The study of the strongest solar event on a minimum of the 24th solar cycle

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Abstract. The strongest solar flares of the 24th solar cycle erupted on September 6, 2017, and it was the 8th strongest solar flare recorded since 1996. This extreme solar flare occurred at the minimum of the 24th solar cycle. The active region is located in the Western Hemisphere and produced the violent explosion of class X9.3 and X2.2 on September 6, X1.3 on September 7, and X8.2 on September 10, 2017. The injection duration of the solar energetic particles of the solar event was 17 minutes. All data for this solar event was collected from the Advanced Composition Explorer and simulated for particles' motion using the transport equation and solved by the numerical technique. We obtained the injection time of the solar energetic particle propagation by comparing fitting between the simulation results and the spacecraft data. Injection time taken by high-energy particles to travel from the Sun to the Earth was found to be in the range of 39 to 743 minutes. At the peak of this solar flare, the coronal mass ejection was detected, which increased the injection time. The Kp-index of this solar flare was 4; thus, there was no effect on the Earth. The Kp-index value increased to 8 on September 7-8, 2017, due to another solar event from the same sunspot region, indicating the effect of solar flare and CME, which resulted in the appearance of aurora.

1. Introduction

Space weather is directly related to the activity of the Sun, which affects the Earth's environment, are the solar energetic particles (SEPs). They have important effects on the Earth, such as interference radio communication, cause of electrical power failures, radiation warning on airplane flights, and aurora phenomena [1]. Most SEPs regard the study of eruption on the Sun, such as solar flares and coronal mass ejection (CME), which increase during the solar cycle. A solar flare is a violent explosion on the surface of the Sun, which releases the SEPs moving in interplanetary medium or space. Most flares occur in active regions around sunspots. The Sun goes through a cycle of activities called the solar cycle, during which the sunspot numbers increase during solar maximum and decrease during solar minimum. Obtaining various solar cycle phases (rise, maximum, and declining) is also important [2]. Numbering the solar cycle started in 1749 [3]. The present 25th solar cycle began around December

2019. We pass the 24th solar cycle (2008-2019) [4], in which there were no large solar flare events for the first two years. There were no solar flares of X-class intensity in 2008-2010. There were 8 solar flares of X-class in 2011, of which the highest solar flare was X6.9 on August 9. We can also note that the violent solar flares of X-class occurred around the time of solar maximum (2011-2014). This solar cycle had an interesting solar event at the end of the cycle in 2017. The violent solar flares on the minimum of the 24th solar cycle occurred on September 6-10, 2017, at same region 2673, which includes X9.3 flare on September 6, 2017, at 11.53 UT, X8.2 flare on September 10, 2017, at 15.35 UT, X2.2 flare on September 6, 2017, at 8.57 UT, and X1.3 on September 7, 2017, at 14.20 UT. Preliminary data of X-ray flux intensity illustrated the violence of the interested solar flare. The brightness of X-ray flux in watts/m^2 shows the intensity of erupted solar flares. It consists of 5 classes: A, B, C, M, and X class. The Geostationary Operational Environmental Satellite (GOES) has provided a platform for the solar x-ray imager and space environment monitoring instruments. The solar flare of X-class is a violent eruption and may affect the Earth. The solar flare of M-class is medium violent. A and B classes are of low intensity, which have little effect on the Earth. This research selected the violent solar flares of X-class during September 6-10, 2017.

2. Solar energetic particle propagation from the Sun to the Earth

Solar energetic particles or SEPs are high-energy particles, such as ions, protons, or electrons, released from the Sun. SEPs are one of the phenomena related to solar flares. Solar flares are a large explosion of electromagnetic radiation with intense variation in brightness on the Sun lasting from minutes to hours. A solar flare occurs when magnetic energy that has built up in the solar atmosphere is suddenly released. The intensity of a solar flare depends on the solar cycle. The solar cycle mainly refers to the cyclic variation of the number of sunspots visible on the photosphere of the Sun. The number of sunspots increases and regularly decreases over time, approximately 11- year cycle. More sunspots may be directly associated with increased solar activity, such as solar flares and CMEs. The highest number of sunspots in any given cycle is recorded and designated as the solar maximum, while the lowest is termed solar minimum. The solar cycle affects activities on the surface of the Sun, such as sunspots caused by the Sun's magnetic fields. Giant eruptions on the Sun, such as solar flares and coronal mass ejections, increase during the solar maximum. These eruptions send powerful bursts of energy and materials into space.

