the flares can be classified broadly into two types (Priest, 1981). Simple short-duration "compact flares" primarily are associated with a closed loop topology while the long lasting events with complex time profiles are associated with a two-ribbon geometry. The loop structures and the arcade of loops clearly indicate the part played by the magnetic fields in the flare phenomena.

Studies of the hard X-ray spikes and the associated microwave data have significantly contributed in substantiating some of the proposed models (Crannell et al., 1978; Brown et al., 1979; Spicer, 1981; Smith and Lilliequist, 1979; Kundu et al., 1982). Earlier investigations have shown that the time profiles of hard X-rays and associated microwave enhancements show great similarity. The impulsive phases in both emissions reveal the most rapid time variations. Recent high time resolution X-ray studies have shown variations on time scales as short as a few tens of milliseconds (Hurley, 1982; Kiplinger, et al., 1983). The microwave bursts are due to gyrosynchrotron emission of the energetic electrons spiraling around the magnetic field lines (Ramaty, 1969), while the hard X-rays are due to bremsstrahlung from the energetic electrons. The following questions can be investigated from the relative time delays in the fine structures of the X-ray and microwave time profiles: Is the same population of energetic electrons responsible for both types of emission? What is the exact location of the two types of emission? Periodicities or quasi-periodicities of such time features could reveal the dynamics within the trapping magnetic regions. Quasiperiodic modulations during the rising phase in a class of events were explained by Wiehl and Matzler (1980) as resulting from a disturbance travelling through the plasma under adiabatic compression .

Spectral studies both of hard X-rays and of microwaves and their modelling have been undertaken to decide the thermal or non-thermal origin of the energetic electrons (Elcan, 1978; Smith and Lilliequist, 1979). Observations of the microwave events at closely spaced frequencies (Magun et al., 1981) clearly show that in most cases the low frequency microwave spectra have a power law spectral index less than 2.0, indicating inhomogenities in the parameters of the emitting region (Dulk and Dennis 1982; Wiehl et al., 1982). It is also known that a distribution of temperatures in the flare plasma can produce power law hard X-ray spectra (Colgate, 1978; Smith and Harmony, 1982). One-dimensional fluid simulations of the solar plasma producing hard X-rays have shown that a thermal model is more efficient energetically than the non-thermal models. It is much easier to heat up plasma to 10^8 K than to accelerate a significant fraction of its electrons to > 100 keV (Smith and Harmony, 1982). Recent results of stereoscopic observations of the hard X-rays have not revealed any directivity of the hard X-ray emission, indicating the absence of directed beams of accelerated electrons (Kane et al., 1980b, Zolcinski et al., 1982).

We present observations of two similar short-duration events, those of 1978 May 5 and of 1978 December 4. Similarities and differences between the hard X-ray and microwave data are discussed, in which the X-ray and microwave spectral analysis for the 1978 December 4 event is shown to argue for the adoption of a thermal model. The microwave spectral analysis also indicates the inhomogeneous character of the source parameters, and the fine time features are interpreted as resulting from the propagation of a disturbance through the source region.

2. Instrumentation

The hard X-ray observations reported here were obtained with the γ-ray burst detector on the solar orbiter, Helios-2. The spacecraft was launched into a heliocentric orbit on 1976 January 16 and operated until the end of 1979, detecting more than 50 solar hard X-ray events. No other solar hard X-ray data are available during this interval (Kane et al., 1980a). Continuous data recovery from the Helios-2 in its solar orbit has enabled the monitoring of events from the back side of the Sun.

The basic detector is a CsI(Tl) scintillator crystal (diameter 3.8 cm, thickness, 1.9 cm). The details of the instrumentation have been previously reported (Cline et al., 1979). Counts of events with energy loss above 120 keV are accumulated in 4, 32 and 250 ms intervals with continuous monitoring and storage in three circulating memories. When the number of counts in any one of these memories exceeds a preset commandable number, a trigger pulse is generated and the circulating memories are frozen, providing the pre-trigger time profile. After the trigger-time, the counts are stored sequentially in another set of three memories to obtain post-trigger time histories. Nested time histories, around the trigger time are obtained for 2 s with 4 ms resolution, for 16s with 32 ms resolution, and for 128 s with 250 ms resolution. Due to the location of the detector on the spinning spacecraft, significant spin-modulation is revealed. The spin-period of Helios-2 was nearly one second; for the present investigation four quarter-second accumulations are added together to minimize the spin-modulation effects.

The microwave data for the events of 1978 May 5 and December 4 were obtained with the Berne radiotelescope at 8.4 and 10.4 GHz with a time resolution of 0.1 s and 1.0 s, respectively. In order to reconstruct the radio spectrum at the time of maximum emission, these data were supplemented by other observations as listed in the Comprehensive Solar Geophysical Reports (Coffey, 1978, 1979).

3. Observations

3.1. Event of 1978 May 5

On 1978 May 5 the Helios-2 solar orbiter was 0.315 AU from the Sun just beyond the west limb, as seen from the Earth (Figure 1). A trigger due a hard X-ray flux enhancement occurred at $10^h22^m21^s$ UT at the spacecraft. The time at which these emissions would have been observed at Earth is $10^h28^m3.5^s$ UT. An Hα flare was reported starting at 10:28 UT with a peak at 10:30 UT in the active region with McMath number 15266 located at north 28° and west 54°.

The microwave data from Berne and the hard X-ray data from Helios-2 offer a stereoscopic view of this event. Very good coverage of the radio emissions at microwave, decimetric and metric band is reported in the Comprehensive Solar Geophysical report (Coffey, 1978). Sudden ionospheric deviations (SID) are reported from 10:27 - 11:54 UT. The Lockheed OSO-8 X-ray mapping heliometer also recorded a spike event at this time (Acton, private communication). The electron detector (> 2 MeV) on the Japanese geostationary meterological satellite, HIMAWARI, recorded an increase in the flux starting at about the same time (Coffey, 1978). An anamolous noise storm depression is reported on May 5th at approximately 10:30 UT (Bohme and Kruger, 1982). The peak of this depression occurs at 113 MHz, ascribed as due to the excess trapped electrons in the loop.

