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Evidence for a Strong Correlation of Solar Proton Events with Solar Radio Bursts *

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Abstract A statistical analysis is made on the correlation between solar proton events with energies > 10 Mev and solar radio bursts during the four-year period from 1997 November to 2000 November. We examine 28 solar proton events and their corresponding solar radio bursts at 15400, 8800, 4995, 2695, 1415, 606, 410 and 245 MHz. The statistical result shows that there is a close association between solar proton events and ≥ 3 solar radio bursts occurring at several frequencies, one or two days before. In particular, it is noteworthy that proton events occurring in pairs within the same month are preceded 1–2 days by individual radio bursts and most of the radio bursts of solar flares occur at all eight frequencies. Those 245 MHz radio bursts associated with proton events have intense peak fluxes (up to 67000 sfu). Solar proton events are preceded 1 or 2 days by ≥ 3 radio bursts at several frequencies and proton events occurring in pairs within the same month are preceded 1 or 2 days by some individual radio bursts. These correlations may be used for providing short-term or medium-term prediction of solar proton events.

Key words: solar proton event – solar radio burst

1 INTRODUCTION

Relationships among radio burst and spectra, H_α flares, X-ray flares and sunspots and CMEs have been used for short-term prediction of proton events and their intensity.

Proton events tend to occur in sunspots with field strengths of 1500–2500 G and with specific configurations. Proton event-associated active regions have large H_α-flare index values (usually more than 100 sfu), and also produce type-III metric bursts. The Ca-II plage index, radio-emission flux, and the maximum intensity of the 9.1-cm radio measurement tend to increase as the proton event approaches. H_α flares of two types are also related to the majority of the proton events (Chakravorti et al. 1991). Cliver (1985) found that only about half of all intense,

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long duration (40 min above 500 sfu) 1 MHz bursts could be associated with F 20 MeV proton events. However, for the subset of such fast drift bursts accompanied by metric Type II and /or Type IV activity, the degree of association with 20 MeV events is 80%. A statistical study of the spectral characteristics of microwave bursts accompanying proton and nonproton flares was given by Stupishin who showed that the essential difference between proton and no proton events might be differences between the sizes of their sources (Stupishin 1991). The probability of observing a solar proton event based on the X-ray fluency provides a correlation that may be used to predict proton event occurrence (Huston et al. 1993). It is known that CME may be a necessary condition for a flare proton event. Peak proton fluxes do correlate with both the speed and the angular sizes of the associated CMEs (Kahler et al. 1983; Kahler et al. 1984).

A real threat to future traditional forecasting techniques relies on the occurrence of a solar X-ray flare to predict the size and occurrence of solar proton events but this means that the prediction lead time can only be a few hours at best. Patrick (2001) has examined solar X-ray and radioactivity for several hundreds of hours prior to recorded proton events suggesting that precursors may exist up to 250 hours prior to the occurrence of proton events.

In this paper, we propose a new method for the short-term and medium-term predictions of solar proton occurrence.

2 DATA ANALYSIS

During the four-year period from 1997 November to 2000 November, which was within solar cycle 23, there were 28 solar proton events. Here, we investigate the solar radio bursts that took place at the following eight frequencies: 15400, 8800, 4995, 2695, 1415, 606, 410 and 245 MHz, 1 or 2 days before the proton events (see http://solar.sec.noaa.gov/ftpdir/indices/SPE.txt and http:// solar.sec.noaa.gov/ ftpmenu/indices.html).

We define a radio burst at several frequencies as one occurring simultaneously at two or more frequencies including 245 MHz. For a radio event at several frequencies, if the burst peak flux at 245 MHz is larger than that at 410 MHz for more than one order of magnitude, the burst is called an individual radio burst.

An example of individual radio burst is illustrated in Table 1.

Table 1 An Example of Individual Radio Burst which Occurred the Day Before the Proton Event of 1997 November 4

Begin (UT)	Max (UT)	End (UT)	Loc/Freq	Particulars
1018	1029	1034	1–8A	M4.2
1022	1026	1035	2695	230
1022	1026	1035	4995	120
1022	1026	1035	8800	120
1022	1026	1048	15400	25
1023	1025	1035	245	40000
1023	1026	1036	410	3100
1023	1026	1037	606	530
1024	1026	1034	1415	610
1025		1031	035–08	V/3
1029		1047	036–08	II/3

Of the 28 proton events in the period 1997 November – 2000 November, six occurred 1–3 days after their corresponding proton flares, five of the flares were on the east side of the solar disk. It was noticed that though there was another flare on the west side on October 26 , there was only a single 245 MHz radio burst on October 25, but no 245 MHz radio burst 1–2 days before the proton event.

Of the 28 proton events, nine were only associated with 245 MHz bursts occurring 1 or 2 days before. For example, in connection with the proton event of 1999 April 24 there was only one 245 MHz burst on April 23, and no bursts at other frequencies on April 22 or 23.

