Interacting and Escaping 100 MeV Solar Protons Observed on 11 and 15 June 1991

Alexei Struminsky
Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation (IZMIRAN), Troitsk, Moscow Reg., 142092, Russia

Abstract

The solar flares of 1991 June 11 and 15 are famous for their prolonged γ-emission with a significant contribution from π^0-decay, which provides a unique evidence that relativistic solar protons can exist in the solar corona for hours. The model of diffusion propagation assuming prolonged and multiple injection fits quite well time profiles of about 100 MeV protons aboard GOES-7 during first 20 hours of these events. Source functions on the Sun required to fit the proton data are in a qualitative agreement with the observed solar γ-emission. The number of protons in the solar source is estimated for different time moments by using the propagation model. For the 15 July 1991 event the number of protons interacting in the solar atmosphere and escaping into the interplanetary space quantitatively agree well with each other, i.e. they are likely of the same population.

1. Introduction

A variety of time profiles of solar proton intensity observed at the Earth orbit suggest a complex and multiple particle injection into the interplanetary space from the acceleration site. It is currently adopted associating prolonged time profiles characteristic for gradual events with acceleration by the coronal mass ejection (CME) driven shock wave in the corona and interplanetary medium (see [10, 12] and references therein). However, this scheme has some difficulties [2, 4]. Processes of prolonged trapping by coronal and interplanetary magnetic field structures might be considered as alternative scenario of solar energetic particle events (SEP). In this case the CME driven shock is not the main accelerator, but the CME lifting loops and opening closed field lines creates favorable conditions for particle release and propagation (or their acceleration) during the post-eruptive phase [1, 5].

The prolonged solar gamma-emission from π^0-decay registered by EGRET and COMTEL aboard CGRO on 11 and 15 June 1991 (see [11] and references therein) show that high-energy protons may exist near the Sun and, therefore, release into the interplanetary space during several hours since the flare onset.

The purpose of this work is to show: 1) the simplest model of diffusion

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propagation assuming prolonged injection from the solar source fits well time profiles of > 100 MeV protons observed on 11 and 15 June 1991; 2) the number of protons in the source obtained from the propagation model do not contradict to those estimated from gamma-ray observations. All necessary particle data were down loaded from the Internet.

These are homologous X12.5 flares with impulsive and gradual phases according to radio and gamma-ray observations. A nearly equal number of protons with similar spectrum were accelerated at the Sun during these events [9]. The ratio of ^{3}He/^{4}He fluxes in the energy range of 50–110 MeV/nucleon measured for these events appeared to be 1–3 orders higher than in the solar corona and contradicts to the model of shock wave acceleration [3].

2. Model

A simple 3D diffusion model describes the interplanetary part of the proton transport in this work. The solution to the diffusion equation for three-dimensional isotropic diffusion with instant particle injection from a source is well known [8]. In a case of prolonged injection a convolution of the injection time profile multiplied on the solution for instant injection determines a particle density in a given point from the source and time moment.

In the energy range of about 100 MeV theoretical and experimental values of proton mean free path (mfp) in the interplanetary space agree with each other within the interval of 0.08–0.3 AU [7]. A value of mfp equal 0.11 AU for 84–200 MeV protons was assumed ad hoc. Necessary injection time profiles (source functions) for the considered events were obtained by demanding to give a good fit on the time profiles observed in the interplanetary space for the first 15–20 hours since the X-ray onset. A time step was equal to 5 min in numerical calculations, i.e. observed time profiles are considered as a superposition of instant injections with different intensities occurred each five minutes.

3. Results and Discussion

Figure 1 shows time profiles of solar proton intensity measured within 84-200 MeV energy bands by the GOES-7 satellite and their fittings by the simple diffusion model with prolonged and multiple injection of protons into the interplanetary. Tables 1 presents the model source functions for 84-200 MeV solar protons obtained assuming the mfp of 0.11 AU.