Figure 1 shows the intensity-time profiles of the hard X-rays and microwaves, together with the dynamic radio spectrum from Zurich, Switzerland (courtesy of A. Benz). The relative locations of the Earth, Sun and the Helios-2 spacecraft are also shown. The hard X-ray burst and the impulsive part of the microwave burst lasted for 52 seconds; both time profiles show a simple single spike. The metric radio emission starts prior to the impulsive hard X-rays. Type III emission at 980 MHz to 810 MHz is also seen thirteen seconds prior to the peak in the hard

X-ray and in microwave. Type V radio emission is also evident in Fig. 1.

The time profile of the hard X-ray burst is symmetrical with e-folding rise and fall times of 20 s. The counting rate of photons above 120 keV increases linearly with time, reaching its peak in 30 s. Fluctuations on this linear rise occur in coincident with similar microwave modulations. The separations between the features are 3.2 s during the rise, 2.5 s around the peak and about 6 s during the fall of the burst. As the microwave flux increases the time separation between successive modulations decreases; the reverse is true during the decay phase of both events. Approximately fifteen seconds after the peak the microwave flux shows a smooth exponential decay. The microwave rise and fall times defined at the quarter power levels in the microwave data are 15 seconds and 20 seconds, respectively.

The significant difference between the microwave and hard X-ray time profiles is the existence of a small increase in the microwave emission prior to the impulsive rise, in coincidence with the metric emission. The other main difference is the existence of the long tail of relatively constant flux lasting for nearly 100 s after the impulsive phase, as shown in Figure 2. The Helios-2 hard X-ray detector (>120 keV) does not show this tail.

No spectral information is available for this hard X-ray event. The radio spectrum was constructed by using the Berne data as well as the maximum flux values published in the SGD Comprehensive Reports (Coffey, 1978). The peak frequency is approximately 8.4 GHz and the spectrum falls off steeply at higher frequencies (Fig 3). At the lower frequencies the power law spectral index of the spectrum is 1.5 while below 1-2 GHz the radio spectrum again rises steeply.

3.2. Event of 1978 December 4

A very similar solar event was seen both in hard X-rays and at radio frequencies on 1978 December 4. Helios-2 was 0.661 AU from the Sun, about

11.5° east of the Sun-Earth line. At $13^h17^m35.4^s$ a trigger was registered. This event was also seen in hard X-rays with ISEE-3, HEAO-A1 and the Soviet spacecraft, Venera 11 and 12. Both high time resolution and spectral data in hard X-rays are available for this event. The total duration of the impulsive enhancement is 10 seconds of which the first five seconds was a swell (slow rise, slow decay). The event in the remaining five seconds show two distinct spikes with two seconds separation between them. Among all the hard X-ray detectors in various satellites, only the ones with low thresholds in energy, reveal the first five second increase. High energy threshold sensors such as those on Venera 11 (≈ 250 keV) did not permit the detection of this increase. Partly because of a high threshold of the sensor and the narrowness of the two spikes, Helios-2 data are strongly modulated and do not reveal the true time profile of the event. Figure 4, reproduced from Kane et al. (1982), shows the hard X-ray and microwave time profiles.

The spectral data for the hard X-rays have been reported for this event by Kane et al. (1982) from the ISEE-3 sensor. They have fitted power law spectra for two peaks. An exponential function of the form $I = I_0 \exp(-E/kT)$ also fits the data as indicated by the χ^2 values in Table 1. The values of kT vary from 15 to 17 keV.

The microwave data at 10.4 GHz show a rise time of 7.7 s and fall time of 12.0 s for the main spike on December 4. The impulsiveness (peak flux/rise time) of the microwave spikes for the May 5th and December 4th events are the same (28.9 SFU/s and 29.2 SFU/s, respectively). In the December 4th event, after the rapid fall of the impulsive phase, a plateau lasting for 80 s is seen, very similar to the May 5th event. The spectral index for the power law fit for the hard X-rays is about 4.3 (Table 1). The peak frequency of the microwave spectrum is around 8.4 GHz with a steep slope at higher frequencies. At the lower frequencies the power law index is approximately unity: significantly less than two. Microwave data at 10.4 GHz show a very similar time behavior to the X-rays except a longer decay time. The total event lasts for about 40 seconds against a total of ten seconds for the hard X-ray enhancement at 150 - 400 keV. The microwave flux at 10.4 GHz appears to be correlated best with the 78 to 154 keV X-ray flux, as shown in Figure 4.

The May 5th 1978 and December 4th 1978 events are clearly similar. Both are short-duration, spiky events of similar magnitude. Both reveal the same rise times in the microwave enhancement. Fine features are seen in the time profiles of both events. Microwave data also reveal the impulsive increases and long-lasting enhanced emissions after the impulsive phase. The May 5th event has a very narrow type III (980 - 810 MHz) burst prior to the microwave and hard X-rays peaks (Figure 1), and the December 4th event has three type III bursts coincident with hard X-ray peaks (Kane et al.,1982).

4. Microwave Analysis

The Microwave Spectrum is known up to 20 GHz for the May 5th event and is shown in Figure 3. In the optically thick portion of the microwave spectrum the flux, I, received from a homogenous thermal source is given by (Crannell et al., 1978)

$$I \propto f^{\alpha} \; A \; T \qquad (1)$$

where f is the observation frequency, A the area of emission and T the plasma temperature. In thermal homogeneous sources, the spectral index, α, is expected to be two. However, the measured spectral index below the peak frequency is less than 2.0 for both events under study. In order to explain the observed $I \propto f^{1.5}$ behaviour (Figure 3) we introduce inhomogenieties in the magnetic field, in the temperature and in the area of the source as follows (Schochlin and Magun, 1979; Dulk and Dennis, 1982).

$$B = B_{max}(r_{min}/r)^{\alpha_B},\ T = T_{max}(r_{min}/r)^{\alpha_T},\ \text{and}\ A = A_{max}(f_{low}/f)^{\alpha_A} \qquad (2)$$

where r is the radius of the source, r_{min} is the radius of the innermost sphere where the temperature and the magnetic field are at the maximum values, T_{max} and B_{max}, respectively. The quantity f_{low} is a frequency at the lower end of the microwave spectrum at $A = A_{max}$. The introduction of such inhomogenieties will alter the frequency dependence of the microwave spectrum below the peak frequency. A detailed discussion of the effects of inhomogenieties on the microwave spectrum are given elsewhere (Dulk and Dennis, 1982; Wiehl et al., 1982).

