The solar energetic particle propagation of solar flare events on 24th solar cycle.

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Abstract. Now the Sun is in the 24th solar cycle. The peak of solar cycle correspond to the number of the Sun activities, which one of them is solar flare. The solar flare is the violent explosion at the solar atmosphere and releases the high energy ion from the Sun to the interplanetary medium. Solar energetic particles or solar cosmic ray have important effect on the Earth, such as disrupt radio communication. We analyze the particle transport of the solar flare events on August 9, 2011, January 27, 2012, and November 3, 2013 in 24th solar cycle. The particle data for each solar flare was obtained from SIS instrument on ACE spacecraft. We simulate the particle transport with the equation of Ruffolo 1995, 1998. We solve the transport equation with the numerical technique of finite different. We find the injection duration from the Sun to the Earth by the compared fitting method of piecewise linear function between the simulation results and particle data from spacecraft. The position of these solar flare events are on the west side of the Sun, which are N18W68, N33W85, and S12W16. We found that mean free path is roughly constant for a single event. This implies that the interplanetary scattering is approximately energy independent, but the level of scattering varies with time. The injection duration decreases with increasing energy. We found the resultant variation of the highest energy and lowest energy, because the effect of space environments and the number of the detected data was small. The high mean free path of the high energy particles showed the transport capability of particles along to the variable magnetic field line. The violent explosion of these solar flares didn’t affect on the Earth magnetic field with Kp-index less than 3.

Keywords: solar flare, solar energetic particle, Kp-index, solar cycle, spacecraft data

1. Introduction

The one of the phenomena on the Sun is the solar flare. The solar flare, solar wind, solar energetic particles or coronal mass ejections are some activities which they occur on the Sun. The solar flares are classified into 2 types: impulsive flare and gradual flare. Impulsive flare causes rapid increasing of solar particle density in time. Gradual flare causes the coronal mass ejection and shock wave in the interplanetary medium. A solar flare is a sudden, rapid and intense variation in brightness and occurs when magnetic energy built up in the solar atmosphere is suddenly released. Radiation is emitted across the electromagnetic spectrum. The magnitude measurement of the solar flare obtains from their strength of X-ray emission. The big X-class flare is the largest explosion in the solar system. The violent solar flares are found on the peak of solar cycle. Recently, the Sun is in the 24th solar cycle (2009-2020) with the peak time in 2012-2014. The frequency of solar flares coincides with the Sun's 11-year cycle. When the solar cycle is at a minimum, active regions are small and rare and few solar flares are detected. Because of the solar flare produces the solar energetic particles (SEPs) move to the Earth, so the flare and associated effects can create the violent radiation storm hit to the Earth, which can damage satellites, communication system, electric power failures, or ground-based technologies. An understanding the SEPs propagation by spacecraft data analysis from the selected solar events, then the advanced warning of the effect from the space weather can prepare in time.

In this work, we study the solar flare events on August 9, 2011, January 27, 2012, and November 3, 2013 in 24th solar cycle. We use the particle data for each solar flare from the Solar Isotope
Spectrometer (SIS instrument) on the Advanced Composition Explorer (ACE spacecraft). We simulate the particle transport with the equation of Ruffolo 1995, 1998. We solve the transport equation with the numerical technique of finite different. We find the injection profile from the Sun to the Earth by the compared fitting method of piecewise linear least square fitting between the simulation results and particle data from spacecraft for the SEPs transport understanding and the space environment.

