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CONDITIONS FOR ARRIVAL OF SOLAR ENERGETIC PROTONS IN EARTH AFTER MAJOR SOLAR FLARES

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Abstract. We analyze the Sun-to-Earth transport of energetic protons accelerated in solar flares. We use a model which assumes that protons move earthward in the Parker electromagnetic field. In this model, protons are shown to be recorded on Earth when they, moving away from the solar flare region, reach the vicinity of the heliospheric current sheet, while Earth is at a distance smaller than the proton Larmor radius from the current sheet neutral line. We present the analysis of experimental data on solar flares in August–September 2011. This analysis shows that the absence of energetic protons recording in the vicinity of Earth for some major solar flares can be explained by the proposed model.

Keywords: solar flares, solar proton events, ground level enhancements.

INTRODUCTION

Solar energetic protons (SEPs) are the particles that accelerate on the Sun during flares and then “escape” into the interplanetary space. Their energy is within the range from several tens of keV to tens and hundreds of MeV, and sometimes even higher. Studying SEPs is essentially important because the SEPs reaching Earth affect near-Earth space and Earth’s atmosphere, inasmuch as solar protons penetrating into the atmosphere at high latitudes cause atmospheric ionization and a change in its chemical composition. Now, the SEPs detected in near-Earth space after major solar flares are generally split into two groups [Reames, 1999, 2013; Desai, Giacalone, 2016; Lazutin, 2020]: 1) protons accelerated in a chromospheric flare; 2) protons accelerated at the fronts of shocks, driven by coronal mass ejections (CMEs), in the lower solar corona [Ellison, Ramaty, 1985; Reames, 1999, 2013]. The processes during which the group 1 protons form are termed impulsive; the processes during which the group 2 protons appear are called gradual [Reames, 1999; Desai, Giacalone, 2016; Lazutin, 2020]. The number of gradual events considerably exceeds that of the impulsive events. This fact is corroborated by the dependence of the longitudinal distribution of the number of impulsive and gradual events (as shown in Figure 2.3 in [Reames, 1999]). CMEs, as a rule, accompany major flaring processes on the Sun and are well-pronounced in interplanetary and near-Earth space [Richardson et al., 2007; Echer et al., 2008; Richardson, 2014].

The protons accelerated directly in flares cause a small number of SEP ground level enhancements, GLEs but only when a flare occurred on the interplanetary magnetic field (IMF) lines conjugate to Earth. Most SEP GLEs are generated by the protons accelerated by CME driven shocks in the solar corona. In this case, the higher the acceleration efficiency, the power, and the intensity of proton fluxes, the closer the parent flare to the magnetoconjugate point and the higher the flare importance [Ellison, Ramaty, 1985; Reames, 1999, 2013; Lazutin, 2020].

To elucidate the SEP emergence in Earth's environment, we should address the following issues: 1) how (by which mechanism) are particles accelerated on the Sun? and 2) how do SEPs escaping the Sun reach Earth’s environment? In this study, we focus on the SEP transport from the Sun to the Earth orbit. Until recently, such transport has been analyzed using two approaches to particle propagation in the heliosphere. The first assumes that the SEP motion is governed by the particles' diffusion and convection in heliospheric plasma. The second implies that SEPs move in the Parker field, i.e. in the heliospheric regular electromagnetic field, whose magnetic component is usually referred to as IMF. Now, most researchers tend to believe that the SEP Sun-to-Earth transport is implemented within the second approach. In this paper, we use the results from our previous paper [Kichigin et al., 2019], in which we present numerical calculations for paths of the protons moving from the Sun to the Earth orbit within the second approach.

BRIEF INFORMATION ON THE MODEL IN USE

In the model from [Kichigin et al., 2019], the path of the protons emitted from a point on the Sun’s surface is derived from the equation for the motion of ions in the Parker heliospheric field. The model assumes SEPs to move without collisions in the heliosphere. We analyze the proton motion by using the following assumptions:

- protons start moving in a magnetic tube, with the energy such that the Larmor radius of particles is smaller than or comparable with the tube radius;
- proton motion in a magnetic tube may be analyzed in the drift approximation, hence the particles retain their magnetic moment;
- from the solar radius $R_\odot$ to $20R_\odot$, the tube's magnetic field is considered almost radial, with its strength decreasing with distance R as per the $H=H_\odot R_\odot^2/r^2$ ratio, where $H_\odot$ is the magnetic field on the Sun's surface;
- due to the field decrease and the magnetic moment conservation, protons in the magnetic tube move almost radially at $>20R_\odot$ from the Sun;
- beyond $R_0 = 20r_\odot$, protons are within the Parker field.

