Solar energetic particle propagation from solar flare

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Abstract. A solar flare is a sudden, rapid, and intense variation in brightness as observed at the Sun. It typically associates with converting magnetic energy to kinetic energy in the form of solar energetic particles (SEPs). The objective of this work is to study the propagation of SEPs from the Sun to the Earth. We simulate the particle propagation for the solar event on August 9, 2011 by using the transport equation from Ruffolo 1995. We solve the transport equation by the numerical technique of finite different method. We find injection duration by fitting the simulation results and the particle data from spacecraft. The X-ray class of the selected solar event is X6.9, the solar flare position on the Sun is N18W68, and the solar wind speed is 551.5 km/s. We found the solar flare on August 9, 2011 is the gradual flare. This flare had the long injection time from the Sun to the Earth corresponding to the shock wave detected after explosion in the interplanetary space 13 minutes. In the path of the solar flare affected on the Earth, the Kp-index (the value of the earth's magnetic field variable) was considered. The Kp-index of these solar flares was less than 3, which they didn't affect on the Earth.

1. Introduction

Solar flares extend out to the layer of the Sun called the corona. The corona is the outermost atmosphere of the Sun, consisting of plasma with extremely high temperature. The temperature is not uniform and it is typically high within magnetic loops locating close to the solar equator. The loops are bright in ultraviolet and X-ray and they are found around the active regions where solar activities generally begin. All solar activity is driven by the solar magnetic field. Solar flare, solar wind, solar energetic particles or coronal mass ejections are some activities that occur at the atmosphere of the Sun [1, 2, 3]. Flares occur when speed up charged particles results from magnetic reconnection collide with plasma in the corona and the chromosphere. The phenomenon of magnetic reconnection leads to this copious acceleration of charged particles. The unconnected magnetic field and the material that it contains may violently expand outwards from the Sun. This shows solar flares typically erupt from the active regions on the Sun where magnetic fields are much stronger on average, where intense magnetic fields penetrate the photosphere to link the corona to the solar interior [4, 5, 6]. Flares are powered by the sudden release of magnetic energy stored in the corona. The solar energetics move around the magnetic field line from the Sun to the Earth. These particles have effect on the Earth such as disrupting radio communication or the colorful light at the Earth's pole called aurora [7].

In this work, the propagation of the solar energetic particles releasing from the Sun to the Earth is studied. We simulate the particle transportation from the solar event on August 9, 2011 with the equation of Ruffolo 1998 [3, 4]. We solve the transport equation by the numerical technique of finite different method. We use the initial data for the simulation from the ACE spacecraft (the advanced composition explorer) data. The simulation results show information of the propagation of the solar energetic particles from the Sun [5].

2. Transport equation
The propagation of solar energetic particle is helixes around the magnetic field line. The intensity of magnetic field line correspond to the distance of particles trajectory from the Sun to the Earth as

$$\frac{1}{L(z)} = -\frac{1}{B}\frac{dB}{dz}$$, where $L(z)$ is the focusing length, B is the intensity of the magnetic field, and z is the distance along to the magnetic field. From the fundamental equation of Fokker-Plank and transport equation of Ruffolo 1995, 1998, we can explain the propagation of the solar energetic particles from the Sun to the Earth as shown in following equation [1, 2, and 3].

$$\frac{\partial \vec{F}(t,\mu,z,p)}{\partial t} = -\frac{\partial}{\partial z}\mu v \vec{F}(t,\mu,z,p) \qquad \text{(streaming)}$$

$$-\frac{\partial}{\partial z}(1-\mu^2\frac{v^2}{c^2})v_{sw}\sec\Psi\,\vec{F}(t,\mu,z,p) \qquad \text{(convection)}$$

$$-\frac{\partial}{\partial u}\frac{v}{2L(z)}1+\left[1+\mu\frac{v_{sw}}{v}\sec\Psi - \mu\frac{v_{sw}v}{c^2}\sec\Psi\right](1-\mu^2)\vec{F}(t,\mu,z,p) \quad \text{(focusing)}$$

$$+\frac{\partial}{\partial u}v_{sw}(\cos\Psi\frac{d}{dr}\sec\Psi)\mu(1-\mu^2)\vec{F}(t,\mu,z,p) \qquad \text{(differential convection)}$$

$$+\frac{\partial}{\partial u}\frac{\varphi(\mu)}{2}\frac{\partial}{\partial\mu}(1-\mu\frac{v_{sw}v}{c^2}\sec\Psi)\vec{F}(t,\mu,z,p) \qquad \text{(scattering)}$$

$$+\frac{\partial}{\partial p}pv_{sw}\left[\frac{\sec\Psi}{2L(z)}(1-\mu^2)+\cos\Psi\frac{d}{dr}(\sec\Psi)\mu^2\right]\vec{F}(t,\mu,z,p). \qquad \text{(deceleration)}$$

