THE ACCELERATION OF ELECTRONS AND IONS IN SOLAR FLARES

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Abstract. We find that gamma-ray line (GRL) emissions start later than the hard X-ray (HXR) emissions during impulsive and extended solar flares. Starting delay is more in the case of extended solar flares suggesting a slow acceleration of electrons and ions, in comparison to impulsive solar flares which indicate different acceleration mechanism for impulsive and extended solar flares. We further infer that during solar flares, electrons and ions are accelerated simultaneously and the delay between HXR and GRL emissions results mainly due to differences in acceleration times of electrons and ions to attain energies required for producing HXR emissions for electrons and GRL emissions for ions. Therefore, we are of view that a single step acceleration mechanism may work in solar flares.

1. Introduction

It is well known that acceleration of electrons and nuclei occurs frequently in solar flares and the accelerated particles are responsible for great variety of solar phenomena. The accelerated electrons produce hard X-ray (HXR) and gamma-ray (GR) continua through bremsstrahlung, while the accelerated nuclei produce gamma-ray line (GRL) and neutrons through various nuclear reactions with the ambient solar atmosphere. The different radiations observed during solar flares, originate at different heights in solar atmosphere and the study of time delay between the microwave (MW), HXR, and GR/GRL emissions will lead to a better understanding about the mechanism of origin and the height at which flares trigger first (Verma, 1988). From the observed onset time delay one can infer about the height at which the flare gets triggered and also about the rate of acceleration of electrons, protons, and nuclei, etc. At present it has been assumed that the most likely acceleration process for electrons and ions in solar flares involves two phases (Brown and Smith, 1980; Nakajima *et al.*, 1983). In the first phase, only electrons are accelerated which produce the well-observed impulsive HXR emissions at energies > 10 keV. This phase also provides the particle injection process for the second phase during which ions and relativistic electrons are accelerated over time-scales of minutes. In the past, many authors have studied the relation between HXR and GR emissions during solar flares (Nakajima *et al.*, 1982, 1983; Bai *et al.*, 1983; Forrest and Chupp, 1983; Yoshimori *et al.*, 1983; Yoshimori, 1984). Forrest and Chupp (1983) find simultaneity between the starting time X-ray (> 40 keV) and GR emissions which they interpreted in terms of simultaneous acceleration of electrons in solar flares. On the other hand, Nakajima *et al.* (1983) studied the same flares and found significant delays between MW, HXR, GRL emissions which (according to them) suggest that two kinds of accelerations take place successively within a few seconds.

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Now from the above it is not clear which types of accelerations take place, i.e., single-phase or two-phase during solar flare occurrence.

Here we are presenting a study based on a comparison of onset times of GRL and HXR emissions observed during solar flares and we also discuss the results.

2. Observational Data, Analysis and Results

The data for GRL and HXR emissions used in the present study were observed by SMM satellite. The GRL flare emissions data have been taken from the list published by Bai and Dennis (1985). The GRL emission onset times were noted from a list published by Rieger (1982) and the HXR emission onset and peak emission times were noted from a list published by Dennis *et al.* (1985). Out of 19 GRL emission flares (Bai and Dennis, 1985) corresponding to 1 flare GRL and HXR data are not available. Furthermore, if the duration of HXR bursts are < 1000 s, we call such flares as impulsive flares (Kane *et al.*, 1980) and if the duration > 1000 s we call such flares as extended solar flares. The HXR and GRL emissions onset time data used in the present study have energies > 25 keV and > 300 keV, respectively. These flares show GRL emissions but for the present study we have used start time of GRL emissions of energies > 300 keV (Table I). A plot of number of flares with HXR and GRL emissions versus the starting time interval between HXR and GRL emissions during impulsive and extended solar flares are shown in Figure 1. As is clear from Figure 1 and Table I, out

TABLE I

Detail of GRL and HXR emissions during solar flares

Date of solar flares	(a) Start of GRL UT	(b) Start of HXR UT	(c) Peak of HXR UT	(a–b) s	(a–c) s	Remark
4 June, 1980	06:54:15	06:53:56	06:54:37	19	− 22	I
7 June, 1980	03:12:10	03:10:51	03:12:15	79	− 05	I
21 June, 1980	01:18:20	01:12:40	01:18:40	340	− 20	E
29 June, 1980	10:41:40	10:40:10	10:41:50	90	− 10	E
1 July, 1980	16:26:50	16:24:59	16:27:29	111	− 39	I
6 Nov., 1980	03:44:07	03:24:10	03:48:00	1200	− 233	E
17 Nov., 1980	02:04:12	02:00:09	02:04:55	240	− 37	I
22 Nov., 1980	04:48:32	04:45:50	04:52:00	162	− 208	E
18 Dec., 1980	19:21:17	19:21:10	19:21:20	25	− 15	I
26 Feb., 1981	14:24:22	14:23:10	14:25:55	72	− 93	I
1 Apr., 1981	01:33:04	01:05:40	01:46:04	1644	− 780	E
10 Apr., 1981	16:46:13	16:33:40	16:51:15	753	− 302	E
26 Apr., 1981	11:45:00	10:54:50	11:48:10	690	− 190	E
27 Apr., 1981	08:04:00	07:40:55	08:12:55	1385	− 535	E
7 Sept., 1981	22:22:51	22:22:25	22:23:20	26	− 31	I
15 Sept., 1981	21:13:57	21:10:15	21:14:40	222	− 43	I
7 Oct., 1981	22:55:40	22:41:35	23:02:35	845	− 355	E
14 Oct., 1981	17:05:00	17:03:20	17:06:30	100	− 90	I

