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PROLONGED RELEASE OF >100 MeV PROTONS FROM LOCAL RADIATION BELTS OF THE SUN

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Abstract. Up to now only observations of gamma ray emission from decayed pions by the CGRO and GAMMA-1 space observatories on June 11 and 15, 1991 have evidenced for prolonged trapping/acceleration of >100 MeV protons in solar flares. Solar proton events of 1997-2002 accompanied by ground level enhancements are considered in this paper. It is shown that a simple diffusion model under suggestion of prolonged and multi step release of solar protons fits quite well solar proton intensity measured within 84-200 MeV energy band by the GOES proton detector. Therefore, prolonged trapping and/or acceleration of protons are a common feature of large solar flares. These processes might be considered as an evidence for existence of local radiation belts of the Sun.

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. Recently Struminsky has considered such a possibility for GLE events of the 22nd solar cycle [1], and three large events (July 14 and November 8, 2000; November 4, 2001) of the current solar cycle [2]. It has been shown that the time profiles of solar protons with energies of about 100 MeV observed during first 15-20 hours do not contradict to the model of 3D diffusive propagation if we assume a prolonged injection from the solar source. Moreover, the source functions required to fit the proton data is in qualitative (June 11, 1991) and quantitative (June 15, 1991) agreement with the observed solar gamma emission [1].

In this paper the same fitting procedure as in [1, 2] is applied to the GLE events of the current solar cycle (**Appendix I**) with emphasizing the following two points: 1) the choice of proton mean free path (mfp) for different events; 2) the relation between the obtained source functions and characteristics of soft X-ray emission. The last problem is illustrated by pairs of events with similar X-ray emission, namely, on November 6, 1997 and April 18, 2001(impulsive); July 14, 2000 and April 15, 2001(combination of impulsive and gradual); November 8, 2000 and December 26, 2001 (purely gradual). As in the case of the 22nd cycle events it appears that independently of the type of X-ray event and flare position on the solar disk, both relatively rapid and slow injections of >100 MeV protons are possible.

Recently Lyubimov G.P. [3] has introduced a notation of the local radiation belts of the Sun defining them as giant quasi-stationary coronal and heliospheric traps for solar cosmic rays. These traps are formed by loop magnetic fields, either of solar or interplanetary origin. A prolonged injection from solar sources into the interplanetary space occurred during the GLE events of the 23rd solar cycle might be considered as another evidence for existence of local radiation belts of the Sun.

Data and Methods

The interplanetary transport is described by a simple 3D diffusion model with an effective radial diffusion coefficient $K_0 = \frac{\lambda \cdot V}{3}$, where λ is the mean free path and V is the particle velocity (see [4] and references therein). The particle density at time t at distance r from the source (normalized over the total number of particles in the source) is given by the expression

$$f(r,t) = \frac{1}{4 \cdot \Gamma(3/2)} (K_0 t)^{-3/2} \exp\left(-\frac{r^2}{4 \cdot K_0 t}\right) \quad .$$

In the case of prolonged injection with time profile $Q(\tau)$ a convolution

$$U(r,t) = \int_0^t Q(t-\tau) \cdot f(r,\tau) d\tau$$

yields the particle density at time t at distance r from the source.

The isotropic CR flux in the interplanetary space can be estimated as $j(r,t) \approx U(r,t) \cdot V/3$.

For the events considered the unknown parameters of the transport model λ and $Q(\tau)$ were obtained by fitting the time profiles observed in the interplanetary space (the approximation should be within errors of one-minute GOES data, at least for the first 15-20 hours after the X-ray onset).

In the energy range of ~100 MeV theoretical and experimental values of proton mfp are consistent, the Palmer consensus interval being of 0.08-0.3 AU [5]. The rate of the proton intensity decrease gives the lower limit of mfp, while the rate of the proton intensity growth provides its upper limit. The observed time profiles are considered to be a result of instant injections occurring on the Sun each five minutes. An injection of constant rate was assumed at each stage and changed step-wise from one stage to another. For a given value of mfp, one can determine the rate and duration of each injection episode.

The results of fitting for the GLE events of the current solar cycle are presented in **Appendix II,** including onsets of the injection episodes, their duration and relative intensity as well as the transport parameters.

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 [6] and references therein). Here we use the ratio of two GOES-10 X-ray channels as an indicator of solar flare processes and compare this with the obtained source functions. Following the adopted classification, we consider impulsive events, mixed events with well-defined impulsive and gradual phases and purely gradual events.

All necessary data were down loaded from the SPIDR database (http//spidr.ngdc.noaa.gov).

Results and Discussion

Impulsive events

A detailed review of observations on November 6, 1997 is presented in [7]. As reported in [8], strong gamma-emission was registered by the Yohkoh detector between 11:52 and 11:56 UT (the extended gamma-production persisted for 600 s) and the OSSE aboard CGRO detected neutrons associated with this flare between 12:08 and 12:28 UT. The ratio of X-ray intensities indicated maximum within first 10 minutes of both events (Fig. 1).