The information of particle acceleration on the surface of the Sun is uncertain. We selected the focused transport equation with the influence of the space environment to explain the SEPs propagation. Plasma from the outermost portion of the Sun continuously flows away and drags the irregular magnetic field out of the Sun. Magnetic field lines are bent spirally as the Sun rotates on its axis [2, 5, 6]. Most SEPs are charged particles; hence they are forced to move in circles around the magnetic field line with a constant speed. The intensity of the magnetic field line corresponds to the distance of the particle's trajectory from the Sun to the Earth. The magnetic field from the Sun to the Earth is irregular, so we focused on the longest distance that SEPs can move along the magnetic field line before getting scattered by the irregularity of the magnetic field, which is termed as the mean free path. The diffusion equation of particles in space and their effects explains the propagation of SEP. From the fundamental equation of Fokker-Plank and the transport equation of Ruffolo [1], we can explain the propagation of solar energetic particles from the Sun to the Earth as shown in equation (1). We simulated the particle propagation with a transport equation and solved it by the numerical method of Finite-differences.

$$\frac{\partial \vec{F}(t,\mu,z,p)}{\partial t} = \left\{ -\frac{\partial}{\partial z}\mu v - \frac{\partial}{\partial z}(1-\mu^2\frac{v^2}{\mathrm{c}^2})v_{sw}\sec\Psi \quad + \frac{\partial}{\partial \mu}v_{sw}(\cos\Psi\frac{\mathrm{d}}{\mathrm{d}r}\sec\Psi)\mu(1-\mu^2) \right.$$
$$-\frac{\partial}{\partial \mu}\frac{v}{2L(z)}\left[1+\mu\frac{v_{sw}}{v}\sec\Psi - \mu\frac{v_{sw}v}{c^2}\sec\Psi\right]\left(1-\mu^2\right)$$

$$+\frac{\partial}{\partial\mu}\frac{\varphi(\mu)}{2}\frac{\partial}{\partial\mu}\left[1-\frac{\mu v_{sw} v\sec\Psi}{2L(z)}+\cos\Psi\frac{\mathrm{d}}{\mathrm{d}r}(\sec\Psi)\mu^2\right]$$

$$+\frac{\partial}{\partial p}pv_{sw}\left[\frac{\sec\Psi}{2L(z)}(1-\mu^2)+\cos\Psi\frac{\mathrm{d}}{\mathrm{d}r}(\sec\Psi)\mu^2\right]\Bigg\}\vec{F}(t,\mu,z,p), \quad (1)$$

where $\vec{F}$ is the distribution function; $\vec{F}(t,\mu,z,p)=\frac{\mathrm{d}^3N}{\mathrm{d}z\mathrm{d}\mu\mathrm{d}p}$, 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 the particle. We focus the mean free path of particle from the relation of $\lambda\equiv\frac{3D}{v}$ where D is the diffusion coefficient; $D=\frac{v^2}{4}\int_{-1}^{1}\frac{(1-\mu^2)^2}{\varphi(\mu)}\mathrm{d}\mu$ in scattering term of $\varphi(\mu)$.

Preliminary data of X-ray flux intensity illustrate the violence of the interested solar flare. The brightness of X-ray flux in watts/m^2 shows the intensity of erupted solar flares. Solar flares of X-class are violent eruptions and may affect Earth. This research selected the violent solar flares of X-class during September 6-10, 2017. We used the particle data for the interested solar event from Solar Isotope Spectrometer (SIS) on the Advanced Composition Explorer (ACE spacecraft) as input data for simulation. The simulation result is the distribution of particles in time for various energy, which corresponds to the mean free path in the diffusion coefficient. The transport equation is a partial differential equation (PDE) consisting of many independent variables [3]. Thus, making us difficult to determine its solution directly. However, as the equation is in the form of PDE, we can apply boundary conditions to the Finite-differences method and determine its solution.

3. Methodology

This research used a quantitative methodology that involves the empirical investigation of observable and measurable variables used for theory testing. We collected data from spacecraft for the solar event from September 6-10, 2017. The data from spacecraft is the distribution function of time of Helium, Carbon, Nitrogen, and Oxygen of the solar event on September 6, 2017. Physical characteristics of the selected solar event at 2673 sunspot number are shown in table 1. The intensity of particles during that time was download from ACE. The space environment data correlated to the solar event of interest came from GOES. The main focus is given to how the data was collected, prepared for its initial values and how simulation was done to calculate the injection time and mean free path (λ) from the transport equation of Ruffolo solved by using the technique of numerical method.