Four phases of the proton injection on the Sun can be distinguished on 1991 June 11 that does not contradict to observations of the γ-emission [9]. According to the model estimates only 20% of accelerated protons leaved the Sun during first 4.5 hours since the flare onset, but the proton injection into the interplanetary space stopped with finishing of pion production in the Sun. This is direct evidence

Table 1. Possible source functions for 84-200 MeV protons with $\lambda = 0.11$ AU.

Flare	onset, min	dur., min.	%	Np
11.06.1991	0	10	0.4	7.0×10^{31}
01:56 UT	10	50	11	
N32W15	60	210	8	
	270	430	80.6	
15.06.1991	0	5	3	5.0×10^{31}
08:10 UT	5	10	83	
N36W70	15	270	14	

that the same population of protons has interacted in the Sun and propagated in the interplanetary space on 1991 June 11.

Contrary, the 1991 June 15 event is characterized by a quick release of the accelerated protons into the interplanetary space. About 86% of the accelerated protons were injected during first 15 minutes since the flare onset. Unfortunately, the γ-observation was not performed at that time [1, 9]. According to the estimates of [6] about $Np\,(E > 30\ \text{MeV}) = (2.9 \pm 0.4) \cdot 10^{32}$ protons should remain close to the Sun between 08:26-09:25 UT. Let us compare this value with our results,totally about $Np\,(E > 84\ \text{MeV}) = 5.0 \cdot 10^{31}$ protons have been accelerated, but only 14% of them have remained near the Sun at 08:26 UT, i.e. for the integral proton spectrum with power law index of 3 (3.5) we have $Np\,(E > 30\ \text{MeV}) = 2.6\,(4.8) \cdot 10^{32}$ protons. Therefore, the number of protons interacting in the Sun and the number of protons in the interplanetary space correspond to each other.

Model time profiles of the proton intensity calculated for the same source function, but for different values of mfp, demonstrate that the main conclusion about the prolonged injection on 11 June 1991 does not depend on this choice. However, it would be not so for the event of 15 June 1991. In a case of small values of mfp it is not necessary considering the prolonged injection, but this contradicts to γ-ray observations. Note the source function should be energy dependent. In both cases duration of GLE is about 3–4 hours after the X-ray onset. According to my estimates about 80% of particles were injected after that time on June 11. These particles had a very soft spectrum and a response of NM to these particles is below background. The spectrum of interacting protons obtained in [6] for 08:26-09:25 UT on June 15, 1991 shows that a majority of high-energy protons have escaped the region of γ-ray emission before.

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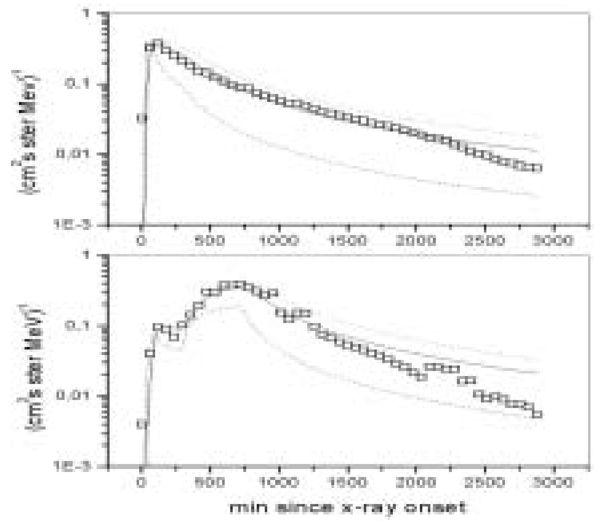

Fig. 1. The solar proton events of 11 (lower panel) and 15 (upper panel) June 1991. Hourly proton intensity measured within 84–200 MeV energy range by GOES-7 averaged beginning the x-ray onset (open squares) and it's model approximation (dot line $\lambda = 0.08$ AU, solid line $\lambda = 0.11$ AU, dash line $\lambda = 0.3$ AU) with source function from Table 1.

4. References

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