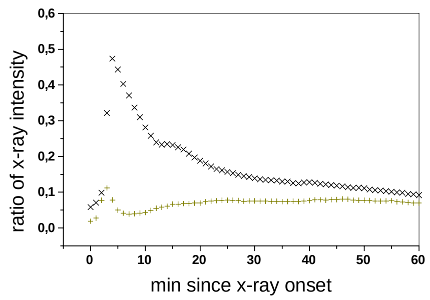

Fig. 1. Ratio of X-ray intensities measured by GOES-10 on November 6, 1997 (crosses) and April 18, 2001 (vertical crosses).

Therefore, the major proton injection on November 6, 1997 occurred after gamma and neutron production on the Sun and was evidently associated with destruction of solar local radiation belts. The background level was rather high after November 4, 1997 and April 15, 2001 events (this fact describes a late enhancement of proton intensity above background in both events (Fig. 2)), so it is impossible to say whether or not a minor injection occurred during the impulsive phase.

The gamma-ray observations on April 18, 2001 have not been reported yet. Note that the X-ray event on April 18, 2001 was behind the solar limb. This possibly accounts for its minor X-ray class.

Mixed events

Both events exhibited a clear impulsive phase, but a noticeable proton injection occurred only close to maximum of the X-ray intensity ratio (Fig. 3). As in the case considered in the previous section, it is impossible to

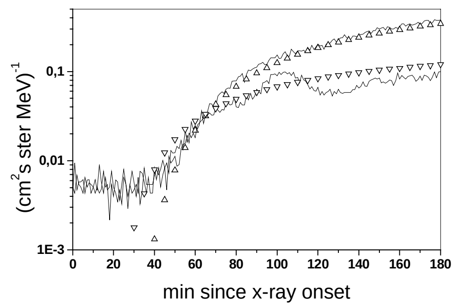

Fig. 2. One-minute proton intensity measured within 84-200 MeV energy band and its 5-min model approximation for SEP events on November 6, 1997 (upward triangles) and April 18, 2001 (downward triangles).

conclude whether a minor injection during the impulsive phase occurred or not.

The authors of [9] employed the Reid-Axford profile as a source function, with the mean free path varying in the range 0.1 - 0.27 AU, to fit NM data. Their source function has similarities to the first two injection episodes considered in this work. However, to fit the time profile of 84-200MeV protons we need longer and more intense injection during the decay phase and the second instant injection about four hours after the X-ray onset. A peak in the soft X-ray intensity makes it reasonable to suggest the second instant injection on the Sun rather than shock wave effects (SSC 15:07 UT, 14 July 2000) in solar cosmic rays.

Having summarized X-ray, EUV, optical, radio and neutron monitor observations, the authors of [10] concluded that the main phase of energy conversion in the low corona had maximum near 10:18 UT. The gamma detectors on Yohkoh observed the 14 July 2000 flare from ~10:20 UT till ~10:40 UT [11]. So, the relativistic solar protons and, at least, 43% of >100 MeV protons were accelerated during the observed gamma-ray emission, but the number of interacting protons is much less than that estimated from the propagation model. It should be mentioned that the Yohkoh gamma-observations for the flare event of 14 July show the lowest energy content in ions compared to any of the 19 SMM flares, with only 3 of the latters having harder spectra [11]. From about 13UT on 14 July the Yohkoh detectors observed gamma-ray lines and continuum, which were attributed to SEP interactions in the Earth's atmosphere. According to our estimates, about 20% of accelerated protons with energies >100 MeV were close to the Sun at that time, so the observed gamma-emission might be partly of the solar origin. The problem needs further consideration, but it would be difficult to set significant limits on low-level gamma-ray emission using Yohkoh [12].

Neither gamma-ray observations of April 15, 2001 nor any fittings of proton intensity have yet been reported.

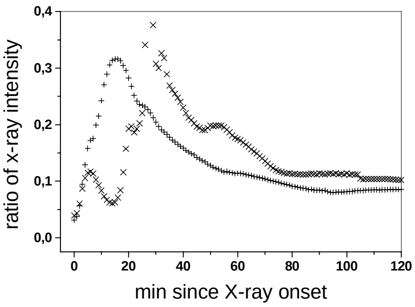

Fig. 3. Ratio of X-ray intensities measured by GOES-10 on July 14, 2000 (vertical crosses) and April 15, 2001 (crosses).

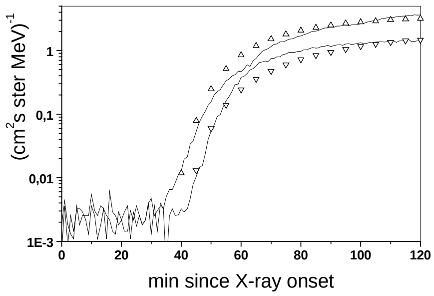

Fig. 4. One-minute proton intensity measured within 84-200 MeV energy band and its 5-min model approximation for SEP events on July 14, 2000 (upward triangles) and April 15, 2001 (downward triangles).