During the maximum phase, the hard X-ray flux from the central core of the source dominates and the spectrum appears exponential from a single temperature plasma. During the rise and fall phase, the distribution of temperatures across the source produces a power-law X-ray spectrum. To calculate the indices of the inhomogenieties, we assume for simplicity a power-law description of the hard X-ray spectrum. Because the two events of this paper show such a high degree of similarity and the X-ray spectral index, γ, is only known for the December 4 burst, we assume γ (May 5) ≈ γ (Dec 4) ≈ 4.3 during the maximum. The inhomegeniety indices derived with this assumption are $\alpha_B = 1.3$, $\alpha_T = 1.1$, $\alpha_A = 1.1$ for the May 5 event.

The temperature for single spike burst plasmas is reported to be in the range of 15 to 63 keV (Crannell et al., 1978), and the gyrosynchrotron radiation is emitted at the 10th to 40th harmonic of the gyrofrequency (Matzler, 1978). The observed peak frequency at 8.4 GHz then indicates magnetic field strengths of 300 to 75 Gauss in the source region. The observed circular polarization of 9% at 8.4 GHz is consistent with a thermal source being optically thick below and turning optically thin near the peak frequency of the spectrum. The microwave spectrum in the optically thick portion extends down to about 2 GHz with $I \propto f^{1.5}$

and then turns up again at lower frequencies (Figure 3). Because the observation frequency has to be greater than the plasma frequency we can estimate the electron density to be less than 5 10^{10} cm^{-3}.

The microwave time profile changes abruptly from the impulsive phase (A in Figure 2) to a much more gradual phase (B in Figure 2). We interpret this rapid change from the impulsive phase to the more gradual component toward the end of the impulsive phase as a change in emission mechanisms from gyrosynchrotron to free-free. The gyrosynchrotron absorption coefficient, K_{GS}, for a plasma in which the emitting electrons have an isotropic pitch angle distribution and a Maxwellian velocity distribution is given by the following relation (Dulk and Marsh, 1982):

$$K_{GS} \approx 5\ 10^{-25}\ T^7\ B^9\ n\ f^{-10} \tag{3}$$

where the temperature, T, is in units of 10^8 K, the magnetic field, B, in Gauss, the electron desnity, n, in 10^8 cm^{-3}, the frequency, f, in GHz, and K_{GS} in cm^{-1}.

For temperatures ranging from 10^5-10^9 K and frequencies from 1-35 GHz the average Gaunt factor is about 9.4 and,therefore, the absorption coefficient for the free-free process is given by (Tucker, 1975):

$$K_{FF} = 1.7\ 10^{-15}\ n^2\ f^{-2}\ T^{-3/2} \tag{4}$$

where the units are as in equation (3).

In Figure 5 we have plotted the two absorption coefficients as a function of temperature between 10^6 to 10^9 K and for electron densities between 5 10^8 and 10^{10} cm^{-3} and magnetic fields between 50 and 500 G. We estimated earlier that the temperature of the plasma is about 2 10^8 K (17 keV) (Table 1) and the electron density about 10^{10} cm^{-3}. For such values the change from free-free to the gyrosynchrotron process occurs at a temparature of about 10^8 K.

During the preheating phase ($T < 10^8$ K), the free-free mechanism is the dominant process. The impulsive phase, however, is characterized by $T > 10^8$ K and the gyrosynchrotron process is the dominant process. As the plasma cools and T falls below 10^8 K, the free-free mechanism begins to dominate again. The abrupt changes from one mechanism to the other at the beginning and the end of the impulsive phase can be explained by the very strong dependence of K_{GS} on the temperature. This allows the gyrosynchrotron process to become very efficient once the plasma has surpassed the critical temperature. During the maximum phase ($T \approx 2.10^8$ K, $n \approx 10^{10}$ cm^{-3} and $B \approx 200$ G) the absorption coefficient for the gyrosynchrotron process is about 3.3 10^{-10} cm^{-1}. Assuming an optical thickness of 0.1 to 1.0, we can estimate the source thickness to be between 3000 and 30,000 km.

5. Flare scenario

From the single spike nature, the short duration in both hard X-rays and microwaves, and the association with a type III event, we conclude that both events are compact with a closed loop gemoetry (Priest, 1982). Therefore, we expect the plasma $\beta < 1$, except possibly during the maximum phase when the temperature is highest. The occurrence of type III radiation for a short period of time indicates that $\beta > 1$ for that interval. Accordingly to Spicer and Brown (1981) the $\beta < 1$ case uses a $j_{\parallel}$ driver for the flare mechanism. A possible mechanism is the tearing mode instability of a sheared plasma magnetic flare configuration. The advantages of such a mechanism are that it can occur in any sheared magnetic configuration, notably in a loop and that no external driver is required. This mechanism is primarily a thermal one, although some particles might be accelerated to high velocities. Assuming a quasi-steady state and neglecting the effect of the electric field, the equation of motion can be written as:

$$\overline{\nabla}p = \overline{j} \times \overline{B} \tag{5}$$

Since we identified the flare driver as $j_{\parallel}$, the equation of motion requires $\nabla p = 0$. During the rapid heating, the plasma must react diamagnetically to ensure pressure equilibrium. But during the most intensive heating, pressure gradients are bound to develop. Pressure gradients are, however, related to a current prependicular to the magnetic field. Again, according to Spicer and Brown (1981), this is a situation in which β is > 1 allowing a certain fraction of the confined particles to escape with a velocity of approximately 1/3 c. These particles may be responsible for the observed type III burst. Only about 0.1% of the flare electrons above 20 keV are required to escape in order to produce the observed type III radiation (Lin 1974). During the later phase of the diamagnetic expansion in which $\beta \gtrsim 1$, particles are still able to escape but they leak into a larger volume. These low velocity electrons do not excite type III emission because their speeds are $\lesssim 1/3$ c. Instead they may be responsible for the observed type V radiation and they may in fact be retrapped by the weaker, overlying magnetic fields. Independently, Bohme and Kruger (1982) came to the same conclusion for their observations of the event of 1978 May 5.