According to the Parker model [Parker, 1958], in the spherical system of coordinates R, θ, φ, at large distances from the Sun ($r \gg R_\odot$), the magnetic field is described by the formulas:

$$H_R(r,\theta)=\mathrm{sign}(\pi/2-\theta)H_\odot R_\odot^2/r^2, \quad (1)$$

$$H_\varphi(r,\theta)=-H_\odot\Omega\sin[\mathrm{sign}(\pi/2-\theta)\theta]R_\odot^2/(ur). \quad (2)$$

In these formulas, Ω is the angular velocity of the Sun rotation; u is the solar wind velocity. Relations (1)–(2) represent the magnetic field in the case when the latter has a positive polarity (away from the Sun) in the northern hemisphere. In this case, directions of the vectors of the solar mechanical and magnetic dipole moments coincide. When the direction of the solar magnetic dipole moment reverses, the field in the northern hemisphere is negative.

The main conclusions drawn in [Kichigin et al., 2019], which follow from solving the problem of SEP motion in the Parker heliospheric field, are as follows:

1. When moving along the IMF lines, protons displace in the direction against the heliospheric electric field vector due to a drift in IMF. The effect of such charged particle displacements was already noted in 1980s in [Bazilevskaya et al., 1981].

2. The result of such a drift is that SEPs in Earth's environment may be observed only in the case when protons are ejected from the flares located in the northern (southern) hemisphere of the Sun provided that the IMF projection on the corresponding hemisphere of the Sun has a positive (negative) polarity. Figure 1 from [Kichigin et al., 2019] illustrates this drift effect and shows 10 GeV proton paths for two opposite IMF polarities in the solar northern hemisphere.

Under real conditions, as is typical for different reasons, we should admit that SEPs deviate somewhat from the calculated path. From observations [Reames, 1999; Desai, Giacalone, 2016; Lazutin, 2020] it follows that the longitudinal angles within which SEPs are ejected directly from a flare region and reach Earth's environment have albeit a small but finite interval ≈30°. One of the possible reasons is the fact that the global magnetic field forms far from the Sun's surface [Schatten et al., 1969; http://wso.stanford.edu/synsourcel.html], hence a high probability of the SEP minor scattering at the section of their path from the flare region to the global magnetic field lines formed at

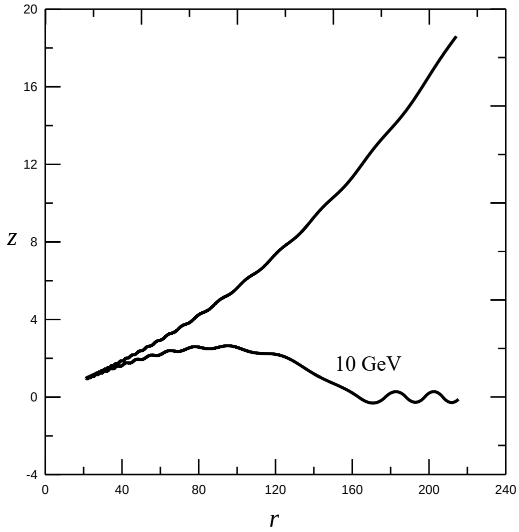

Figure 1. 10 GeV proton paths for the positive (lower curve) and negative (upper curve) polarities of the magnetic field in the solar northern hemisphere. The protons were ejected from $R_0=21.4R_\odot$ with an initial distance from the Z-axis $z=0.999R_\odot$ (latitude angle θ = 2.5°). Distances along the axes are in solar radii. Both curves terminate at a distance equal to the Earth orbit radius $R_E=214R_\odot$ from the Sun

