29th International Cosmic Ray Conference Pune (2005) **1**, 293-296

Modeling of propagation of solar protons in 3D heliosphere (<4 AU)

I. V. Zimovets[a,b] and A. B. Struminsky[a,b,c]
(a) Space Research Institute of RAS, Profsoyuznaya st., 84/32, Moscow 117997, Russia
(b) Moscow Institute of Physics and Technology, Institutsky lane, 9, Dolgoprudny, Moscow region, Russia
(c) IZMIRAN, Troitsk, Moscow region, 142092, Russia
Presenter: I. Zimovets (ivanzim@mail.ru), rus-zimovets-I-abs1-sh21-poster

Qualitative analysis of observations of solar protons events in the solar activity maximum in 2000 - 2001 years at the Ulysses (high latitudes of heliosphere) and GOES (ecliptic plane) spacecrafts has been done already many times. Probably, during the first 30 hours of the considered events protons have propagated mainly along interplanetary magnetic field lines from the place of their injection directly into the field tube after their coronal diffusion in a spherical shell close to the Sun, but cross-field diffusion of the protons was necessary only for the smoothing of space gradients at the late phase of the events [1]. Here we model the propagation of 40 - 125 MeV solar protons during several events in the frame of this scenario and estimate spatial and temporal characteristics of the source and propagation parameters.

1. Introduction

There are a lot of energetic processes on the Sun the result of which is the injection of various particles into the interplanetary medium. The injections prove themselves as increases of particle intensity, which one can observe with the help of some spacecrafts. Till recently all measurements of solar cosmic rays (SCR) were performed in the ecliptic plane. This situation radically changed after launching of the Ulysses spacecraft, which orbit allows investigating the heliosphere in three dimensions, including high latitudes [2].

During the period of the last solar activity maximum in 2000 – 2001 years occurred several solar energetic events, which one could associate with increases of the SCR intensity aboard spacecrafts. Different research groups analyzed observations of solar energetic particles. Underline the following: (a) it is unlikely that the main acceleration mechanism of SCR is the acceleration by CME driven shocks [3]; (b) probably the SCR injection is prolong in space and time, after the injection into the interplanetary medium SCR propagate along magnetic field lines [1].

Probably for the first time an idea about particle coronal diffusion was posed by Reid [4]. Ng and Gleeson expanded this model for the spherical geometry [5]. They proposed an isotropic diffusion of particles over the solar surface after their injection in some point and further diffusion along magnetic field tubes in the interplanetary medium. But they had a chance to compare their model only with experimental data from the ecliptic plane because there were not any spacecrafts out of the ecliptic.

We consider similar model but now we already have a chance to compare our model results with data from the Ulysses spacecraft obtained at high latitudes. We work with solar proton intensities within the energy range of 40 – 120 MeV measured by COSPIN/KET. Protons of these energies don't feel the little heterogeneities of the interplanetary magnetic field and a number of these protons are large enough to single out them from the interplanetary background. Also we model the propagation of solar protons in a heliospheric region, which stretches no more than four AU from the Sun because the Ulysses was just in this region in 2000 – 2001 years.

2. The model

We are consistent with the concept of a prolonged source of particles on the Sun's surface. Suppose that some amount of protons were accelerated till prescribed energy (we don't discuss in what way the protons were accelerated). After that the protons can somehow wander over the solar surface (presume they isotropic diffuse) and partly fly away into the interplanetary medium, where the protons propagate inside the magnetic field tubes and can't skip from one tube to another [5] (the ratio of the perpendicular to parallel diffusion coefficient is often assumed to be small [6]). The intensity of the protons in each point of the Sun's surface is described for small times by the equation

$$I = \frac{N_0 R_0^2}{4\pi t k_0} \exp\left(-\frac{\Omega^2 R_0^2}{4 t k_0} - \frac{t}{A} \right) \tag{1}$$

where N_0 - a total number of injected protons in a source, R_0 - the radius of the thin layer where the protons propagate (we suppose it is equivalent to the Solar radius), k_0 - the diffusion coefficient, A - the waste coefficient which determine an outcrop of the protons into the interplanetary medium, Ω - an angle distance between a flare and a concerned point.