The small modulations superimposed on the single peak may be caused by a disturbance travelling through the source at the ion-sound speed. The modulations are seen when the disturbance impinges into the lower portion of the source, where the magnetic field is stronger and the density is greater. This explains the coindicence of the modulations in hard X-rays and microwaves. The travel time, τ, of the disturbance along the flux tube of length, L, is given by:

$$\tau = L/C_s \tag{6}$$

where C_s is the ion-sound speed expressed by $(kT_e/M)^{1/2}$ where T_e is the electron temperature and M the ion mass. We assume that the plasma is an ideal gas and write the equation of state as

$$pV = NkT \qquad (7)$$

The volume of the loop is given by

$$V = \pi r^2 L \qquad (8)$$

where r is the minor radius.

Replacing kT in the formula for the ion-sound speed by the ideal gas law and using the explicit expression for the volume of the loop we are able to write the travel time, τ, as:

$$\tau = \sqrt{\frac{M\ N}{p\pi}}\ \frac{L^{1/2}}{r} \qquad (9)$$

Pressure gradients within the loop may exist during the maximum phase of the event, and we assume as a simple approximation the following dependency on r:

$$p(r) = p_o(r_o/r)^{\alpha_p} \qquad (10)$$

where p_o is the pressure at r_o and α_p is the pressure inhomogeniety index.

The low frequency microwave spectral index of m = 1.5 indicates inhomogenieties in the temperature which can be described by a corresponding temperature inhomogeniety index, α_T, (Equation 2). Since $p \propto T$, we may set $\alpha_p = \alpha_T$. The quantity α_T on the other hand can be calculated from the hard X-ray spectral index, γ (Dulk and Dennis, 1982):

$$\alpha_T = 6/(2\gamma-3). \qquad (11)$$

Substituting for p from equation (10) into equation (9) allows us to express τ as a function of r,

$$\tau = \sqrt{\frac{M\ N}{\pi\ p_o r_o^{\alpha_T}}}\ \frac{L^{1/2}}{r^{(2-\alpha_T)/2}}\ . \qquad (12)$$

Because $\beta \approx 1$, we can set the gas pressure, p_0, in equation (12) equal to the magnetic pressure, $P = B^2/8\pi$. For measured values of $B \approx 200$ G, $\tau = 3$ s, and $\gamma = 4.3$, and typical values of $N = 10^{36}$ electrons and an expansion ratio $r/r_i \approx 1.3$ with $r_i = 1500$ km, we find $L \approx 8000$ km, which is in good agreement with observations of compact sources. Here, r_i is the initial and r is the final minor radius of the loop.

If the confined plasma is heated, it expands in the direction perpendicular to the loop axis to restore pressure equilibrium.

From the diamagnetic relation,

$$\frac{B_i^2}{8\pi} = \frac{B^2}{8\pi} + nkT \quad , \tag{13}$$

one can estimate the spatial changes in the loop. The index, i, indicates initial conditions prior to the diamagnetic reaction.

The conservation of magnetic flux leads to the following equation:

$$B_i \, r_i^2 = B \, r^2 \tag{14}$$

and this can be used in equation 13 to obtain the relation

$$r/r_i = (1 + \beta)^{1/4} \tag{15}$$

For an expansion ratio $r/r_i = 1.3$, we need $\beta \approx 1.5$. By assuming the number of particles in the flux tube to be roughly constant and using Equations (8) and (14), we obtain

$$\beta/\beta_i = \frac{T \quad r^2}{T_i \quad r_i{}^2} \tag{16}$$

For a spherical volume, β/β_i would be proportional to r/r_i instead of to the square of this ratio.

Prior to the diamagnetic expansion, β_i must be < 1 to ensure particle trapping; we estimate $\beta_i \approx 1/3$. For $r/r_i \approx 1.3$ and $\beta \approx 1.5$, we obtain $T/T_i \approx 2.7$. For a maximum temperature, T, of $\approx 2\ 10^8$ K, we then estimate $T_i \approx 7\ 10^7$ K. This pre-impulsive phase plasma temperature is consistent with the free-free emission mechanism as discussed in section 4. However, it clearly requires a pre-heating mechanism, which is evidenced by the slow pre-burst increase observed in the microwave range.

6. Discussion

The similarity in hard X-ray and microwave time profiles has been demonstrated in this study and in previous investigations. The ground-based microwave data with higher sensitivity and higher time resolution reveal significant fine time structure (Figure 1 and Figure 4) also present in the hard X-ray flux. These features are interpreted as signatures of physical processes in the source region. The May 5th event was observed stereoscopically in a symmetric configuration (see positions of Earth, Sun and Heilos-2 in Figure 1). The close similarity between the time profiles of hard X-rays and microwaves (Figure 1) suggests the absence of any directionality in the hard X-ray emission. This fact makes beam models unlikely for this event. A separate study of hard X-ray events observed by Helios-2 in various configurations relative to the Sun - Earth line and ground based microwave events is in progress in order to investigate the absence of the directionality of radiation.

Our study reveals that, during the time of maximum, a thermal fit to the hard X-ray spectrum is as acceptable as a power-law approximation. At the time of peak emission the central core of the source is at its highest temperature, much above the temperature of the surrounding plasma. At lower flux levels the source region looks more like a multi-thermal plasma which produces a hard X-ray spectrum characterized with a power-law.

The well-observed microwave spectra below the peak frequency for both events clearly indicate the presence of inhomogenieties within the source.

Absorption processes inside and outside the source would make the spectral index even larger and not smaller than two as observed. The inhomogeniety indices indicate a source with a diverging magnetic field, a falling off of the temperature away from the central core, and radiation at higher frequencies originating from smaller areas of higher density and higher magnetic field strength, mostly at the feet of the loop. This decrease of the emission area with higher frequencies in the optical thick part of the spectrum is in agreement with VLA observations in which burst sizes have been observed to be 10-15 arcsec at 5 GHz and 2-3 arcsec at 15 GHz (Marsh and Hurford, 1980). The VLA observations further indicate that the observed microwave bursts occurred along a highly sheared magnetic neutral line (Marsh *et al.*, 1982), in agreement with the burst scenario outlined by Spicer and Brown (1981).

The microwave data at 8.4 and 10.4 GHz show statistically significant time fluctuations during the entire duration of the events. Integration time and counting rate statistics of the hard X-ray observations do not allow a study of such fluctuations from hard X-ray data alone, but the present study shows the simultaneous occurrence of such fluctuations in both microwaves and hard X-rays. We interpret these modulations as resulting from a disturbance travelling through the hot source at the ion-sound speed. The modulations are seen when the disturbance impinges into the lower portion of the source, where the magnetic field is stronger and the density is greater. This then explains the simultaneous occurrence of the modulations in hard X-rays and microwaves.