From 1997 November to 2000 November, there were 1072 days without solar proton events or were followed 1 or 2 days later by proton events. There were only 155 days with up to ≥ 3 radio bursts at several frequencies, 32 of these were 3–7 days before the proton event occurrence, and 12 were 1–5 days after the proton event occurrence. The numbers of the radio bursts at several frequencies occurring 1–2 days before proton events are shown in Table 2.

Table 2 Numbers of Radio Bursts at Several Frequencies Occurring 1–2 days before Proton Events

Date	Number	Date	Number	Date	Number
1997		1999		2000	
2 Nov	3	21 Jan	0	12 Jul	3
3 Nov	8	22 Jan	3	13 Jul	10
4 Nov		23 Jan		14 Jul	
4 Nov	2	22 Apr	0	20 Jul	21
5 Nov	4	23 Apr	0	21 Jul	7
6 Nov		24 Apr		22 Jul	
1998					
18 Apr	0	3 May	1	26 Jul	1
19 Apr	1	4 May	0	27 Jul	0
20 Apr		5 May		28 Jul	
31 Apr	3	31 May	4	9 Aug	3
1 May	8	1 Jun	1	10 Aug	0
2 May		2 Jun		11 Aug	
4 May	4	2 Jun	0	10 Sep	0
5 May	3	3 Jun	5	11 Sep	0
6 May		4 Jun		12 Sep	
22 Aug	2	16 Feb	0	14 Oct	1
23 Aug	1	17 Feb	5	15 Oct	0
24 Aug		16 Feb		14 Oct	
23 Sep	8	2 Apr	1	24 Oct	0
24 Sep	3	3 Apr	0	25 Oct	0
25 Sep		4 Apr		26 Oct	
28 Sep	5	5 Jun	0	6 Nov	1
29 Sep	3	6 Jun	5	7 Nov	0
30 Sep		7 Jun		8 Nov	
6 Nov	13	8 Jun	1	22 Nov	5
7 Nov	4	9 Jun	0	23 Nov	9
8 Nov		10 Jun		24 Nov	
12 Nov	1				
13 Nov	0				
14 Nov					

From Table 2 it can be seen that 20 out of the 28 proton events were associated with radio bursts at several frequencies, 2 days before their occurrence. The number of radio burst at several frequencies was up to 21. Here 19 of 28 proton events were preceded by radio events at several frequencies, the day before. The number of radio bursts at several frequencies was up to 10. In addition, 16 out of the 28 proton events were associated with ≥ 3 radio bursts at several frequencies, 1 or 2 days before their occurrence.

Table 3 and Table 4 show, respectively for "isolated" and "paired" proton events (occurrig within the same month), the numbers of individual radio bursts prior to the proton events by 1–2 days.

Table 3 Numbers of Individual Radio Bursts Occurring 1–2 days before "Isolated" Proton Events

Date	Number	Date	Number	Date	Number
1997		1999		2000	
2 Nov	2	21 Jan	0	12 Jul	1
3 Nov	6	22 Jan	1	13 Jul	4
4 Nov		23 Jan		14 Jul	
4 Nov	2	22 Apr	0	20 Jul	9
5 Nov	2	23 Apr	0	21 Jul	2
6 Nov		24 Apr		22 Jul	
1998					
18 Apr	0	3 May	0	26 Jul	0
19 Apr	0	4 May	0	27 Jul	0
20 Apr		5 May		28 Jul	
30 Apr	2	31 May	1	9 Aug	0
1 May	5	1 Jun	3	10 Aug	0
2 May		2 Jun		11 Aug	
4 May	3	2 Jun	0	10 Sep	0
5 May	2	3 Jun	1	11 Sep	0
6 May		4 Jun		12 Sep	
22 Aug	2	16 Feb	0	14 Oct	0
23 Aug	0	17 Feb	1	15 Oct	1
24 Aug		18 Feb		16 Oct	
23 Sep	2	2 Apr	0	24 Oct	0
24 Sep	1	3 Apr	0	25 Oct	0
25 Sep		4 Apr		26 Oct	
28 Sep	0	5 Jun	0	6 Nov	2
29 Sep	1	6 Jun	1	7 Nov	0
30 Sep		7 Jun		8 Nov	
6 Nov	5	8 Jun	0	22 Nov	3
7 Nov	2	9 Jun	0	23 Nov	4
8 Nov		10 Jun		24 Nov	
12 Nov	0				
13 Nov	0				
14 Nov					

Table 4 Numbers of Individual Radio Bursts Taking Place 1–2 Days Prior to "Paired" Proton Events Occurring within the Same Month