Magnetic field lines constitute plane spirals of Archimedes in the ecliptic plane and spirals of Archimedes coiled on a cone at non zero latitudes. Of course it is ideal picture but it is logically to suppose that the reality is on average the same.

3. Model results

Table 1 shows considered seven solar energetic events of 2000-2001 years. We model first 80 hours after X-ray onset. Probably after that time effects of the cross-field diffusion become important. The model results only for the event 5 see on figure 1 (for short). In another cases situation is analogous on the whole.

Table 1. Characteristics of the consider solar events

Data of an event	Number of an event	Day of an year	Flare			
			Onset, min	Coordinate	N0	N0i/N01
14 July 2000	1	196	10:20	N22 W07	6*E+35	1
12 Sep 2000	2	256	11:45	S17 W09	5*E+34	0.08
8 Nov 2000	3	313	22:53	N10 W77	3*E+35	0.5
4 Nov 2001	4	308	16:13	N06 W18	6*E+34	0.1
24 Sep 2001	5	267	09:30	S16 E23	3*E+35	0.5
22 Nov 2001	6	326	20:20	S25 W67	1*E+35	0.17
26 Dec 2001	7	360	04:30	N08 W54	8*E+33	0.01

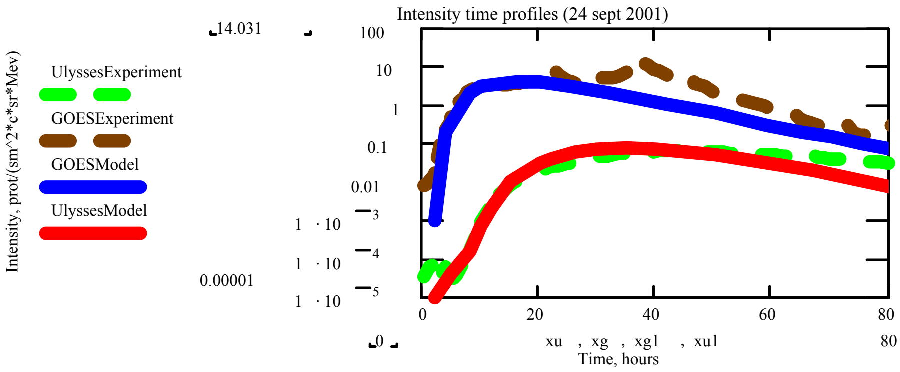

Figure 1. Intensity time profile of the protons on 24 September 2001 on the spacecrafts.

We can obtain model time profiles which differ from experimental ones no more than one order by a necessary choice of the model parameters (N0, A, k0, K). On average the parameter A is equal to 15 hours, a significances of the parameter N0 showed on Table 1, K (an interplanetary diffusion coefficient) is equal to 0.01 ((A. U.)^2)/hours, on average k0/R0^2 is equal to 0.01 (hours)^(-1). Mean free path for the considered protons on the Sun is about 100 kilometers. Some deviations of model intensity from experimental one (the smooth model graph and the rough experimental graph) appear due to irregularities of the solar wind.

The model results don't strongly depend on parameters of the interplanetary medium such as a diffusion coefficient K. In all cases we assume the diffusion coefficient equal to 0.01 (AU^2)/hours. We can modify it large enough (two orders) but at that the result doesn't strongly change. On the other hand the parameters of the solar source influence very strongly on behavior of intensity time profiles. So we propose that the Sun plays a greater role forming solar proton intensity time profiles in the interplanetary medium than the interplanetary medium herself.

Also the model intensity time profiles calculated for different events very strongly depend on a mutual location of the flare position and the spacecraft's footpoint (lower in details). Calculating a footpoint we need to use a solar wind speed but its distribution over the Sun is unknown. We have to use its average values; as a result, an accuracy of a determination of footpoint location probably is not large. Therefore we have a good chance to "play" on a choice of the solar wind speed.

