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QUASI-PERIODIC PULSATIONS IN SOLAR HARD X-RAY AND MICROWAVE FLARES

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For more than a decade, various studies have pointed out that hard X-ray and microwave time profiles of some solar flares show quasi-periodic fluctuations or pulsations (Parks and Winckler 1969, 1971; Frost 1969; Cribbens and Matthews 1969; Janssens and White 1969, 1970; Janssens et al. 1973; Maxwell and Fitzwilliam 1973; Anderson and Mahoney 1974; Cliver et al. 1976; Wiehl and Matzler 1980). Nevertheless, it was not until recently that a flare displaying large amplitude quasi-periodic pulsations in X-rays and microwaves was observed with good spectral coverage and with a sufficient time resolution. The event occurred on 1980 June 7 at ~ 0312 UT, and exhibits seven intense pulses with a quasi-periodicity of ~ 8s in microwaves ($f \gtrsim 3$ GHz), hard X-rays ($E \gtrsim 20$ keV) and gamma-ray lines. Details of this event are given by Kane et al. (1983), Kiplinger et al. (1983), Forrest and Chupp (1983), and Nakajima et al. (1983), and in several additional papers cited by them. This flare strongly suggests that, in the impulsive phase of a flare, electrons and ions are accelerated simultaneously in a train of quasi-periodic pulses which may arise as a consequence of some MHD/plasma process such as a current loop coalescence (Tajima et al. 1982; Nakajima et al. 1984; Sakai et al. 1986). Therefore, a study of similar events for confirming common characteristics of this type of flare is expected to provide deeper insight into basic flare processes.

On 1983 May 12 at ~ 0253 UT, another good example of this type of flares was observed both in hard X-rays and in microwaves (Kiplinger et al. 1984). Time profiles of microwave intensity (R+L) at five frequencies are shown in Figure 1 together with curves representing the degree of polarization (R-L)/(R+L). Similar to the 1980 June 7 event, this event consists of seven dominant pulses with a remarkable regularity; the mean interval between pulses is ~ 16s with the ratio of the maximum interval to the minimum interval being ~ 2.1. It is to be noted that such a regularity should seldom occur as the result of randomly scattered pulses. The probability of such a regularity in the occurrences of seven pulses is $\sim 3 \times 10^{-4}$ if the pulses are distributed according to a Poisson distribution.

Temporal and spectral characteristics of this flare are compared with the event of 1980 June 7 in Table I. As can be seen from the table, the two flares resemble each other not only in their time profiles but also in other characteristics as follows:

a. The microwave source, observed with the Nobeyama 17 GHz interferometer for both cases, is almost stationary in the pulsating phase (see Figure 2). (The 1983 May 12 source shows an eastward motion in the decay phase after the pulsation. This motion may be a projection of an upward motion with a velocity of ~ 100 km s^{-1}.)

b. Several observed quantities vary in synchronism with the intensity variation, i.e.,

(i) The hard X-ray spectrum hardens at the times peaks and softens at the times of valleys,

(ii) The peak frequency of microwave spectrum, f_p, increases at the times of peaks and decreases at the times of valleys, and,

(iii) The degree of circular polarization of microwaves at $f \simeq f_p$ decreases at the times of peaks and increases at the times of valleys, while that at frequencies $f > f_p$ (data is not available for the 1980 June 7 event due to its high f_p) increases slightly at the times of peaks.

All these variations are superposed on a more gradual variation. It should be noted that the variation of hard X-ray spectrum between peaks and valleys is less pronounced in the 1980 May 12 event and that the 6th and 7th peaks of this event reveal a progressive hardening of X-ray spectra.

