Prolonged Release of 100 MeV Solar Protons in the GLE Events of 1997-2002

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Abstract

The solar proton events of 1991 June 11 and 15 provide evidence that > 100 MeV protons interacting in the solar atmosphere and escaping into the interplanetary space are from the same population. Events of 1997–2002 accompanied by ground level enhancements are considered. The model of diffusion propagation assuming prolonged and multiple release of solar protons fits quite well proton intensity measured within 84–200 MeV energy band. The number of protons in the solar source is estimated for different time moments by using the propagation model. The obtained numbers of interacting protons suggest that the relevant instrument should observe prolonged γ-emission with a significant contribution from π^0-decay in many of the considered events. Apparently a notation of local radiation belts of the Sun should be introduced.

1. Introduction

Prolonged trapping and/or acceleration of solar protons in the corona during post-eruptive flare phase are a possible alternative for their shock acceleration in the interplanetary medium [1–2]. Recently Struminsky have considered such a possibility for GLE events of the 22nd solar cycle [5], three large events (July 14 and November 8, 2000; November 4, 2001) of the current solar cycle [6]. It has been shown that the observed time profiles of > 100 MeV solar protons do not contradict to the model of 3D diffusion propagation assuming the prolonged injection from the solar source. Moreover, the source functions required to fit the proton data is in qualitative (June 11, 1991) and in quantitative (June 15, 1991) agreement with the observed solar gamma emission [7].

In this work the same fitting is applied to the GLE events of the current solar emphasizing two points: 1) a choice of proton mean free path (mfp) for different events; 2) a relation between the obtained source functions and characteristics of soft X-ray emission. The last problem is illustrated by the impulsive event of May 2, 1998, the gradual event with clear impulse of April 15, 2001 and the pure gradual event of December 26, 2001.

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2. Data and Methods

A value of mfp is an important parameter of the transport model. In the energy range of about 100 MeV theoretical and experimental values of proton mfp agree with each other (the Palmer consensus interval of 0.08–0.3 AU [4]). Fitting time-profiles of proton intensity it is possible to estimate both a value of mfp and a source function for particular event. A decay rate of proton intensity gives a lower limit of mfp, but a rise rate of proton intensity provides its upper limit. For a given value of mfp one can determine an injection rate and its duration.

The effective thermodynamic parameters (temperature, emission measure) of the emitting plasma can be determined from observations of the soft X-ray radiation in two different energy bands under the isothermal approximation (see [8] and references therein). For simplicity a ratio of two X-ray channels is used as a measure of the effective temperature. This ratio is compared with the obtained source functions.

3. Results and Discussion

Results of mfp selection and a choice of the source function are presented in Table 1. It would be interesting to compare the obtained values of mfp with predictions of the quasi linear theory. Important in all considered events it is necessary assuming the prolonged injection of solar protons. Apparently processes of prolonged trapping and/or acceleration are common features of large solar flares and a notation of local radiation belts of the Sun should be introduced [3]. An arrival time for first protons relatively the injection onset is determined only by a value of mfp and do not depend on heliolongitude of the flare. It is 30 min for $\lambda = 0.11$ AU and about 10–15 min for $\lambda = 0.3$ AU.

The lower panel of Figure 1 shows a ratio of two X-ray channels for three flares and onsets of major proton injection from the Sun. Clear that maximums of the ratio correlate quite well with injection onsets. It is suggested to use this ratio as a tool determining onsets of major proton injection.

4. Summary

The number of protons in the solar source is estimated for different time moments by using the propagation model for GLE events of 1997–2002 years.

Mfp if estimated from time profiles of ~ 100 MeV protons observed during GLE events of 1997–2002 years.

Values of mfp are varied from event to event and are within the Palmer consensus range.

Onsets of major particle injections correspond to temperature maximums in the flare region.