Table 1. Physical characteristics of interested solar events.

Solar event	X-ray Class	Start time of flare	End time of flare	Shock wave time
6/9/2017	X2.2	08.57 UT	09.17 UT	
	X9.3	11.53 UT	12.10 UT	12.02 UT
7/9/2017	X1.3	14.20 UT	14.55 UT	
10/9/2017	X8.2	15.35 UT	16.31 UT	16.38 UT

We collected the data measured by SIS instrument on ACE spacecraft and calculated the initial values necessary for the program to simulate particle motion. The selected solar event has X-class solar flare, X9.3 and X8.2 erupted from S09W45 on the Sun with solar wind speeds of 494 and 560 km/s, respectively. The X9.3 was the largest flare in the 24^{th} solar cycle. The increased solar activity periods during solar minimum is a rare occurrence. This unusual event occurred at the solar minimum in

September 2017, at the end of the 24th solar cycle [5]. On September 6, 2017, the most significant X-class flare in a decade erupted from active region 2673. Another X-class flare X8.2 was produced from the same position when X9.3 was just crossing the west limb. The sunspot region 2673 was one of the most active regions during the entire cycle, creating 4 X-class flares, including two of the largest flares in the cycle.

The data obtained from the ACE spacecraft was used in the simulation motion of particles by using the transport equation. The equation was solved using numerical methods to find the flux of particles in time at the best mean free path. We used the technique of the piecewise linear least-squares method for optimization of the injection duration. After the results are obtained from particle motion simulation, we analyzed the movement of high-energy particles and compared the data with actual data from the spacecraft. We used the linear least-squares fitting technique to find the mean free path and analyzed the injection time using the FWHM (full width at half maximum) method [6]. When the appropriate average distance is obtained, the result of fitting data will give the particle released in time, which can be graphed to determine the time of particles released from the Sun to the Earth.

4. Result

The Sun is continuously erupting charged particles in the form of solar flares, coronal mass ejections, or solar storms, which affect the Earth. So, we conducted a study of space conditions during the solar eruption in September 2017. There were 28 eruptions of M-class and 4 of X-class from September 6-10, 2017. We have found a rapid expansion of sunspots on 2673 on September 6, 2017, which was the most violent, X9.3, and on September 10, 2017, there was X8.2, the second most violent in the 24th cycle. The detail of this solar eruption from spacecraft is shown in table 2. The observed CME spread forward to the Earth and reached Earth's magnetosphere in the morning of September 7, 2017. There was a second CME from the same active region targeting the Earth on September 6, 2017, at 12:24 UT (This is the last CME in this series, most likely contributing to the complex ejecta later detected in situ) [7]. The second CME's shock wave reached Earth's magnetosphere in the afternoon of September 8, 2017. The simulation result in table 3 shows the mean free path of various elements and their injection time for the selected solar event on September 6, 2017, and the sample of fitting result for Nitrogen at 23.096 MeV/n as shown in figure 1.

Table 2. Data for the solar eruption in September.

Date	Start (UT)	Maximum (UT)	End (UT)	CME	CME time (UT)
6/9/2017	8:57	9.10	9:17	Not found	-
	11:53	12.02	12:10	Type II, IV	12.01, 12.24
7/9/2017	10:11	10.15	10:18	Type IV	10.35
	14:20	14.36	14:55	Type II	18.31
10/9/2017	15:35	16.06	16:31	Type II, IV	15.54

Table 3. The simulation results of the solar event occurred on September 6, 2017.

Element	Energy (MeV/n)	Mean free path (AU)	Injection time (min)	Element	Energy (MeV/n)	Mean free path (AU)	Injection time (min)
Nitrogen	8.009	0.805± 0.033	614	Carbon	7.443	1.350± 0.044	415
	13.317	0.508± 0.077	141		9.839	1.369± 0.053	379
	23.096	0.904± 0.022	339		15.505	1.795± 0.166	361
Oxygen	8.538	1.069± 0.079	281		21.229	0.827± 0.106	115
	11.427	1.717± 0.053	161		28.883	1.454± 0.208	39
	24.839	0.863± 0.153	74	Helium	5.390	0.914± 0.076	198
	49.832	0.960± 0.371	232		6.685	1.531± 0.097	171

The time for releasing particles from the Sun was between 39-743 minutes. The result shows that the duration of particles from the Sun decreases as the energy level of the particles increases. The trend of the mean free path is roughly constant for each element. The solar energetic particle with the high energy roughly has a high mean free path, and the diffusion of the particle will be less.