a distance R^* from the Sun ($R^*>2R_\odot$). In the path section from the Sun's surface to the radius R^*, Coulomb collisions, irregular magnetic fields, coronal plasma irregularities, etc. may also lead to charged particle scattering. Another reason is SEP's finite Larmor radius along the earthward path. As follows from our model [Kichigin et al., 2019], protons reach Earth by moving along the lower path shown in Figure 1. Consequently, protons are recorded on Earth in cases when the protons moving from a solar flare region reach the heliospheric current sheet neighborhood, and Earth is at a smaller distance than the proton Larmor radius from the current sheet neutral line. We may therefore consider that the lines of theoretical proton paths are mean values for coordinates of particles moving earthward, i.e. SEPs may be in the vicinity of the coordinates of the calculated lines at a distance ~$1R_\odot$. Accounting for this fact and also assuming that there are some deviations of the real solar global field from theoretical values, we suppose that scattering of real SEP paths near the calculated values may be $\gtrsim 1R_\odot$. Considering proton scattering near the calculated paths, we should admit that our model describes a Sun-to-Earth SEP transport pattern averaged over the Larmor radius.

OBSERVATIONAL DATA

To test our model, we have analyzed the flare events that occurred during the ascending phase of solar cycle 24 in August–September 2011. We used such characteristics as an IMF image on the Sun's surface [http://wso.stanford.edu/synsourcel.html], SEP presence/absence in Earth's environment, as well as the location, flare point, and data on CME presence/absence for each particular flare [https://cdaw.gsfc.nasa.gov/CME_list/sepe].

Solar Proton Events in August–September 2011

N	Data	Coordinates	IMPORTANT Xray/opt	AR	CME to / v / T/pa
1	2011-08-09	N18W68	M2.5/1B	11263	0348/1146/141/272
2	2011-09-04	N18W84	M3.2/SF	11286	–
3	2011-09-05	N18W87	M1.6/SF	11286	–
4	2011-09-08	N14W40	M6.7/1N	11283	1636/0214/037/311
5	2011-09-09	N13W52	M1.2/1F	11283	–
6	2011-09-10	N12W61	M1.1/SN	11283	0848/0610/169/257
7	2011-09-22	N24W55	M1.04	–	–
8	2011-09-23	N25W63	M1.6/1N	11295	–
9	2011-09-23	N23W73	M1.6/SF	11295	2348/0337/021/326
10	2011-09-24	S29W67	M1.2/SF	11303	–
11	2011-09-25	S28W71	M1.5	11303	–
12	2011-09-25	S28W75	M2.2/SF	11303	–

Notes:

Xray/opt – X-ray class and optical importance of flare;

AR – solar active region;

CME – coronal mass ejection: t_0 – first C2 appearance; v – linear speed [km/s]; T – type: halo and partial halo; p_a – position angle measured from solar north in degrees (counterclockwise).

