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ANOTHER CLUE ABOUT PARTICLE ACCELERATION IN IMPULSIVE HARD X-RAY/MICROWAVE BURSTS

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ABSTRACT

In a sample of impulsive bursts with rise times less than 30 s, a correlation between burst rise times and the frequency of maximum microwave emission has been found. The implications for source structure and dynamics are discussed in this paper. Previously evidence was found that such bursts are caused by some propagating disturbance such as a shock wave or thermal conduction front. Combining that evidence with the microwave and hard X-ray spectral information suggests that the most rapid bursts are emitted from the most compact and intensely magnetized sources. The most rapid bursts also exhibited the hardest X-ray spectra, as published previously. These facts are important clues to understanding the physical process responsible for impulsive bursts. A model for the bursts is suggested, based on the observations and inferences described.

Subject headings: acceleration of particles — Sun: radio radiation — X-rays: bursts

1. INTRODUCTION

Evidence has been reported in several papers (Crannell et al. 1978; Batchelor et al. 1985; Batchelor 1989; Schmahl et al. 1990) that simultaneous impulsive bursts of microwaves and hard X-rays originate in sources with characteristic length scales proportional to the rise times of the bursts, for rise times in the range of 0.1–24 s. That is, one may derive a source area A, using the microwave flux S_2 at a frequency f_2 in the optically thick segment of the burst spectrum (e.g., Fig. 1) and the hard X-ray spectral index γ (employing an appropriate model to derive the electron distribution from the hard X-ray spectrum: the thick-target model, trap-plus-precipitation model, or thermal model). This source area A scales as the square of the hard X-ray burst rise time t_r. The square root of this derived area, L_0, if it is taken as a characteristic length scale of the source, scales linearly with rise time (see Fig. 1*a* of Batchelor 1990, for example).

The possible significance of this length-time relationship as evidence of a characteristic propagation velocity leads one to investigate the other relationships of the available physical parameters of these bursts, looking for more clues to physical processes that cause impulsive flare emissions. Even with the spectacular images of impulsive phenomena recorded with the *Yohkoh* instruments, it is not possible to address flare hard X-ray source changes on the sub-second time scale, as we can do with this study.

Although Batchelor et al. (1985) suggested that the thermal model interpretation of the observational parameters uniquely accounted for the relation between L_0 and t_r, a later analysis of the observations by Batchelor (1989) showed that the *nonthermal* thick-target and trap-plus-precipitation models for the hard X-ray production also implied a similar scaling relation. Apparently, whatever model we assume, the combined analysis of parameters of the hard X-ray and microwave burst spectra reveals important clues to the process that accelerates high-energy particles in impulsive flares. The questions raised by these clues will not be fully answered until hard X-ray or microwave images of impulsive bursts are available with sub-second cadences.

The most recent imaging observations of hard X-ray source properties, made with the *Yohkoh* Hard X-Ray Telescope and reported by Acton et al. (1992), Sakao et al. (1992), Matsushita et al. (1992), and in papers elsewhere in this issue, suggest the view that the thick-target, trap-plus-precipitation, and thermal models may *each* account for the hard X-ray source structures (morphology and spectral property variance with altitude in the solar corona) in *some* flares. However, the weight of observational evidence appears to be in support of the thick-target model for the "flash phase" of most impulsive flares, due to the close correspondence of most hard X-ray images with magnetic arch footpoint regions, as marked by Hα, magnetograph, and even white-light flare structures (Hudson et al. 1992). Matsushita et al. (1992) report that the higher energy X-ray photons originate at lower altitudes in the solar atmosphere, consistent with the thick-target model. On the other hand, Sakao et al. (1992) report that the dissipative thermal model may not be inconsistent with their observations of the evolution of hard X-ray sources in different energy bands. With these recent observations in mind, some more properties of the sources may be inferred from further study of the burst parameters in this set.