4. Discussion of the model

The model copes with a posed task. The model can adequately describe a behavior of an intensity time profile simultaneously on both spacecrafts during first 80 hours after a beginning of a corresponding event.

Probably the model is able to explain the next phenomenon: maximum of the solar protons intensity at GOES changes by 2 – 3 orders from one event to another but changes at Ulysses are only several times [1-2], and on this occasion in [1] proposed that probably there is high latitude region near the Sun with near equal intensity from a point to a point and from an event to an event. Since the model results show that the interplanetary medium weakly influences on intensity time profiles, and also protons can't jump from one magnetic tube to another (cross-field diffusion coefficient is zero), then the proton intensity in some point of the interplanetary space directly depends on proton intensity close to the solar surface as determined by (1).

There is a square of an angle distance between a flare position and a spacecraft's footpoint in the exponent. In its turn the angle distance consists of a sum of squares of latitudinal and a longitudinal distances.
Ulysses' latitude is large in our events but GOES' latitude is always zero. One can see from Table 1 a flare's latitude is always small. So Ulysses' latitudinal distance is always large but GOES' latitudinal distance is always small. Therefore Ulysses' total angle distance weakly depends on a longitudinal distance but for GOES it is not right. This picture is clearly seen in Fig. 2.

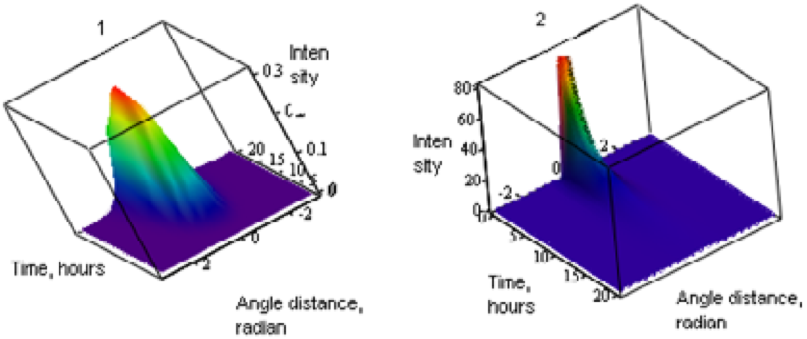

Figure 2. An angle and time dependence of an intensity of protons in some points of the solar surface: 1) the solar latitude of 63 degree; 2) the solar equator. We consider an angle distance between a point of a flare and some point of solar surface.

5. Conclusion

We considered the model of a diffusion coronal transport of protons with energies of 40 – 120 MeV and further their diffusion propagation in the interplanetary medium along magnetic field lines. In all considered seven events the model could adequately describe the experimental intensity time profiles simultaneously at Ulysses and GOES. The model confirms the assumption about the important influence of solar source, which is prolonged in space and time, on solar proton intensity observed in the interplanetary medium. It can explain similarities for Ulysses and distinctions for GOES intensity time profiles. Also we estimate the parameters of a coronal diffusion, a total number of emitted protons of a given energy and the interplanetary diffusion coefficient. Of course for the examination of our parameters we need to know an experimental ones (or oblique ones). It is significant that the processes on the Sun might be more difficult and manifold than considered in the model. Probably we don't take into account a lot of interesting processes. But even in our rough approach it is a success to reasonably describe considered events.

6. Acknowledgements

This work was partially supported by the Leading Scientific School Grant (HIII-1739.2003.2).

References

[1] Struminsky A. et al., JASR, in press (2005).
[2] McKibben R.B., AnnGeo, 21, 1217-1228, (2003).
[3] Dalla S.,et al., GRL, 30, 19, 8035, doi: 10.1029/2003GL017139, (2003).
[4] Reid G. C., J. Geophys. Res., 69, 2659, (1964).
[5] Ng C. K., Gleeson L. J., Solar Phys., v. 46, p. 347-375, (1976).
[6] Giacalone J., Jokipii J. R., Mazur J. E., ApJ., 532: L75-L78, (2000).