With this interpretation, the time between successive features in both the microwave and hard X-ray time profiles is related to the radius of the source by $\tau \propto r^{(\alpha_T-2)/2}$ (Equation 12). For $\alpha_T < 2$ the exponent is negative and one expects a decreasing τ with increasing radius. This might be the case when the magnetic field expands in order to achieve pressure equilibirum under a diamagnetic reaction.

At the fixed frequency where we measure the time, τ, the microwave flux I is proportional to A T (Equation 1). By using equation (2b) and $A = \pi r^2$ we obtain

$$I \propto r^{2-\alpha} T \tag{17}$$

Introducing this expression into equation (12) leads us to a following relation between the microwave flux and the observed time separation

$$\tau \propto I^{-1/2} . \tag{18}$$

By correlating the duration between successive modulations and the flux at the end of the interval, we obtain $\tau \propto I^{-0.7}$. This result is in fair agreement with our estimate and with an earlier result for a different event (Wiehl and Matzler, 1980).

These modulations could also be a signature of successive acceleration processes due to tearing modes (Spicer, 1976).

7. Conclusions

Our study of two similar spike events both in hard X-rays and in microwaves has revealed the following:

- No time lags or profile differences even for stereoscopic observations, indicating absence of directionality of the X-ray emission.
- A microwave spectral index of less than two in the optically thick part, indicating inhomogenieties in the source parameters.
- The emission of a decimetric type III burst 13 s before the peak of one of the hard X-ray events. This is in contrast to recently reported results of simultaneous hard X-ray spikes and type III bursts (Kane *et al.*, 1982).

- The existence of fine features in the microwave time profile that are coincident within 0.5 s with similar features in the hard X-ray time profile. These modulations have been interpreted as a signature of the dynamics of confined electrons. An alternate explanation is that the fluctuations result from successive impulsive injections of fast electrons.

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TABLE 1. Spectral Parameters for the Solar Flare on 1978 December 4

(see Figure 5)

I	Peak	χ^2	Degrees of Freedom
64 exp(-E/15)	M_1	0.55	3
70 exp(-E/17)	M_2	1.2	5
$4.1 \times 10^7 E^{-4.4}$	M_1	2.3	3
$2.6 \times 10^7 E^{-4.2}$	M_2	4.8	5

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Figure Captions

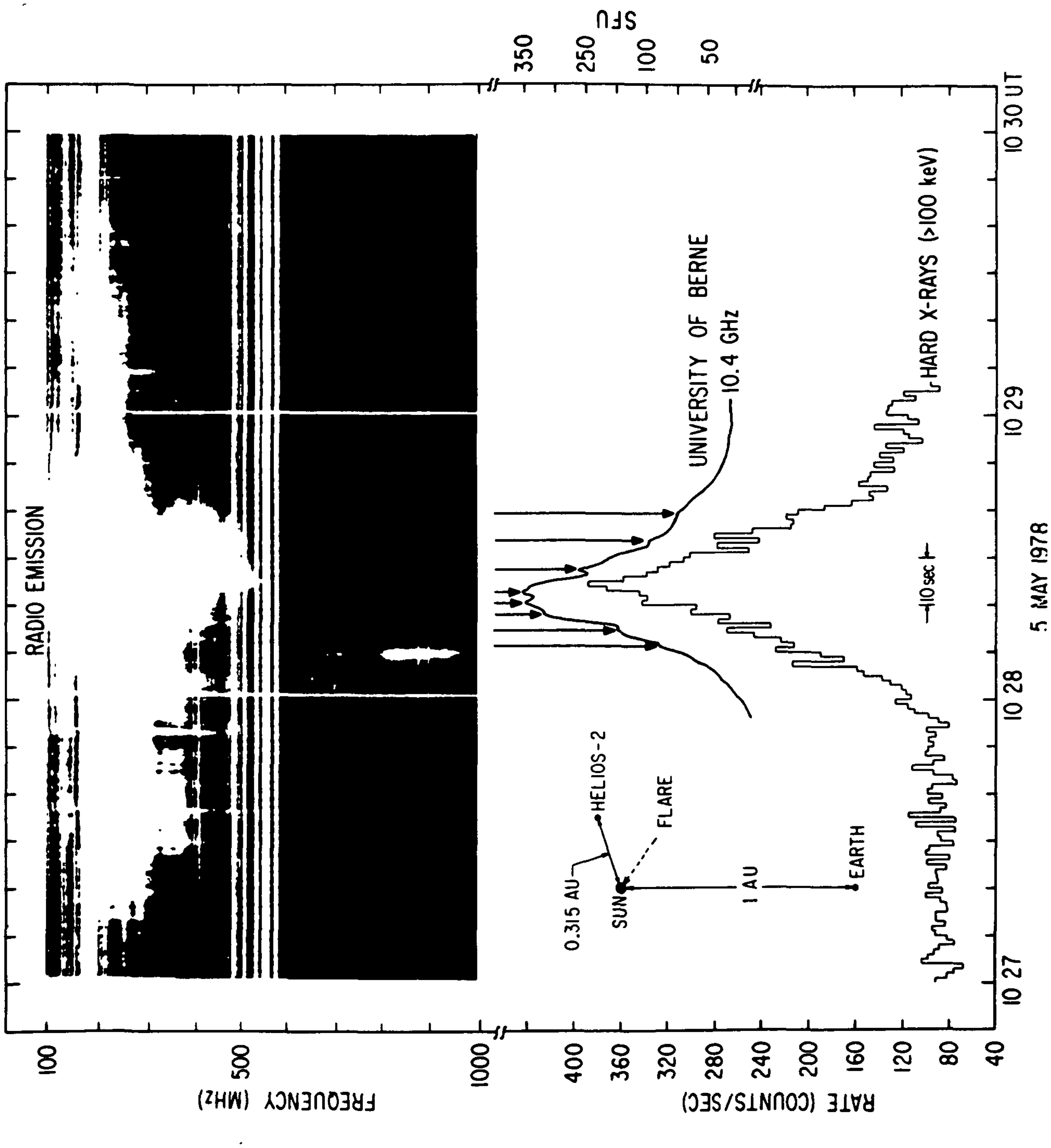
Figure 1: Flare of 1978 May 5 as observed by Helios-2 in the hard X-rays, in Berne at 10.4 GHz and in Zurich in the range from 1000 to 100 MHz. Note the modulations in the microwave time profile indicated by the arrows. The type III event preceeds the main maximum by 13 seconds. The configuration of the sun, earth and spacecraft is also depicted.