I: impulsive solar flares.
E: extended solar flares.

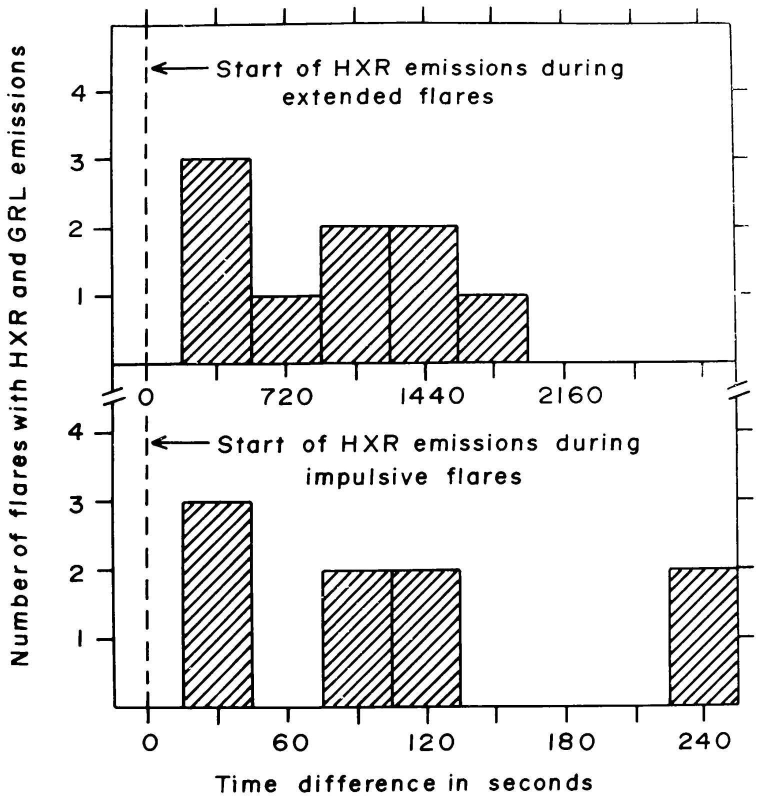

Fig. 1. Plot of number of flares with HXR and GRL emissions versus starting time difference between HXR and GRL emissions during impulsive and extended solar flares.

of data for 18 flares used in the present study 9 are extended solar flares. From Figure 1 it is also clear that the GRL emissions start up to 30 s after the onset of HXR emissions during impulsive solar flares and during extended solar flares GRL emissions start up to 360 s after the onset of HXR emissions. In Figure 2 we have plotted the number of flares with GRL and HXR emissions versus time difference in start of GRL and peak of HXR emissions during impulsive and extended solar flares. The 0 shown in Figures 1 and 2 includes ± 5 s, which is the accuracy of HXR emission data. From Figure 2 it is clear that the GRL emissions start sometimes alongwith HXR emissions and mostly up to 45 s before the peak of HXR emissions during impulsive solar flares. During extended solar flares GRL emissions start up to 2–6 min before the peak of HXR emissions (see Figure 2). The above set of data sample is small but clearly shows that there are two types of solar bursts: impulsive and extended. Figures 1 and 2 also show clearly that there is an onset time delay between HXR and GRL emission bursts during solar flares.