The 34 bursts in this study—some of them subbursts within multiply impulsive flares—were chosen as representatives of impulsive acceleration taking place on time scales shorter than 25 s, in an attempt to address the "flash phase" physics, before large-scale hydrodynamic motions and gradual phase heating complicate the source structure. The observed parameters and derived parameters from the thermal model were given in Table 1 of Batchelor et al. (1985), and Tables 1 and 2 of Batchelor (1986); the derived parameters from the nonthermal models were given in Table 1 of Batchelor (1989). We shall consider a previously unpublished parameter of these bursts also, the frequency of maximum microwave emission at the time of the hard X-ray burst maximum, denoted f_{peak} and tabulated in Table 1 here.

Besides the length-time correlation, Batchelor (1990) reported other clues about impulsive microwave/hard X-ray bursts. There was also a general tendency for the most rapid

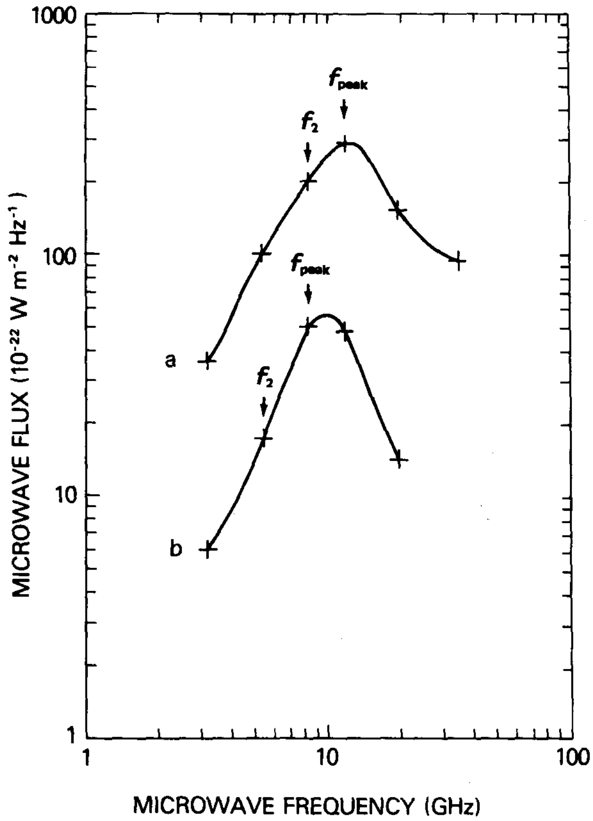

FIG. 1.—Examples of two microwave burst spectra, each at the time of hard X-ray burst maximum (Bern data). (*a*) 1981 August 10 0658:50 UT; (*b*) 1981 May 4 0838:03 UT. The values S_2 and f_2 were used in previous papers. This paper discusses correlations of the parameter f_{peak} with the hard X-ray rise time t_r.

bursts (small t_r) to exhibit the "hardest" X-ray spectra (lowest values of γ). This was important confirmation that the microwaves and hard X-rays in fact radiated from closely related electron populations. Also, the scatterplot of f_2 versus γ showed a rough anticorrelation, consistent with gyrosynchrotron radiation as the emission mechanism. Consequently, then, there was a rough anticorrelation of f_2 and t_r.

The correlation of parameters of these bursts that I wish to highlight in *this* paper is tabulated in Table 1, and expressed as the scatterplot of the frequency f_{peak} of most intense observed microwave emission versus rise time in hard X-rays t_r (Fig. 2). Both f_2 and f_{peak} are lower bounds of the frequency f_{max} for which optical depth equals unity, and f_{peak} is probably a better approximation of the actual f_{max}. One may investigate whether the values of f_{peak} in these bursts reflect the general decline of maximum optically thick microwave frequency f_{max} versus hard X-ray spectral index γ that was to be expected, given the functional dependence of optical depth upon magnetic field, electron distribution, and viewing angle in gyrosynchrotron sources (see Dulk & Marsh 1982). As established by Batchelor (1990), t_r and γ were roughly correlated, so we might anticipate a correlation of the pairs (t_r, f_{peak}) as well.