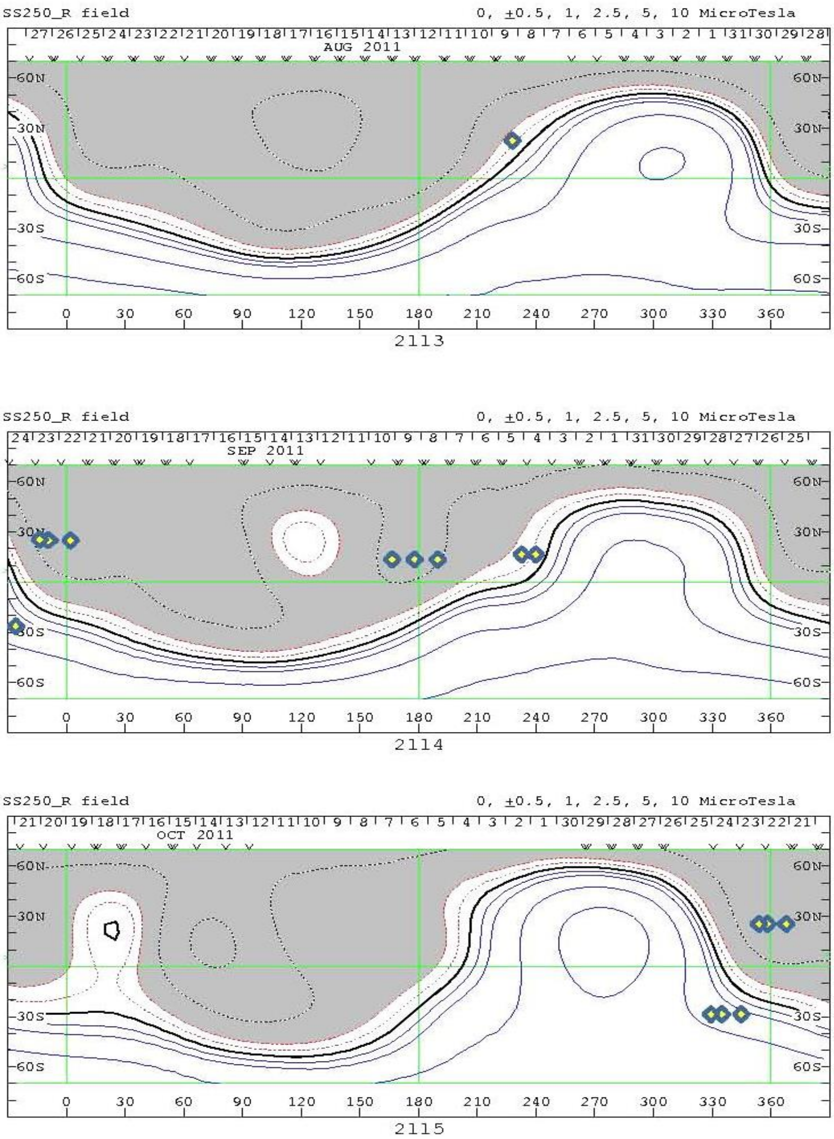

Figure 2. Solar corona magnetic field map [http://wso.stanford.edu/synsourcel.html]. Blue isolines and light shading indicate positive regions. The neutral line is black. Rhombs mark coordinates of the flares of M1 class and higher that were located at the longitudes from which the Earth-conjugated IMF lines come

We have selected flare events in which three main conditions are necessarily fulfilled: 1) the flare X-ray class should be >M1, 2) the flare location should be west of W30° on the visible solar disk, 3) the flares accompanied by halo CMEs were excluded from the analysis.

Table presents some characteristics for these events [Logachev et al., 2019].

Thus, we are concerned with major flares whose location was on the Sun's surface within the region with Earth-conjugated IMF lines. More than half (8 cases) of 12 flares we selected were not accompanied by CMEs. We may categorize the events caused by such flares, according to the terminology [Reames, 1999; Desai, Giacalone, 2016; Lazutin, 2020], as impulsive. Note that, by definition, SEPs in such events are generated directly at the flare location. It was natural to expect that the four flares accompanied by CMEs caused SEP GLE on Earth because the CME-driven shocks are well known [Reames, 2013; Berezhko, Krymsky, 1988; Berezhko et al., 1997; Reames, 1995; Ng et al., 2003] to lead to the acceleration of particles that (upon reaching Earth) produce such an enhancement. However, in our case, these CMEs were narrow-beam and propagated away from Earth; therefore, the SEP flux they produced decreased to the galactic background, and there was no SEP increase near Earth.

RESULTS AND CONCLUSIONS

Figure 2 presents a solar corona magnetic field map, which contains coordinates of the major flares we selected. The coronal magnetic field was calculated from observations of the photospheric field by the potential field model [http://wso.stanford.edu/synsourcel.html]. The photospheric field is assumed to be radial, and the source surface is located at $3.25R_{\odot}$.

Table 1 and Figure 2 demonstrate that all the flares we selected are located on the Sun within the region where the Earth-conjugated IMF lines start. Nine flares were in the Sun's northern hemisphere within the region where the IMF polarity was negative, and three flares were observed in the southern hemisphere where the IMF polarity was positive.

According to Figure 1 demonstrating the proton paths calculated by our model for the northern hemisphere flares, all the protons accelerated and ejected from the flare region move along the upper path, i.e. away from the equatorial plane, and hence they do not reach Earth's environment, which is corroborated by the absence of SEP GLEs on Earth. SEPs accelerated in the southern hemisphere flares, according to our model, also move away from the equatorial plane and are not recorded near Earth.

We can formulate the main conclusion of this paper as follows: for all the major chromospheric solar flares observed in the X-ray band, the absence of flare-accelerated energetic protons in Earth's environment may be well explained by our model for SEP propagation in the heliosphere [Kichigin et al., 2019].

We dedicate this paper to the memory of Dr. G.N. Kichigin (1939–2021). It is the last scientific study of the outstanding theorist.

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