Where F is the distribution function; $\vec{F}(t,\mu,z,p) = \dfrac{d^3N}{dzd\mu dp}$, θ is the pitch angle, μ is the cosine of pitch angle, v_{sw} is the solar wind speed, Ψ is the angle between $\hat{r}$ and $\hat{z}$, c is the light speed, v is the particle speed (km/s), $\varphi(\mu)$ is the scattering coefficient, and p is the momentum of particle.

The streaming term shows the particle propagation in z direction, convection term shows the trajectory of particles by solar wind, focusing term shows the intensity of the magnetic field and distance of magnetic field, differential convection term shows the trajectory of particles at the different point of solar wind, scattering term explains the propagation of SEPs along to the irregularity magnetic field line, and the deceleration term shows the particle motion corresponds to the decreasing of momentum.

In the part of scattering depends on the pitch angle, in this work, we focus the mean free path of particle from the relation of $\lambda \equiv \dfrac{3D}{v}$ where D is the diffusion coefficient; $D = \dfrac{v^2}{4}\int_{-1}^{1}\dfrac{(1-\mu^2)^2}{\varphi(\mu)}d\mu$ in scattering term.

3. The interplanetary magnetic field

The interplanetary magnetic field is the magnetic field from the Sun to the Earth. The solar wind drags magnetic field lines out from the Sun while the Sun is rotating, then the magnetic field lines are curved and are highly turbulent [2]. Because of the SEPs are the charged particles, so their propagation along to the magnetic field line are helix. The interplanetary magnetic field and the solar winds speed are shown in parameters of v_{sw}, Ψ and $L(z)$ as in Figure 1.
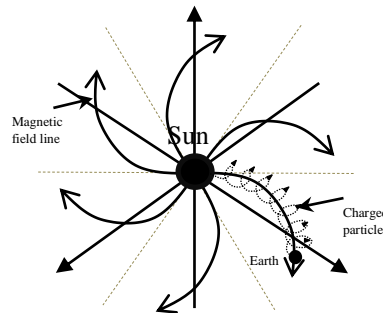

Figure 1. Sketch of interplanetary magnetic field and the solar wind

4. Transport simulation

We simulate the particle propagation for the solar event on August 9, 2011 with the transport equation of Ruffolo 1995, 1998. We use the numerical technique of finite different method for transport equation solving. The boundary condition of μ are equal to ± 1, it means the particles don't flow in and flow out from the boundary of $|\mu| > 1.$ We study the profile of the solar energetic particle propagation from the Sun to the Earth along to the magnetic field line for He at the various energy. The background data of solar event on August 9, 2011 consist of the X-ray class of this flare is X6.9, the solar flare position on the Sun is N18W68, and the solar wind speed is 551.5 km/s.

5. Methodology

We study the information of SEPs from selected solar event by comparing results from a simulation program with the data from ACE spacecraft. The simulation program simulates the various effects on the SEPs transport with the various mean free paths. The mean free path is the longest distance of particle moves along to the magnetic field line before it is scattered by the irregularity magnetic field. The simulation results show the particle distribution for He at the various energy level. The propagation simulation of the solar energetic particles is solved by finite different method to study the particle distribution at the different mean free the paths.