The values of the parameter f_{peak} were obtained by inspecting the spectrum of each microwave/X-ray burst at the time of the hard X-ray maximum (30–300 keV). As noted by the referee of this paper, some caution is due in interpreting the physical significance of f_{peak}, because the possibility of free-free absorption by thermal plasma between the microwave source and the observer exists (Ramaty & Petrosian 1972). Absorption is also possible due to the Razin effect and to gyroresonance absorption (Ginzburg & Syrovatskii 1965). The observable indication of these absorption processes is a steep slope in the spectrum at frequencies below some knee in the spectral shape. In 32 of the 34 bursts and subbursts considered herein, there is no segment of the observed spectrum with a slope exceeding 2, so absorption of the gyrosynchrotron radiation is not indicated. In the spectrum of the burst on 1980 June 4 0654:19 UT there is a slope of approximately 2.7 between the frequencies 8.4 and 11.8 GHz (the latter being the f_{peak}), indicating that this point should be regarded suspiciously for possible bias due to absorption. The burst on 1980 November 6 0650:52 UT also exhibited a steep slope of approximately 3 between 5.2 and 8.4 GHz, but the f_{peak} was at 11.8 GHz, so this value is less problematic.

As may be seen in the scatterplot (Fig. 2) the shortest rise times t_r are correlated with the highest values of observed f_{peak}. A linear least-squares regression analysis was performed on the values $\log_{10} f_{peak}$ versus $\log_{10} t_r$, assuming a 1 σ uncertainty in f_{peak} of 2 GHz, and yielding a value for χ^2 of 0.54 per degree of freedom. This implies that there is a 1.6% probability of ob-

TABLE 1

IMPULSIVE FLARE HARD X-RAY/MICROWAVE BURST PARAMETERS

Date	UT	t_r	f_{peak}
1980 Mar 29	0918:09	3.0	11.8
1980 Mar 29	0955:06	5.2	11.8
1980 Jun 04	0654:19	7.0	11.8[a]
1980 Jun 29	1041:35	3.6	11.8
1980 Jul 01	1626:53	0.8	19.6
1980 Jul 01	1626:56	0.9	35.0
1980 Jul 01	1626:59	0.8	19.6
1980 Jul 01	1627:02	1.0	35.0
1980 Jul 01	1627:04	0.8	28.0
1980 Jul 01	1627:08	1.0	35.0
1980 Jul 01	1627:13	1.4	35.0
1980 Oct 09	1123:58	5.2	8.4
1980 Nov 05	2233:02	24.	9.4
1980 Nov 06	0650:51	20.	11.8[a]
1980 Nov 08	1450:25	7.0	11.8
1980 Nov 18	0718:08	2.2	35.0
1980 Dec 17	0845:37	3.2	11.8
1981 Mar 23	0655:49	6.0	11.8
1981 Apr 10	1644:53	10.	8.4
1981 Apr 15	0643:09	3.8	8.4
1981 Apr 18	1049:28	5.0	11.8
1981 Apr 26	1115:31	11.	5.2
1981 May 04 ...	0838:03	1.8	8.4
1981 Jul 19	0533:25	12.	35.0
1981 Jul 20	1311:27	22.	8.4
1981 Aug 10	0658:50	2.6	11.8
1981 Dec 07	1451:02	10.	35.0
1984 May 21 ...	1326:29.8	0.2	90.0
1984 May 21 ...	1326:31.0	0.1	90.0
1984 May 21 ...	1326:31.2	0.1	90.0
1984 May 21 ...	1326:31.4	0.1	90.0
1984 May 21 ...	1326:38.1	0.1	90.0
1984 May 21 ...	1326:38.4	0.1	90.0
1984 May 21 ...	1326:38.6	0.1	90.0

[a] Indicates bursts with spectra which exhibited a steep segment at low frequencies, possibly indicating absorption and a possible bias toward higher f_{peak}.