Figure 2: Extended microwave time profile at 10.4 GHz, exhibiting the impulsive (A) and plateau (B) intervals.

Figure 3: Microwave spectrum at the time of maximum emission of the event of 1978 May 5.

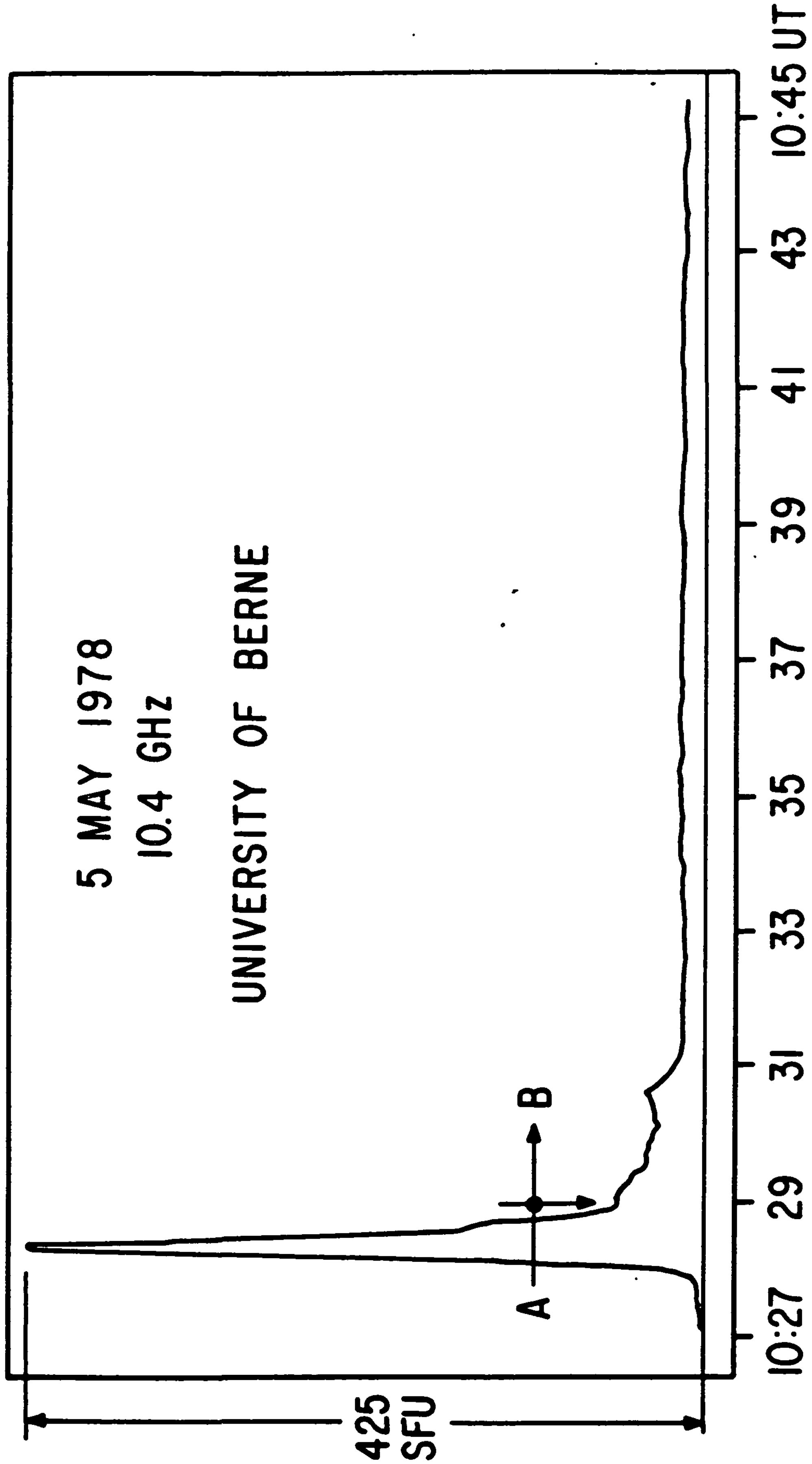
Figure 4: Absorption coefficients for the free-free and gyrosynchrotron processes for electron densities of 5.10^8 cm^{-3} (---), 10^9 cm^{-3} (____), 5.10^9 cm^{-3} (____.____), and 10^{10} cm^{-3} (____..____) and magnetic fields in the range of 50-500 Gauss.

Figure 5: Time profiles of the burst of 1978 December 4 in the X-range from 26 to 398 keV and microwaves at 10.4 GHz. Arrows indicate the modulations. Reprinted from Kane *et al.*, 1982.



RADIO EMISSION
FREQUENCY (MHz)
100
500
1000
RATE (COUNTS/SEC)
400
360
320
280
240
200
160
120
80
40
SFU
350
250
100
50
UNIVERSITY OF BERNE
10.4 GHz
HARD X-RAYS (>100 keV)
110 sec
HELIOS-2
FLARE
0.315 AU
SUN
1 AU
EARTH
10 27
10 28
10 29
10 30 UT
5 MAY 1978