6. Result

We use the transport equation to explain SEPs in space which includes the various effects with the technique of finite different. Most of spacecraft data are used to analyze the solar energetic particle intensity. The interested solar event is August 9, 2011 with the 6.9 x-ray intensity. We look at the profile of the He intensity in time at the various energy levels (4.032, 6.685, 11.493 MeV/n) to study the arriving information of SEPs at the Earth as shown in Figure 2. The left hand side of Figure 2 shows the detected SEP intensity in time from spacecraft (at the Earth), while the right hand side of this Figure shows the simulation of the SEP intensity in time at the Sun. The SEP transport simulation shows the intensity of particles in time after the solar flare occurs, but the spacecraft takes a long time to detect the intensity of particles in time after they move along the magnetic field line from the Sun to the Earth. We study the relationship of the SEPs intensity versus the various mean free paths (0.4, 0.8, 1.2 AU) for explaining the distribution of SEPs in time near the earth and beyond as shown in Figure 3. The value of Kp-index (the variation value of the Earth's magnetic field) of this flare less than 3, which shows this flare didn't effect on the Earth.
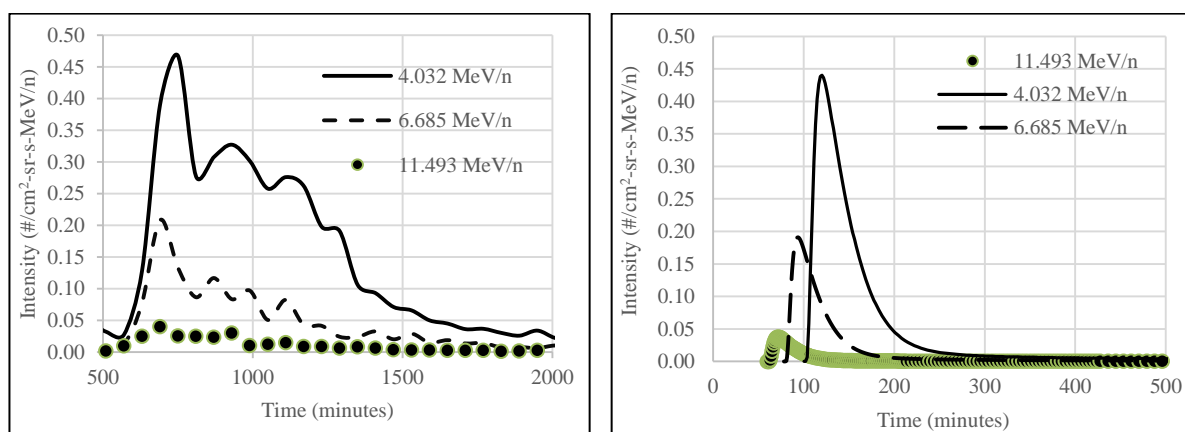

Figure 2. The intensity data of He (#/cm^2-sr-s-MeV/n) at the various energy level (4.032; solid line, 6.685; dashed line, and 11.493; dot line MeV/n) for the transport simulation results on August 9, 2011. The particle data from spacecraft (particle intensity in time at the Earth) for each energy show on the left figure, and the SEP simulation results (particle intensity in time at the Sun) at λ = 1.0 AU show on the right figure.
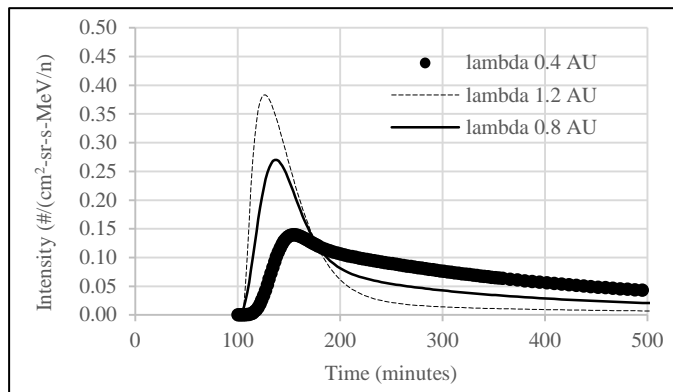
Figure 3. The intensity data for He 4.032 MeV/n for lambda 1.2 AU (dot line), 0.8 AU (dashed line), and 0.4 AU (solid line) for the transport simulation results on August, 9, 2011.

7. Conclusion

The simulation results for the particle intensity injection from the Sun shown the information of pulses are same. The strong particle intensity increases closer to the Sun and diffusion is weaker. The highest intensity peak was found in the lowest energy. The high solar energy particles arrive the Earth before the low energy. From simulation results can use to determine the information of the SEP transport from the Sun to the Earth, which similar to approximate theories of Earl et al. 1995 [7], when we set the focusing length to be constant in the program. The pulse propagation will occur in the weak focusing region, and the pulse slowly decay in the diffusion region as the propagation speed steadily decrease with increasing z. From the pulse propagation of particles released from the Sun for the various mean free path (λ), it is found that the pulse occurs very rapidly as seen in during of the particles arrived the Earth. The propagation of SEPs along to the magnetic field line is long for the longest mean free path, which the particle scattering by the irregularity of the magnetic field is small. We found the propagation of particles will follow the magnetic field fastest for the longest mean free path (that implies the weakest scattering), which correlates to Earl et. al., 1995, which Earl shows the pulse will occur in the weak focusing region and slowly decay in the diffusive region as shown in the time profile of a pulse for the high λ is narrow and high, but for the lower value of λ the high of the peak is small. We tried to find the best λ for this solar event by using the technique of piecewise linear least square fitting.

8. Acknowledgments

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