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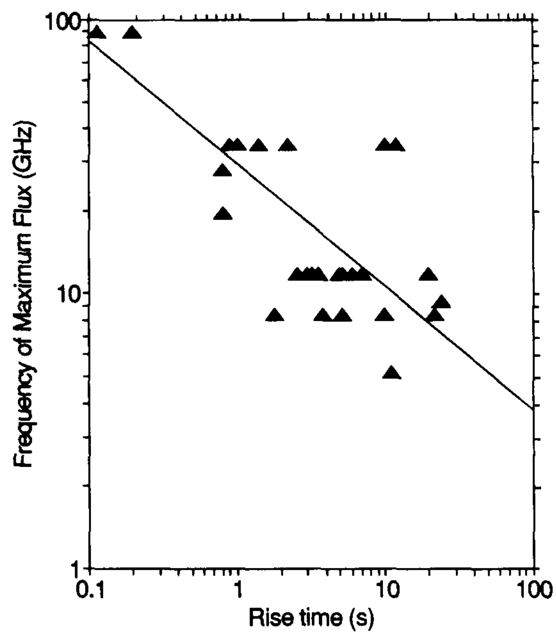

FIG. 2.—Scatterplot of the frequency f_{peak} of highest observed microwave flux in the spectrum at the time of hard X-ray maximum vs. hard X-ray rise time t_r for 34 hard X-ray/microwave rises. Diagonal line represents best-fit least-squares relationship: $f_{peak} = 28.6$ GHz $\times\ t_r^{-0.43}$. Note that the point at extreme upper left (0.1 s, 90 GHz) represents *six* separate subbursts with observationally indistinguishable parameters, which occurred in the flare on 1984 May 21 1326 UT.

taining a smaller value of χ^2 from an uncorrelated set of pairs (t_r, f_{peak}), indicating an excellent fit (Bevington 1969; Press et al. 1992). The best-fit log-log relation, $f_{peak} = 28.6$ GHz $\times\ t_r^{-0.43}$, is represented as the diagonal line crossing the figure. Our suspicions of bias in two values of f_{peak} due to absorption may be allayed by noting that both of the suspicious points lie close by the best-fit line. (A comparable correlation has been noted for 57 microwave bursts by Ren-Yang, Magun, & Schanda 1990, but they measured the *microwave* t_r in a quite different manner.)

In studying Figure 2, it should be noted that the 90 GHz observations are all from a single multiply impulsive flare on 1984 May 21 1326 UT which is apparently of a very rare kind, no others having appeared in the literature to the author's knowledge. This flare included numerous subbursts in which the spectral slope was monotonically positive from 7 to 90 GHz, with a spectral index consistent with normal optically thick emission (Kaufmann et al. 1985; Correia et al. 1986). Seven subbursts from the flare were included in the present study, and the reader may wonder whether the correlation reported herein is unduly strengthened by the inclusion of these unusual bursts. Six of these subbursts are represented by a single point in the extreme upper left of the scatterplot (Fig. 2), because they did not have sufficiently different rise times to be distinguished at the observed time resolution. As noted by Klein (1986) and Batchelor (1990), these bursts are consistent with the usual gyrosynchrotron radiation bursts in impulsive flares, except that they apparently occurred within sources of unusually high magnetic field intensity, so it would seem appropriate to include them in this analysis. Nevertheless, it is worth addressing how much they affect the correlation. In fact, if these seven bursts are excluded from the linear least-squares fit, the best fit becomes $f_{peak} = 22.3$ GHz $\times\ t_r^{-0.29}$ with a value of χ^2 of 0.60 per degree of freedom, and a probability of 6.3% that a better χ^2 would result from a set of uncorrelated parameter pairs. Thus the correlation is still significant, even if the 1984 May 21 observations are excluded.