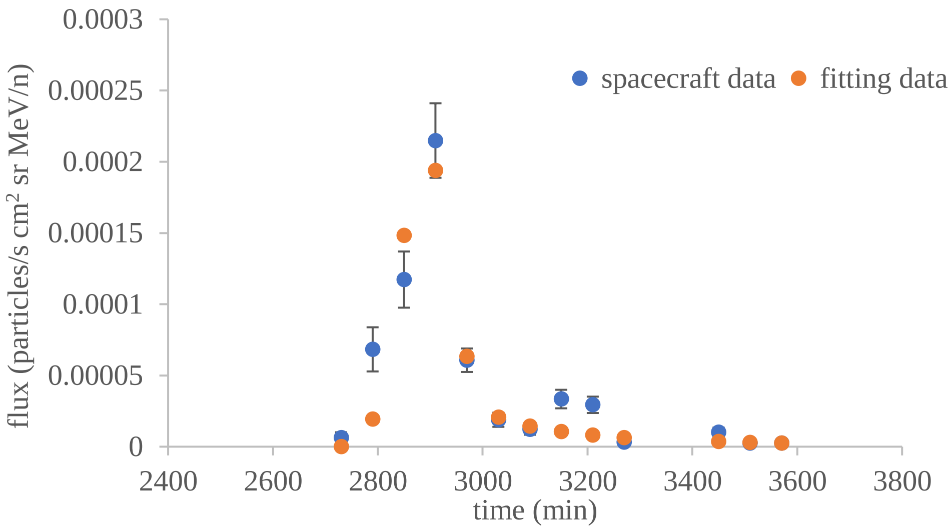

Figure 1. Shows the fitting result of Nitrogen at 23.096 MeV/n for the solar event on 6th September, 2017.

5. Conclusion

The study mainly focused on the solar event on September 6, 2017, where the most violent solar flare was observed during the solar minimum of the 24th solar cycle. The X9.3 was the strongest solar flare that started at 11:53 UT, peaked at 12:02 UT, and ended at 12:10 UT, which lasted for 17 minutes. It erupted at a position of S10W30 with a solar wind speed of 575 km/s. This flare was followed by CME, causing the acceleration of particles in space. CME in the profile of radio type IV and type II was detected close to the peak of this flare at 12.01 UT, which increased the injection time. The propagation of SEPs was simulated by the Ruffolo equation and solved by the Finite-differences method. The injection duration was estimated by the curve-fitting of piecewise linear least-squares fitting between the spacecraft data and simulation results in the profile of the distribution of particles in time. We found that the mean free path of this event was roughly constant for each particle which is different for the solar event at the maximum of the solar cycle. The Kp-index of this solar flare was 4; thus, there was no effect on the Earth. The Kp-index increased to 8 on September 7-8, 2017, due to another solar event from the same sunspot region indicating the effect of solar flare and CME, which resulted in the appearance of aurora in the United States, France, Kazakhstan, and Australia. The Kp-index is an excellent indicator for disturbances in the Earth's magnetic field. Kp-index is an integer of 0–9, with 1 being calm and 5 or more indicating a geomagnetic storm.

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References

[1] Roelof E C 1969 Propagation of solar cosmic rays in the interplanetary magnetic field *Lectures in High-Energy Astrophysics*, (NASA SP-199) (Washington D C: NASA Goddard Space Flight Center) p 111

[2] Ruffolo D, Khumlumlert T and Youngdee W 1998 Deconvolution of interplanetary transport of solar energetic particles *J. Geophys. Res.* **103** 20591

[3] Gopalswamy N 2012 Energetic particle and other space weather events of solar cycle 24 *AIP Conf. Proc.* **1500**(1) 14–9

[4] Kane R P 2014 Evolution of solar indices during the maximum solar cycle 24 *Indian J. Radio Space Phys.* **43** 151–5

[5] Tshering K and Khumlumlert T 2020 An analysis of the solar energetic particle propagation of the maximum solar flare on 24th solar cycle *NGRC2020 Conf. Proc.* pp 4324–30

[6] Baisri P, Khumlumlert T and Aiemsa-ad N 2017 Solar energetic particle propagation from solar flare *J. Phys.: Conf. Ser.* **901**(1) 012015

[7] Werner A L E, Yordanova E, Dimmock A P and Temmer M 2019 Modeling the multiple CME interaction event on 6-9 September 2017 with WSA-ENLIL+Cone *Space Weather* **17** 357–69