Fig. 1



5 MAY 1978
10.4 GHz
UNIVERSITY OF BERNE
A
B
425 SFU
10:27
29
31
33
35
37
39
41
43
10:45 UT

Fig. 2

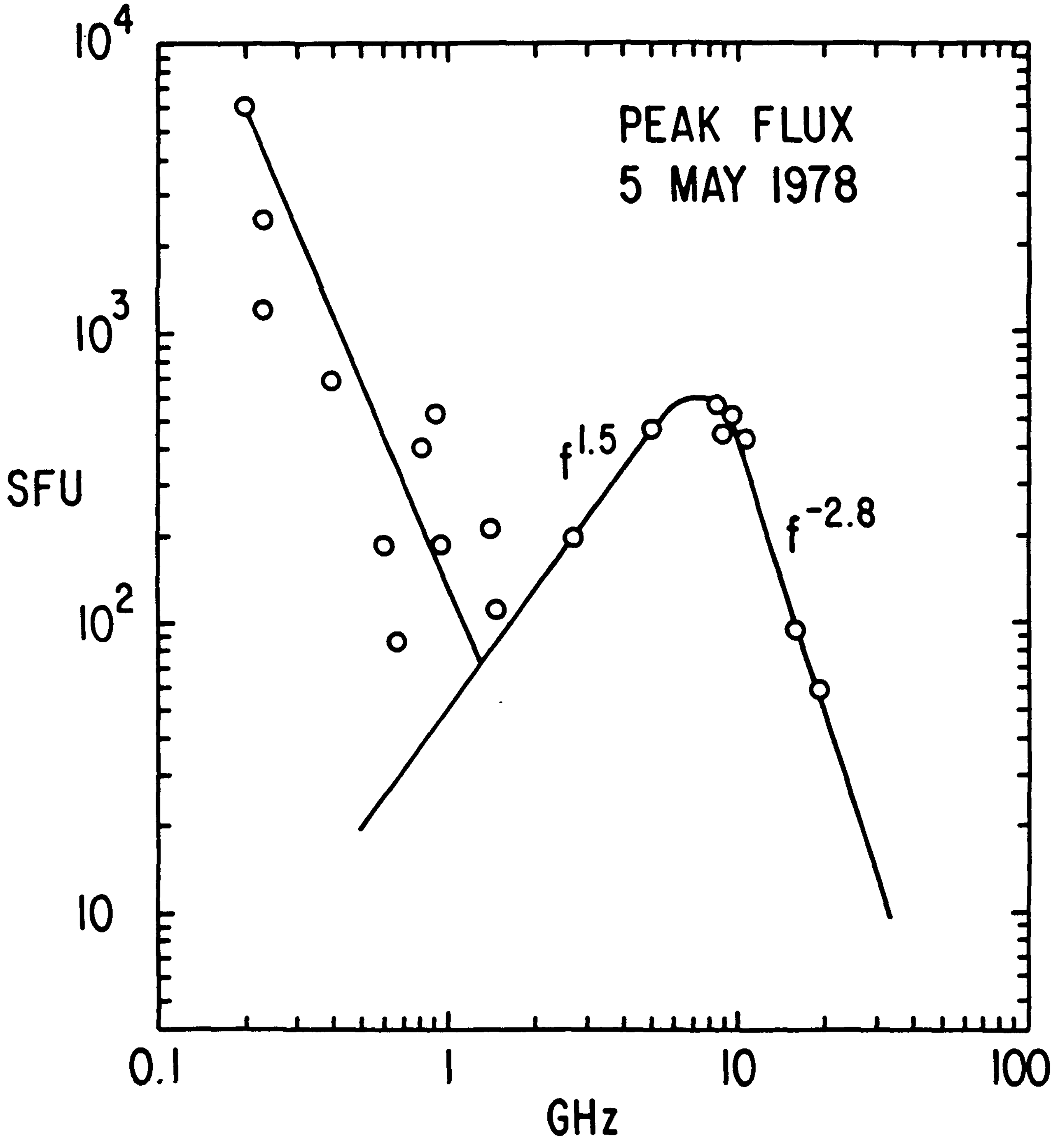
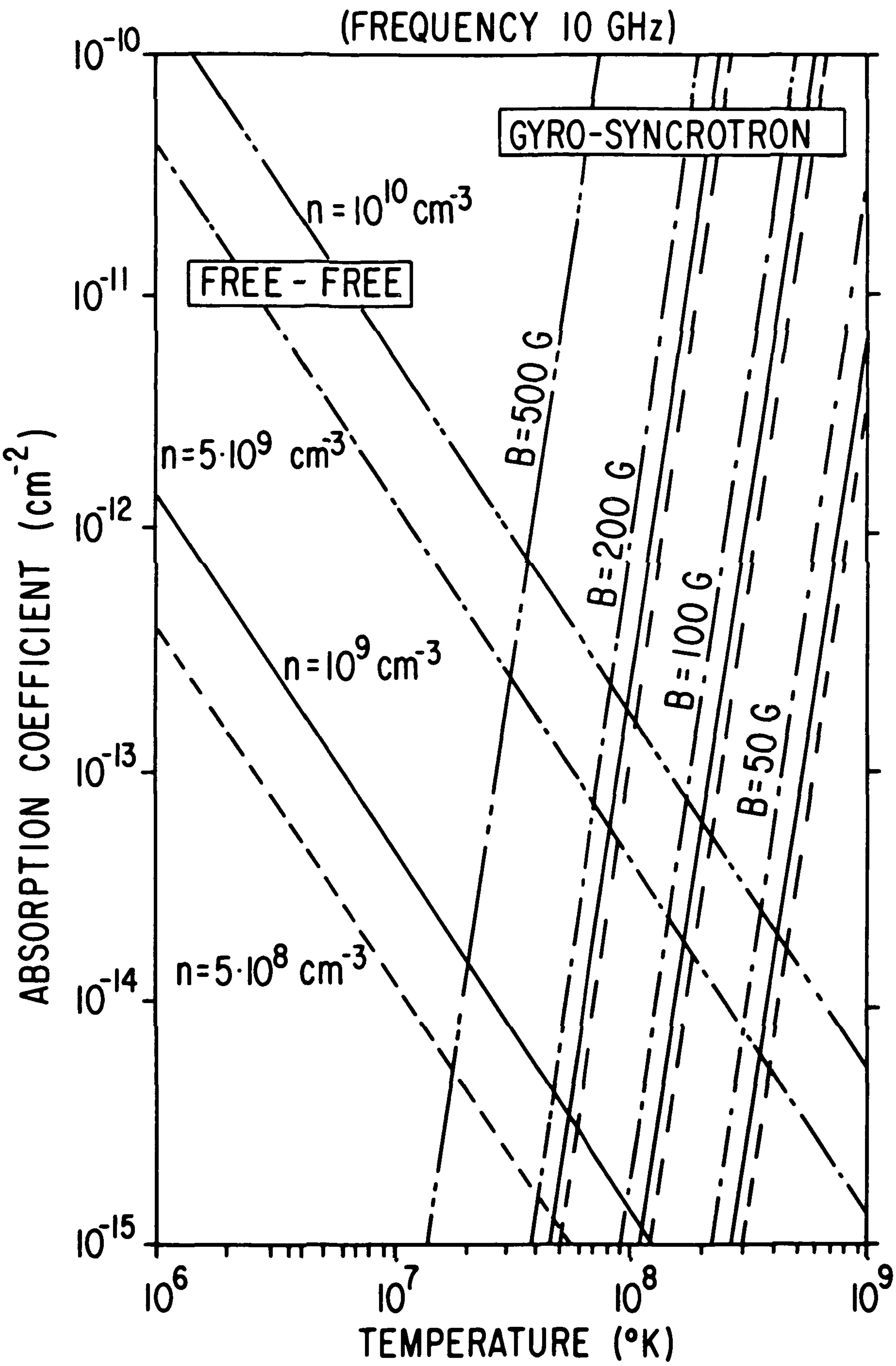
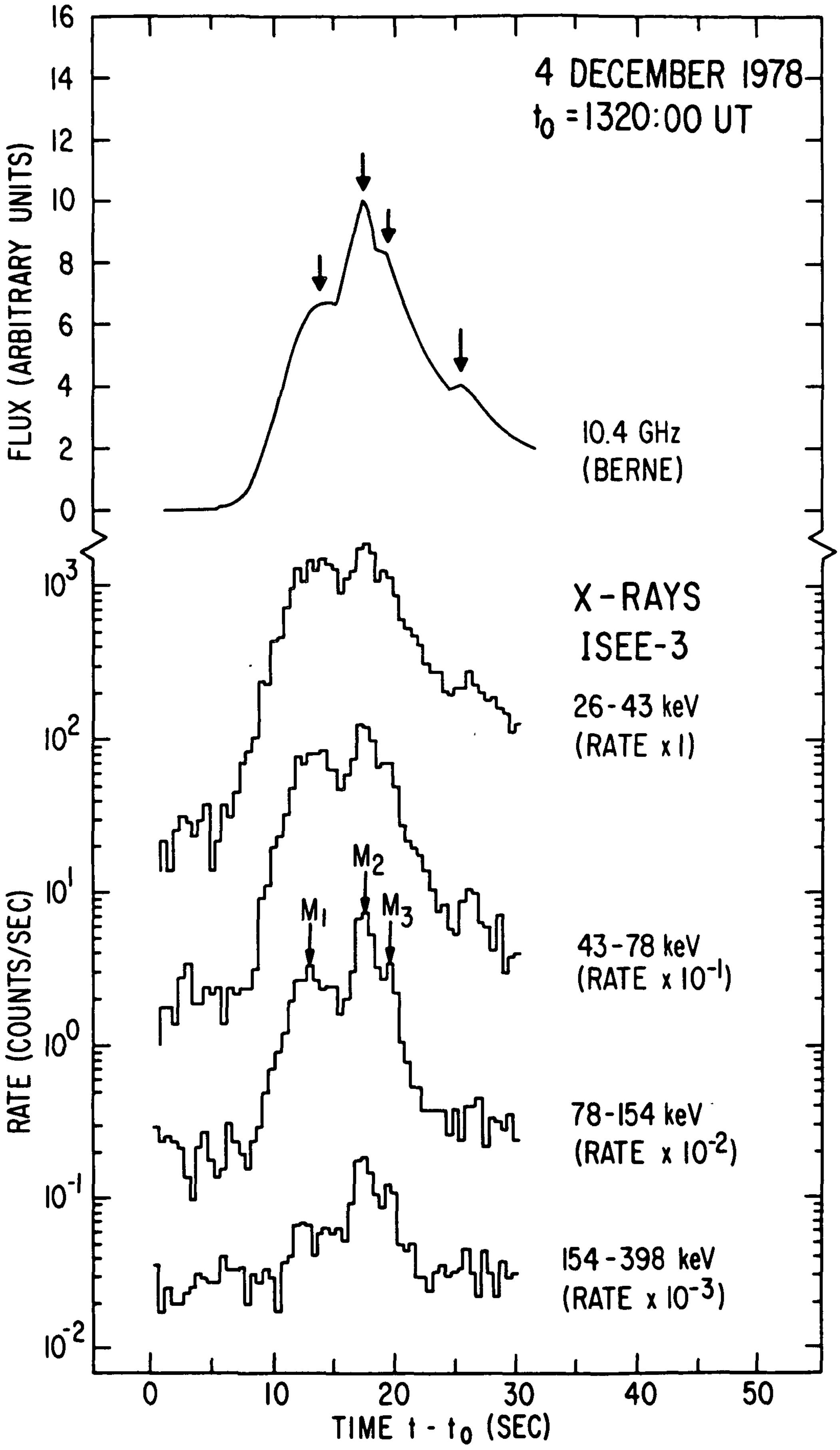