Noting the dependence of optical depth—and therefore f_{max}—on other physical parameters, we can infer that rapid burst rises are associated with sites of intense magnetic field and sources of "harder" accelerated electron distributions. Given what we know about the magnetic structures in the solar atmosphere, and the high correlation of short t_r with small L_0, the evidence suggests that compact, highly magnetized regions produce the most energetic accelerated electron distributions in the shortest times.

Because these results address time scales that are not yet accessible to image-based studies of source evolution, in this respect they surpass existing image-based studies in providing insight into the nature of the impulsive flare mechanism. We can hope for more detailed understanding of the impulsive phase when images in X-rays above 30 keV can be obtained with cadences shorter than a few seconds.

2. DISCUSSION

Taken together, these observations suggest characteristics of the particle acceleration environment. The length-time scaling constant, approximately 10^8 cm s^{-1}, may be adopted as a characteristic velocity of a propagating causative agent, which accelerates the electrons in a burst source. Such a source is in all probability a coronal magnetic arch or arcade, as shown in *SMM* and *Yohkoh* images, so that the length scale L_0 may approximate the arch dimensions. The smaller sources are also characterized by relatively large values of magnetic field, as would be expected in relatively compact arches at low altitudes in active regions (Fig. 3 of Batchelor 1990; see also Kaufmann et al. 1986; Klein 1986). The high magnetic field values in such compact sources could provide relatively high amounts of available energy if the fields were configured as nonpotential fields, for more efficient acceleration of particles than in regions of weaker fields.

A shock wave, set off perhaps by a destabilized active region filament and propagating through a magnetic arch or arcade, would be a good candidate to explain this size scaling of the hard X-ray and microwave burst sources in terms of a velocity. Shock waves are sometimes observed in the corona, traveling at velocities of order 10^8 cm s^{-1} (e.g., Uchida, Altschuler, & Newkirk 1973). Alfvén waves seem less likely to account for the derived constant velocity on size scales from 10^2 to 10^4 km, as discussed by Batchelor (1990). Collisionless conduction fronts might also lead to source expansions at the required velocities (Starr et al. 1988), but the observational evidence for conduction fronts is less solid than for shocks.

A model for impulsive hard X-ray/microwave bursts based on shock acceleration may be envisioned along the lines of the diagram in Figure 3. The figure is meant to represent a magnetic arch or the cross section of the arcade over a filament, perpendicular to the plane of the page. The broken circle near the figure's center represents a shock front, expanding from its point of origin, a destabilized or erupting filament. Particle

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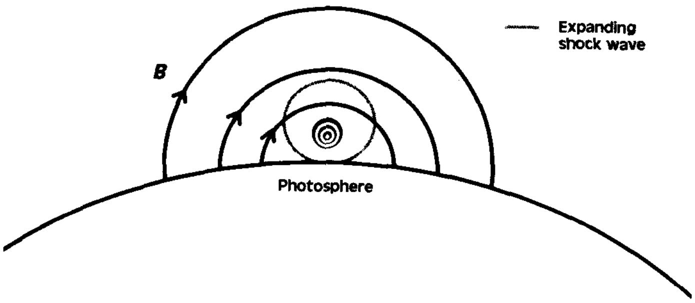

FIG. 3.—Diagram of shock acceleration conceptual model for impulsive hard X-ray/microwave bursts (perpendicular shock case).

acceleration at the shock front is the proposed source of energetic particle injection and would continue as long as there is sufficiently dense plasma (but not *too* dense) residing on field flux tubes which are approximately perpendicular to the shock normal vector. When the shock front expanded beyond the system, insufficient matter to supply the energetic particles would be available, and the burst would quickly peak in flux. (Alternatively, in an arcade or nest of arches, the same shock might traverse more than one arch, resulting in a series of subbursts.)

Further analysis of the *Yohkoh* images will provide ample opportunities to test this model.

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