2. Theoretical background and propagation equation.
The objective of this work is understand the acceleration information of the SEPs near the Sun and the trajectory of particles from the Sun to the interplanetary medium as a function of time. This research fits the data from spacecraft in order to determine the released particles from the Sun to the Earth as a function of time and energy. The solar wind flows from the outermost portion of the Sun because of the pressure difference. 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. The magnetic field of this work, lying along the Archimedean spiral at a distance \( r \) from the Sun, is

\[
B(r, \theta) = B_0(\theta) \left( \frac{r_0}{r} \right)^2 \left( e_r - \frac{Qr \sin \theta}{u} e_\phi \right),
\]

where \( \Omega \) is the angular rate of the Sun’s rotation, \( u \) is the plasma velocity, \( \theta \) is the angle between the velocity of particle and the magnetic field line, \( r_0 \) is the corotation radius of the Sun, \( e_r \) and \( e_\phi \) are unit vector in the radial and azimuthal direction, respectively (Roelof 1969). We consider the influence that affect the SEPs transport to explain the propagation of SEPs in space. This transport equation includes systematic change in the position along the magnetic field, \( z \), the pitch angle cosine, \( \mu = \cos \theta \), momentum, \( p \), and random change in the pitch angle scattering in \( \mu \). The density of particles were defined in term of the distribution function, \( F(t, \mu, z, p) = \frac{d^3N}{d\mu dz dp} \). The distribution function is developed by a Fokker-Planck equation,

\[
\frac{\partial F(t, \mu, z, p)}{\partial t} = \frac{\partial}{\partial z} \left( \frac{\partial}{\partial z} F \right) - \frac{\partial}{\partial \mu} \left( \frac{\partial}{\partial \mu} F \right) - \frac{\partial}{\partial \mu} \left( \frac{\partial}{\partial \mu} \left( \frac{E}{F} \right) \right) - \frac{\partial}{\partial p} \left( \frac{\partial}{\partial p} \left( \frac{E}{F} \right) \right).
\]

Where \( \varphi(\mu) \) is the coefficient of pitch angle scattering (Earl 1973), and \( \frac{E}{E_0} = 1 - \left( \frac{\mu v_w \sec \varphi}{c^2} \right) \) is the ratio of energy in solar wind frame and fixed frame. Finally we use the suitable transport equation (Ruffolo 1998) for simulating the SEPs. Where the angle between the field line and the radial direction is \( \psi \), \( L(z) \) is the focusing length; \( \frac{1}{L(z)} = - \frac{1}{B} \frac{\partial B}{\partial z} \), \( \varphi(\mu) \) is the pitch-angle scattering coefficient, \( r \) is the radial distance from the Sun, \( v \) is the particle speed, \( v_w \) is the solar wind speed, and \( c \) is the light speed. In the Ruffolo 1998 equation. We focus the mean free path \( (\lambda) \) of particle from the relation of \( \lambda = \frac{3D}{v} \) where \( D \) is the diffusion coefficient; \( D = \frac{v^2}{4} \int_{-1}^{1} \frac{(1-\mu^2)^2}{\varphi(\mu)} d\mu \) in the part of scattering term.

3. Methodology
In this work, we choose the solar flare events during the peak of 24th solar cycle (2011-2014). The interested solar events on August 9, 2011, January 27, 2012, and November 3, 2013 are selected. The solar flare information of each solar event is shown in table 1.
Table 1. The solar flare information for each solar event.

| Date         | Position | X-ray   | Solar wind speed (km/s) | Shock wave | Duration time (min) | Max Kp index |
|--------------|----------|---------|-------------------------|------------|---------------------|--------------|
| 3 Nov. 2013  | S12W16   | M5.0    | 387.8                   | -          | 10                  | 3            |

Gradual flare

| Date         | Position | X-ray   | Solar wind speed (km/s) | Shock wave | Duration time (min) | Max Kp index |
|--------------|----------|---------|-------------------------|------------|---------------------|--------------|
| 9 Aug. 2011  | N17W69   | X6.9    | 600                     | /          | 20                  | 3            |
| 27 Jan 2012  | N33W85   | X1.7    | 552.5                   | /          | 37                  | 2            |

The transport equation of SEPs was solved by the numerical technique of finite different method in the C program. The initial values of simulation were prepared from the spacecraft data for basic variable calculating. The simulation results are the particle distribution as a function of time for each energy of the mean free path.