Fig. 3



(FREQUENCY 10 GHz)
GYRO-SYNCROTRON
FREE - FREE
n = 10^10 cm^-3
n=5·10^9 cm^-3
n=10^9 cm^-3
n=5·10^8 cm^-3
B=500 G
B=200 G
B=100 G
B=50 G
ABSORPTION COEFFICIENT (cm^-2)
TEMPERATURE (°K)
10^-10
10^-11
10^-12
10^-13
10^-14
10^-15
10^6
10^7
10^8
10^9

Fig. 4



4 DECEMBER 1978
t_0 =1320:00 UT
FLUX (ARBITRARY UNITS)
10.4 GHz
(BERNE)
X-RAYS
ISEE-3
26-43 keV
(RATE x1)
43-78 keV
(RATE x 10^{-1})
78-154 keV
(RATE x 10^{-2})
154-398 keV
(RATE x 10^{-3})
M_1
M_2
M_3
RATE (COUNTS/SEC)
TIME $t - t_0$ (SEC)

Fig. 5

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16. Abstract

Two short duration single spike events of 1978 May 5 and December 4 exhibit similar time profiles in the microwave and hard X-ray ranges, indicating emission from compact sources. Microwave spectal observations exhibit inhomogenieties present in the source parameters. The existence of fine time structures in the microwave time profiles at 10.4 GHz from Berne are interpreted as a signature of the dynamics of a disturbance travelling through the source at the ion-sound speed. Stereoscopic observations with the hard X-ray detector on the solar orbiter, Helios-2, and the Berne microwave antennae do no indicate any time lag or differences in the time profiles during the impulsive phase. This is taken as evidence for the absence of directionality of emission making beam models unlikely for short duration single spike events.

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