Date	Number	Date	Number	Date	Number
1997		1998		2000	
2 Nov	2	12 Nov	0	20 Jul	9
3 Nov	6	13 Nov	0	21 Jul	2
4 Nov		14 Nov		22 Jul	
		1999			
4 Nov	2	31 May	1	26 Jul	0
5 Nov	2	1 Jun	3	27 Jul	0
6 Nov		2 Jun		28 Jul	
1998					
30 Apr	2	2 Jun	0	14 Oct	0
1 May	5	3 Jun	1	15 Oct	1
2 May		4 Jun		16 Oct	
		2000			
4 May	3	5 Jun	0	24 Oct	0
5 May	2	6 Jun	1	25 Oct	0
6 May		7 Jun		26 Oct	
23 Sep	2	8 Jun	0	6 Nov	2
24 Sep	1	9 Jun	0	7 Nov	0
25 Sep		10 Jun		8 Nov	
28 Sep	0	12 Jul	1	22 Nov	3
29 Sep	1	13 Jul	4	23 Nov	4
30 Sep		14 Jul		24 Nov	
6 Nov	5				
5 Nov	2				
8 Nov					

Table 3 indicates that, of the 28 proton events 16 were preceded by individual radio bursts on the day before (up to 6 bursts at a time), of these 16 proton events 14 were "paired events" occurring in the same month. Again, of the 28 proton events, 13 were preceded by (up to nine at a time) individual radio bursts 2 days before, and 12 out of the 13 were "paired events".

A statistical analysis is made on the correlation between the "paired" proton events and the 245 MHz radio bursts. The results are shown in Table 5. Column 2 shows the flux density of the most intense 245 MHz burst during the two days before the proton event; Column 3, the peak flux density of the 245 MHz burst of the proton flare; Column 4, the number of frequencies at which radio emission is seen in the proton flare.

Of the 28 radio bursts 12 associated with solar proton flares were seen at eight frequencies. Table 5 shows that 10 of the 12 related to "paired" proton events. It can also be seen that the "paired" proton events were associated with 245 MHz radio bursts occurring 1 or 2 days before, and had high densities (from 130 sfu up to 67000 sfu). Moreover, their corresponding 245 MHz radio bursts of proton flare also had high densities (from 110 sfu up to 65000 sfu).

Table 5 "Paired" Proton Events that Occurred within the Same Month and their Associated 245 MHz Radio Bursts

Date	Maximum of 245MHz bursts (sfu)	Flux of Solar flares (sfu)	Number of Frequencies
1997			
4 Nov	40000	9800	8
6 Nov	9800	54000	8
1998			
2 May	1700	14000	8
6 May	2700	65000	8
25 Sep	7300	2900	8
30 Sep	2800	78	6
8 Nov	67000	No detection	No detection
14 Nov	240	No burst	0
1999			
2 Jun	1700	No burst	0
4 Jun	1100	660	8
2000			
7 Jun	320	320	7
10 Jun	950	110	8
14 Jul	2700	3100	8
22 Jul	7500	140	8
28 Jul	130	No detection	No detection
16 Oct	240	No burst	4
26 Oct	130	No burst	0
8 Nov	180	No burst	2
24 Nov	12000	7200	8

3 DISCUSSION

The results of the present study can be summarized as follows. During the 4 year period that we investigated, the 245 MHz radio bursts of proton flares had high peak fluxes up to 65000 sfu. Furthermore, the 245 MHz radio bursts occurring 2 days before the event also had high densities of up to 67000 sfu. Of the solar proton events 71% occurred 1–2 days after radio bursts at several frequencies, and 68% of the proton events were associated with radio bursts at several frequencies that took place the day before. Here, ≥ 3 radio bursts at several frequencies occurred only on 14% of these 1072 days. Therefore, when ≥ 3 radio bursts at several frequencies occur on a same day, a proton event will probably occur 1 or 2 days later. In addition, 46% of solar proton events were preceded by individual radio bursts 2 days before, and 92% of "paired" solar proton events (those occurring within the same month) were preceded by individual radio bursts. In the proton events 57% were preceded by individual radio bursts the day before, while 89% of the "paired" solar proton events were associated with individual radio bursts. In the radio bursts of proton flares 43% took place at eight frequencies, and 83% of such proton flares were associated with proton events occurring in pairs within the same month.

The above results show that when some intense 245 MHz radio burst and radio individual bursts are seen to precede a proton event by 1–2 days, and when the 245 MHz burst of the solar proton flare has a high peak density, then there is a high probability of another proton event occurring in the same month.

These ≥ 3 radio bursts at several frequencies within one day and individual radio bursts might therefore provide a good indicator for the short- and medium-term prediction of proton events. Solar proton events appear to be closely associated with 245 MHz radio bursts. To understand the physics of this correlation, it is important to understand the environment in which they occur as well as the relevant processes of acceleration and energy release.

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