These common characteristics summarized above appear to be consistent

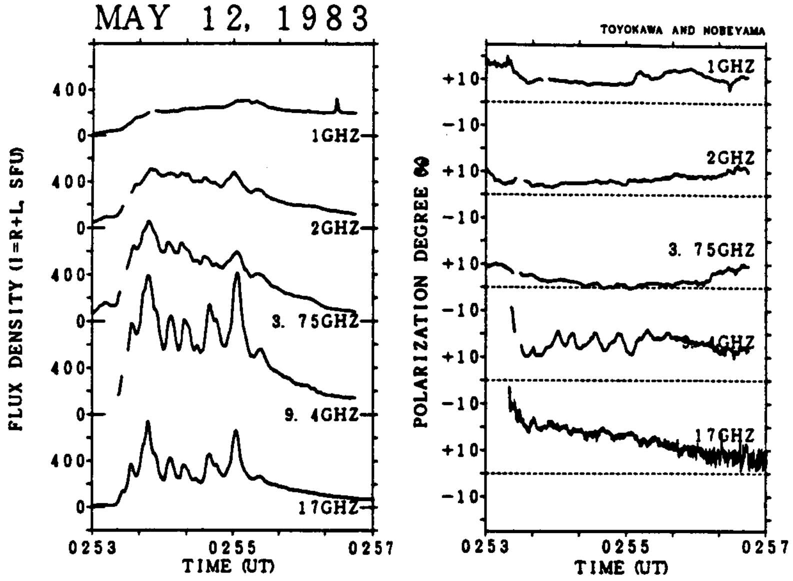

Figure 1: The flare of 1983 May 12 in microwaves. Time profiles in intensity (I=R+L, left) and the degree of polarization (p=(R-L)/(R+L), right) are shown at five frequencies. Observations were made at Toyokawa (1, 2, 3.75 and 9.4 GHz; by courtesy of S. Enome) and at Nobeyama (17 GHz).

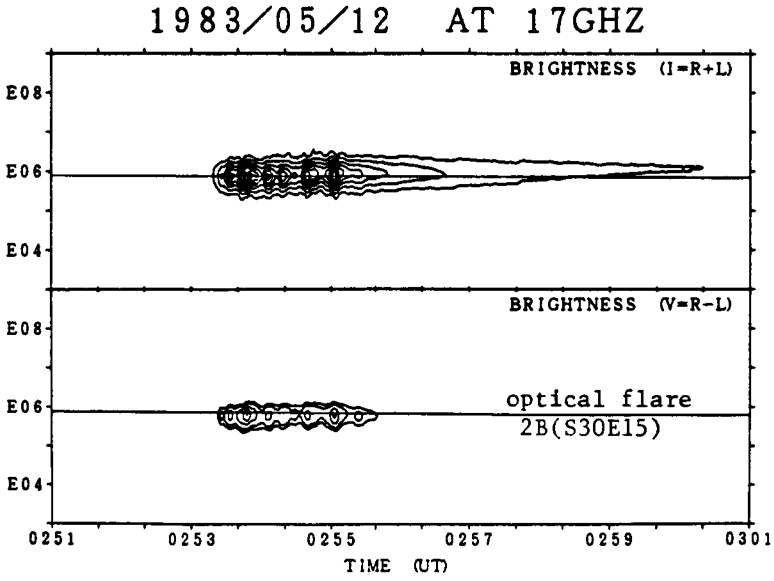

Figure 2: One-dimensional (E-W) contour map with time of the 1983 May 12 flare at 17 GHz. Contour lines are drawn at 90, 80 ..., 10, and 3% levels for the I=R+L map (upper), and at 20, 15, 10, 5, and 3% levels for the V=R-L map (lower), of the maximum brightness of I=R+L. The Hα flare position, S30E15, is denoted by a straight line.

Table I. Comparison between the 1980 June 7 and the 1983 May 12 flares.

	1980 June 7	1980 May 12
A. Quasi-periodicity	$\tau \sim 8$s N = 7 MW,HXR, γ-lines	$\tau \sim 16$s N = 7 MW, HXR
B. Microwaves		
B1. Source size	$\lesssim 5''$	$\sim 20''$
position (17 GHz, East-West)	stationary ($< 3''$)	almost stationary ($\lesssim 5''$) upward motion ($\sim$ 100km/s) after pulsation
B2. Spectra (f_p: peak frequency)	(f_p: increases at peaks, decreases at valleys)	
	$f_p \gtrsim 17$ GHz gradually decreasing	$f_p \sim 9.4$ GHz gradually increasing
B3. Degree of polarization at $f \sim f_p$	(decreases at peaks, increases at valleys) (i.e. anti-correlation with intensity)	
at $f > f_p$	---	positive correlation with intensity
B4. Peak timings		
with HXR's	0.3s delay	1-2s delay
high f vs low f	low-f delay	complex
C. Hard X-rays		
C1. Spectra ($E^{-\gamma}$)	(hardens at peaks, softens at valleys)	
	$\Delta\gamma \sim 1$	$\Delta\gamma \sim 0.4$
	γ :2.5 → 3.5 (gradually softening)	γ :4.0 → 3.3 (gradually hardening)
C2. Peak timings	< 0.2s delay at high E	$\sim$1s delay at high E
D. Remarks	subpeak structure homologous events	

with a model in which acceleration of electrons (and also ions in the case of the 1980 June 7 event) takes place repeatedly in a single loop or a system of loops. The interval between this repeated acceleration is governed by some characteristic time scale such as the Alfven transit time, i.e., the length (or the radius) of the loop(s) divided by the Alfven velocity. At the times of peaks, electrons are accelerated in the loop(s) and stream down into a thick-target hard X-ray source where they give rise to hard X-rays by bremsstrahlung and lose their energy by collisions. Also a certain fraction of the electrons accelerated in the individual pulses are reflected and trapped in the loop(s) by magnetic mirrors. These electrons have a relatively long life-time and give rise to a gradual background component.