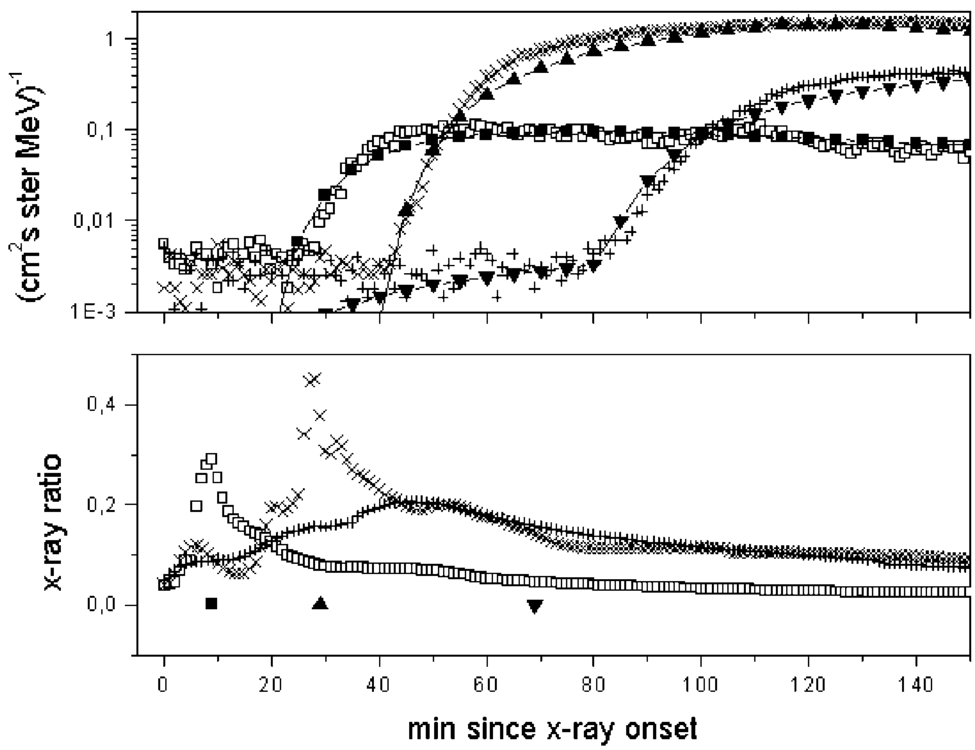

Fig. 1. Solar proton events of 2 May 1998 (open and black squares), 15 April 2001 (crosses and up triangles) and 26 December 2001 (vertical crosses and down triangles). Upper panel: the 1-min intensity of solar protons measured within 84–200 MeV energy range by GOES-10 and it's model approximation. Lower panel: the ratio of GOES-10 soft X-ray intensities and onsets of major proton injections (see Table 1).

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5. References

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Table 1. Possible source functions for 84–200 MeV protons: A — injection time (min) since X-ray onset; B — relative intensity %; C — proton arrival time (min) since X-ray onset; D — mfp, AU; E$\cdot 10^{31}$ — total number of > 100 MeV protons.

Flare	A	B	C	D	E	Flare	A	B	C	D	E
06.11.1997	0	1	50	0.11	8.2	15.04.2001	0	—	45	0.25	16
11:49 UT	30	60				13:19 UT	30	99			
S18W63	200	28				S20W85	100	—			
	370	1				18.04.2001	0	0.5	50	0.2	3.4
	600	10				02:11 UT	30	64			
02.05.1998	0	66	25	0.15	0.68	S20W115	235	0.5			
13:31 UT	5	—					285	35			
S15W15	135	34				04.11.2001	0	—	40	0.11	11
06.05.1998	0	58	25	0.17	0.41	16:03 UT	20	38			
07:58 UT	5	—				N06W18	30	3			
S11W65	200	42					170	14			
24.08.1998	0	20	55	0.11	0.64		175	10			
21:50 UT	35	33					375	24			
N30E07	75	25					385	1			
	375	22					615	10			
14.07.2000	0	—	35	0.11	56	26.12.2001	0	—	80	0.3	4.6
10:03 UT	20	43				04:32UT	70	99			
N22W07	30	34				N08W54	140	—			
	150	—				24.08.2002	0	—	40	0.25	3.2
	250	23				04:32 UT	10	99			
08.11.2000	0	—	60	0.11	66	S20W85	65	—			
22:42 UT	40	33									
N10W77	50	1									
	150	16									
	155	27									
	275	23									