3. Discussion and Conclusions

The present study shows that the GRL emissions start only after the onset of HXR emissions during impulsive and extended solar flares. The starting delay is less between

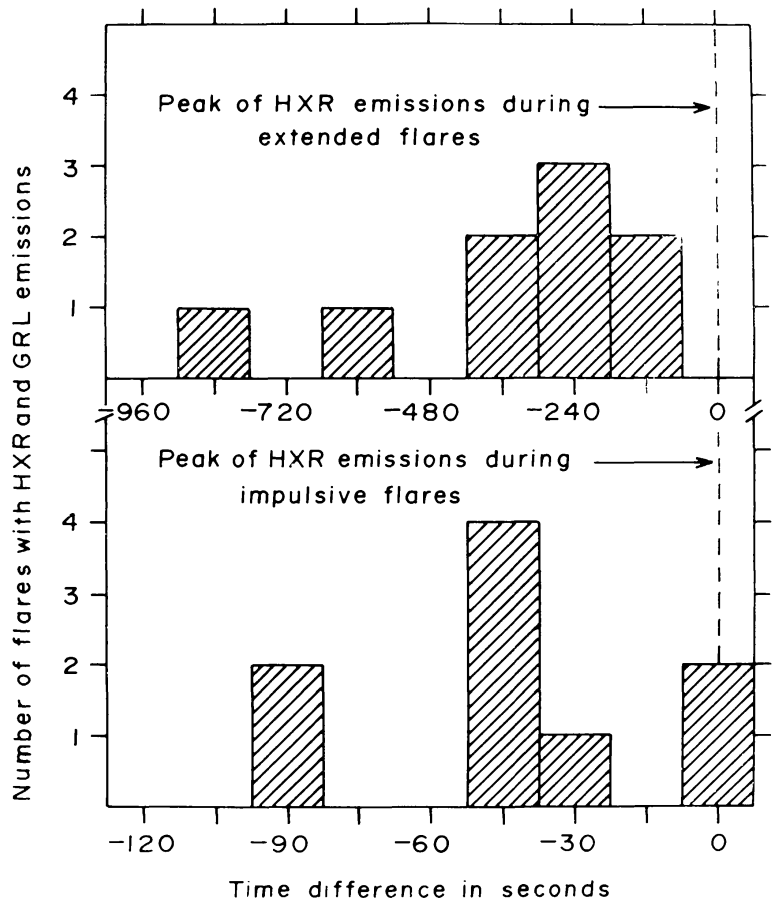

Fig. 2. Plot of number of flares with HXR and GRL emissions versus time difference between start of GRL emissions and peak of HXR emissions during impulsive and extended solar flares.

GRL and HXR emissions during impulsive flares as compared to extended solar flares (Figures 1 and 2). This suggests that the particles producing GRL emissions are accelerated faster in the case of impulsive solar flares in comparison to extended solar flares. According to Yoshimori (1984), one way to choose between the simultaneous acceleration of electrons and ions and mechanism with successive acceleration of electrons and ions would be to compare the starting time of HXR and GRL emissions during solar flares. Furthermore, according to him the first possibility requires a simultaneous starting time, while the second possibility requires that GRL emissions start later than the HXR emissions. In the present investigation as mentioned above, GRL emissions start significantly later to the HXR emissions which according to Yoshimori *et al.* (1983), Yoshimori (1984), and Nakajima *et al.* (1983) should be due to successive acceleration of electrons and ions. But we surmise that electrons and ions are accelerated simultaneously during solar flares and time delay observed between GRL and HXR can be explained. Earlier Forrest and Chupp (1983) found no time delay within 2 s and supported the hypothesis of simultaneous acceleration of electrons and ions during solar flares. The HXR emissions are produced by accelerated electrons through bremsstrahlung mechanism and GRL emissions are produced by accelerated protons and nuclei through nuclear reactions and other phenomena after interaction with solar atmosphere. During flare occurrence electrons, protons and nuclei are accelerated in the same electric field, therefore, the electrons will be accelerated faster than the protons (proton to electron mass ratio is 1836) and nuclei and will attain requisite energies earlier than the protons for producing HXR emissions, although during the acceleration the electrons will also lose energy faster in the acceleration region (e.g., through Coulomb collisions). But still the net energy gain is larger for electrons. Further higher energy nuclei are more massive than the protons and will need more time for acceleration to attain energies for producing GRL emissions. So we feel that the differences in mass of electrons, protons and nuclei will create differences in acceleration rates, thereby the electrons will attain higher energies earlier than the protons and nuclei for producing HXR emissions. The other factors responsible for the time delay between GRL and HXR emissions may be the differences in locations of sources of two bursts and differences in mechanism involved in the production of GRL and HXR emissions. The source location of GRL and HXR bursts sources will not add much time delay because both the GRL and HXR emissions come from the footpoints of flare loops (lower chromosphere). Furthermore, it is also noted that the onset time delay between GRL and HXR bursts vary from one flare to another (Table I). The onset time delay between HXR and GRL emissions may also depend on the gradient of magnetic fields in the active region at the flare site. If the field gradient are large the time delay between the two emissions will be small and if the field gradient are small the onset time delay between GRL and HXR emissions will be large. This way, we can explain the different time delay (small to large) observed between GRL and HXR emissions during the impulsive and extended solar flares. Therefore, as discussed above we are of the view that a single step acceleration mechanism seems to be rather helpful in understanding the acceleration processes in solar flares.

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