In this model, the differences in the hard X-ray spectra between the peaks and the valleys may be explained by the existence of more than one hard X-ray source. For simplicity, let us assume that hard X-rays are emitted only from the thick-target source at the times of peaks, whereas they are emitted only by trapped electrons at the times of valleys. Also we will assume that the spectral evolution of trapped electrons is negligible so that the thin-target approximation for the hard X-ray radiation is applicable. In this case, we get the maximum peak-to-valley difference in spectral index $\Delta\gamma = 1.5$. Note that the observed values, $\Delta\gamma \simeq 1.0$ for the 1980 June 7 event and $\Delta\gamma \simeq 0.4$ for the 1983 May 12 event, are smaller than this maximum value. This suggests that the above scenario is nearly correct but needs some modifications. It is likely that both the thick-target source and the trapped-electron source emit hard X-rays continuously with their relative contributions varying over the peaks and valleys. The smaller $\Delta\gamma$ observed in the 1983 May 12 event when compared to that observed in the 1980 June 7 event is in accordance with a higher trapping efficiency of electrons; this explanation seems consistent with several characteristics of the former event such as a progressive hardening of the X-ray spectrum and a delay of microwaves and higher-energy hard X-rays with respect to lower energy hard X-rays.

The higher peak frequency of the microwave spectrum, f_p, at the times of peaks than at the times of valleys is not only due to a larger number of energetic electrons but also due to a stronger magnetic field. The positive correlation between the degree of polarization and intensity at frequencies $f > f_p$ requires that the magnetic field is stronger at the times of peaks than at the times of valleys. This result is consistent with our scenario, because down-streaming electrons should encounter a stronger magnetic field than the trapped electrons. Finally, the anti-correlation between the variation in the degree of polarization and that in intensity, found at around the peak frequencies, $f \simeq f_p$, is naturally explained by variations in optical depth. This variation in optical depth is observed as a positive correlation of f_p with intensity.

In order to further explore these observational results and theoretical scenarios, a study of nine additional quasi-periodic events has been incorporated with the results from the two flares described above. These 11 flares were selected from a sample of 135 digitally recorded events which were observed with the Nobeyama 17 GHz polarimeter from January 1979 through June 1983. All events were required to have a peak flux exceeding 150 sfu and were selected by criteria similar to those used by Cliver et al. (1976). Out of the 11 events selected, polarimeter data from Toyokawa Radio Observatory at 1, 2, 3.75 and 9.4 GHz are available for nine events (digital data kindly provided by S. Enome); Nobeyama 17 GHz interferometer data are available for seven events; and HXRBS data are available for four events.

A brief summary of the analyses of these events is:

(1) The mean periods identified in the 11 quasi-periodic events are scattered in the range of 8 to 36 s with the number of pulses varying between 4 and 15.

(2) The microwave source is stationary in three out of seven events (3/7), or shows a small shift of < 10" in the pulsating phase (4/7). In the latter cases, the motion appears continuous rather than random. Two events suggest an upward motion ($\sim$ 100 km s^{-1}) in the decay phase after the pulsation.

(3) The summaries b(i) to (iii) for the events on 1980 June 7 and 1983 May 12 apply to most cases:
   - (i) Hard X-ray spectral hardening at peaks (4/4), with $\Delta\gamma = 0.4 - 1.0$.
   - (ii) Increases of f_p at the times of peaks (6/9). In one out of the remaining three events, f_p is remains nearly constant. For the other two cases, the change in peak frequency cannot be estimated because $f_p >> 17$ GHz or because of small amplitude of pulses at $f < 10$ GHz.
   - (iii) The anti-correlation of the degree of polarization with intensity at frequencies $f \simeq f_p$ (7/10). Two of the remaining three events are unpolarized. The other is the only exception whose degree of polarization decreases gradually with time and shows no correlation with the rapidly varying intensity.
   - (iv) Using data at 17 GHz, correlation of the degree of polarization with the intensity at $f > f_p$ has been examined for six events which exhibits $f_p < 17$GHz. We find that two events with $f_p < 9$ GHz show a weak positive correlation, one event with $f_p \simeq 10$ GHz shows no correlation, two events with $f_p \simeq 12$ GHz show a weak negative correlation, and the remaining one event is unpolarized. This result is consistent with the statement in point b(iii) in the previous summary.

(4) Flares from the same active region which produced a quasi-periodic

event have been searched for homologous, quasi-periodic events. Such a homologous flare has been found in 6 of the 11 events, and the mean periods are similar between homologous pairs of flares in 5 out of the 6 cases. This is supporting evidence for a physical reality of the quasi-periodicities.

A more detailed examination is still in progress and will be summarized in a more extensive paper in the near future.

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