Gradual events

Main episodes of proton injection during these events occurred after maximum of the X-ray intensity ratio, but the character of proton injection was different. Episodes of instant and intense injection were followed by prolonged and relatively weak release of solar protons into the interplanetary space in the November 8, 2000 event. However, solar protons were being continuously injected with slow and constant rate for more than one hour on December 26, 2001. The propagation time of the protons that were first to arrive is about 15-20 minutes.

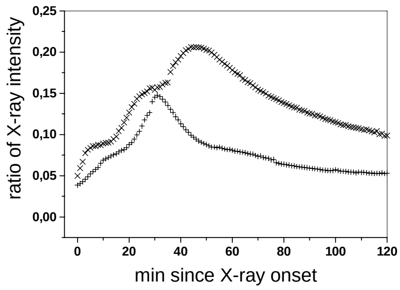

Fig. 5. Ratio of X-ray intensity measured by GOES-10 on November 8, 2000 (vertical crosses) and December 26, 2001 (crosses).

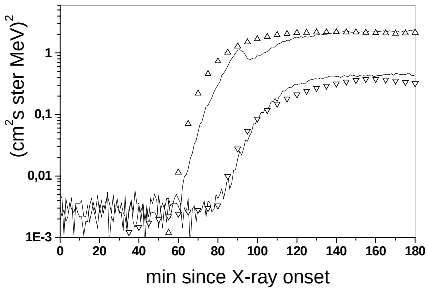

Fig. 6. One-minute proton intensity measured within 84-200 MeV energy band and its 5-min model approximation for SEP events on November 8, 2000 (upward triangles) and December 26, 2001 (downward triangles).

Summary

- The proton number of the solar source is estimated for different times by using the 3D diffusive propagation model for GLE events of 1997-2002.
- Prolonged and multi step release of solar protons should be suggested to fit the time profiles of proton intensity measured within 84-200 MeV energy band by the GOES proton detector.
- Estimations of mfp vary from one event to another keeping within the Palmer consensus range.
- Onsets of major particle injections correlate with manifestations of the post-flare activity visible in time profiles of the soft X-ray intensity ratio.
- Both rather rapid and slow injections of >100 MeV protons are possible irrespective of the X-ray event type and flare position on the solar disk.
- Prolonged trapping and/or acceleration of protons which is common for large solar flares might be considered as an evidence of local radiation belts of the Sun.

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Appendix I Characteristics of parent solar events

Date	X-ray event			Coord
	Imp	x-ray onset	x-ray max	
6 Nov 1997	X9.4, imp	11:49	11:55	S18W63
2 May 1998	X1.1, imp?	13:31	13:42	S15W15
6 May 1998	X2.7, imp?	07:58	08:09	S11W65
24 Aug 1998	X1.0, grad	21:50	22:12	N30E07
2000 Jul 14	X5.7, grad	10:03	10:24	N22W07
2000 Nov 8	M7.4, grad	22:42	23:28	N10W77
15 Apr 2001	X14.4, grad	13:19	13:50	S20W85
18 Apr 2001	C2.2, grad	02:11	02:15	S20W115
2001 Nov 4	X1.0, grad	16:03	16:20	N06W18
26 Dec 2001	M7.1, grad	04:32	05:37	N08W54
24 Aug 2002	X3.1, grad	00:49	01:12	S02W81

Appendix II Source functions and propagation condition of solar protons

X-ray onset, UT	Min since onset	%	First arrival, min	MFP, AU	Total 10^{31}
6 Nov 1997, 11:49	0	<1	50	0.11	17
	30	60			
	200	28			
	370	>1			
	600	10			
2 May 1998, 13:31	0	66	25	0.15	0.68
	5	-			
	135	34			
6 May 1998, 07:58	0	58	25	0.17	0.41
	5	-			
	200	42			
24 Aug 1998, 21:50	0	20	55	0.11	0.64
	35	33			
	75	25			
	375	>22			
14 Jul 2000, 10:03	0	-	35	0.11	56
	20	43			
	30	34			
	150	-			
	250	23			
8 Nov 2000, 22:42	0	-	60	0.11	66
	40	33			
	50	1			
	150	16			
	155	27			
	275	23			
15 Apr 2001, 13:19	0	-	45	0.25	16
	30	>99			
	100	-			
18 Apr 2001, 02:11	0	-	50	0.2	2.9
	10	68			
	200	-			
	285	32			
4 Nov 2001, 16:03	0	-	40	0.11	11
	20	38			
	30	3			
	170	14			
	175	10			
	375	24			
	385	1			
	615	10			
26 Dec 2001, 04:32	0	-	80	0.3	4.6
	70	>99			
	140	-			
24 Aug 2002, 00:49	0	-	40	0.25	3.2
	10	>99			
	65	-			