We use the technique of the piecewise linear least square method for optimization of the injection duration. The best fitting will show by the value of $\chi^2$. The $\chi^2$ value is the difference between the results from the transport simulation program and the data from spacecraft and is defined as

$$\chi^2 = \sum_{i=1}^{N} \left[ \frac{y_i - \sum_{k=1}^{M} a_k X_k(x_i)}{\sigma_i} \right]^2,$$

where $(x_i, y_i)$ is the data point from spacecraft, $\sigma_i$ is the uncertainty of data point, $N$ is the number of data points, $X_k(x_i)$ are the arbitrary fixed function of $x$, $\{a_k\}$ are the parameters to be fitted and $M$ is the number of fitted functions. We model the injection function versus time near the Sun as a piecewise linear function, in which the best fit value with the best mean free path, $\lambda$ (Ruffolo, et al 1998). Finally we get the best piecewise linear injection function and $\chi^2$ value for each mean free path. We find the injection duration of the interested solar event in the term of full width at half maximum of the injection function.

4. Result

The data fitting between the transport equation simulation and the data from SIS instrument on ACE spacecraft for He at the energy range of 4.032-22.959 MeV/n shown in table 2.

Table 2: The data fitting for the interested solar events during 24th solar cycle.

| Solar event | Element | Energy (MeV/n) | $\lambda$ (AU) | Duration time (min) |
|-------------|---------|----------------|----------------|--------------------|
| August 9, 2011 | He      | 4.032          | 0.670          | 43                 |
|             |         | 5.390          | 0.707          | 110                |
|             |         | 6.685          | 0.737          | 90                 |
|             |         | 11.493         | 0.562          | 214                |
| January 27, 2012 |        | 4.032          | 0.612          | 1400               |
|             |         | 5.390          | 0.416          | 720                |
|             |         | 6.685          | 0.482          | 798                |
|             |         | 8.418          | 0.487          | 936                |
|             |         | 15.623         | 0.542          | 864                |
| November 3, 2013 |       | 4.032          | 0.690          | 668                |
|             |         | 5.390          | 0.790          | 359                |
|             |         | 6.685          | 0.887          | 447                |

We found mean free path is roughly constant for each event as shown in Table 2. There are some fluctuations, overall the injection duration of the higher energy is shorter than for the lower energy particles. The both of gradual flares found the emission of type II radio (effect of CME in the
interplanetary medium) after their explosion: 13 minutes for solar event on August 9, 2011 and 5 minutes for solar event on January 27, 2012.

5. Conclusion
The transport simulation results of the solar energetic particles on August 9, 2011 January 27, 2012 and November 3, 2013 show the trend of the mean free path is roughly constant for each event. The mean free path is an important parameter of interplanetary transport, this implied that interplanetary scattering is approximately energy independent, but the level of scattering varies with time. This is consistent with results of Palmer (1982) and Bieber et al. (1994). The injection duration depends on the energy level. We found some fluctuations, overall the mean free path of the higher energy particles is shorter than for the lower energy particles. This means that the acceleration of these energetic particles by the CME-driven shock is greatest at the Sun, and particle are also accelerated while the CME propagates outward from the Sun, and the CME-driven shock lost the ability to accelerate the SEPs after traveling a certain distance from the Sun [3, 8]. The injection duration time from the data fitting of the solar event on August 9, 2011 January 27, 2012 and November 3, 2013 is more than the injection time from spacecraft because the coronal mass ejection, solar wind speed or the irregularity of the magnetic field from the Sun to the Earth affect to the particle propagation. The violent explosion of these solar flares don’t affect on the Earth magnetic field because the Kp-index less than 3, which that means the Earth doesn’t get any effect of disturbances in the Earth's magnetic field. In the future work, we will study the initial condition of the transport equation, which cover the effect of CMEs on the transport equation.

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