The Solar Flare Analysis during the 23rd and 24th Solar Cycles

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We analyzed the solar flare and space environment data during the 23rd and 24th solar cycle. The excellent indicator of disturbances in the Earth's magnetic field (the Kp index), the number of violent of the solar flares and the powerful solar flare with the X-ray class of solar flares in 23rd solar cycle is more than 24th solar cycle. Most of solar events in 23th and 24th solar cycle occurred at southern and northern parts of the Sun, respectively. The position of the solar flares corresponded to the reverse of the Sun's magnetic field for every 11 years. We analyze the particle transport of the solar flare events on November 4, 2003 in 24th solar cycle by solving the transport equation with the numerical technique of finite different. We found the injection duration from the Sun to the Earth decreases with increasing energy.

Keywords: solar flare, space weather, Kp-index, solar cycle, spacecraft data

1. Introduction

Space weather is relative to the Earth, which provides the environments information of solar system, such as the solar wind, space environments, solar flare, and magnetosphere. Solar energetic particles (SEPs) are released from the Sun or the solar flare, one of space weather affecting on the Earth. A *solar flare* is a violent explosion on the Sun in our solar system [1,2]. 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. 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. The amount of *solar flares* corresponds to the number of sunspot because they are formed at the same active regions of sunspots. The detected solar flares vary according to the same 11-year *cycle*. The *solar cycle* is the nearly periodic 11-year change in the Sun's activity and the number of sunspots, flares, and other space environments. It was discovered in 1843 by Samuel Heinrich Schwabe, who noticed a periodic variation in the average number of sunspots [3,4,7]. George Ellery Hale's observations revealed that the complete magnetic cycle takes two solar cycles, or 22 years, before returning to same state. Recently, the Sun is in the 24^{th} solar cycle during the year of 2009-2020 with the peak time of 2012-2014. This research was focused on variation of space environments during the 23^{rd} and 24^{th} the solar cycles. This research compiles and analysis the information of solar cycle events and space variation was compiled and analyzed to find the concordance with the variation of solar cycle. The analyzed data in this research consists of the number of solar flares on the Sun, specific solar flare events with the X-ray class of X class and M class in 23^{rd} solar cycle and 24^{th} solar cycle, the solar wind speed, the disturbances of Earth's magnetic field and the explosion location of solar flare on the Sun. The data of solar flare position has concordance with sunspot that occurs at northern and southern of the Sun. An understanding the SEPs propagation and environment during the solar cycle by spacecraft data analysis from the selected solar events, then the advanced warning of the effect from the space weather can prepare in time.

2. Theoretical background

The solar flare, solar wind, solar energetic particles or coronal mass ejections are some activities which occur on the Sun. 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. 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 acceleration of charged particles. The unconnected magnetic field and the material that it contains may violently expand outwards from the Sun. The magnitude measurement of the solar flares obtains from their strength of X-ray emission. The big X-class and M-class flares are the first and second large explosion in the solar system, respectively. Frequency of solar flares coincides with the Sun's 11-year cycle. The variation of space environments corresponds to period of the solar cycle. The Sun's magnetic field completely flips every 11 years. This means that the Sun's north and south poles switch places. In addition, it takes about another 11 years for the Sun's north and south poles to flip back again. The solar cycle effects on activity of the Sun, causing the number of sunspots, violent and huge solar flare, and solar wind speed. The information from spacecraft was studied and collected. The beginning of the solar cycle is the solar minimum, which the Sun has the least sunspots and solar activity. The middle of the solar cycle is the solar maximum, which the Sun has the most sunspots. The activity of the Sun is back to the solar minimum at the end of cycle, and then a new cycle begins [3,4,7]. The activities on the Sun, such as solar flare with the high X-ray class, solar wind speed, solar energetic particles, causing the change of the solar cycle. They powerfully effects on electrical equipment on the Earth, such as satellites, communication system, or ground-based technologies [3,6]. The Kp-index value is the global geomagnetic storm index. It is an excellent indicator of disturbances in the Earth's magnetic field with scale between 0 – 9 and known as the planetary index with value of 1 and more than 5 indicating clam and geomagnetic storm, respectively. It is also derived from the maximum fluctuations of horizontal components observed on a magnetometer during a three-hour interval.

This research fits the solar flare data from spacecraft in order to determine the released particles from the Sun to the Earth as a function of time and energy. We consider the influence that affect the SEPs transport to explain the propagation of SEPs in space. The density of particles were defined in term of the distribution function, $F(t,\mu,z,p)=\frac{d^3N}{d\mu dzdp}$. The distribution function is developed by a Fokker –Planck equation,

$$\frac{\partial F(t,\mu,z,p)}{\partial t}=-\frac{\partial}{\partial z}\left(\frac{\Delta z}{\Delta t}F\right)-\frac{\partial}{\partial \mu}\left(\frac{\Delta \mu}{\Delta t}F\right)-\frac{\partial}{\partial \mu}\left[\frac{\varphi(\mu)}{2}\frac{\partial}{\partial \mu}\left(\frac{E'}{E}F\right)\right]-\frac{\partial}{\partial p}\left(\frac{\Delta p}{\Delta t}F\right). \qquad (1)$$

Where $\varphi(\mu)$ the coefficient of pitch angle scattering (Earl 1973), and $\frac{E'}{E}\equiv 1-\frac{(\mu v v_{sw}\sec\varphi)}{c^2}$ 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 ψ, $L(z)$ 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_{sw} is the solar wind speed, c is the light speed, position along the magnetic field, z, the pitch angle cosine, $\mu = \cos\theta$, momentum, p, and random change in the pitch angle scattering in μ.

3. Methodology

In this work, the space data of interest come from the ACE (the Advanced Composition Explorer) spacecraft was analysed to study the solar flare events on the Sun, the space environments, and the Kp-index during on 23rd and 24th solar cycles. The number of solar flares of each solar cycle, and violent magnitude of the flares in term of X-ray class, solar winds speed, the position of solar flares on the Sun, and the index value of the Earth's magnetic field disturb were obtained by comparing the space variation between 23rd and 24th solar cycles. The spacecraft data we studied were downloaded from http://www.srl.caltech.edu/ACE. This website has a large amount of data on solar events and space environment data as detected by the instrument on ACE spacecraft. 966 solar events in 23rd solar cycle (1996- 2008) and 549 solar events in 24th solar cycle (2009-2020) were analysed. The data was also obtained from GOES (Geostationary Operational Environmental *Satellites*) for analysing the violent solar flares. The GOES x-ray flux is used to detect solar activity and solar flare. Large solar x-ray with X-class effects on the Earth's atmosphere. The X-class flare, the strongest flare, has a peak of x-ray intensity flux of order of 10^{-4}

W/m^2. The M-class flare or the second strong flare has a peak flux of order of 10^{-5} W/m^2. It was found that 125 X-class solar events and 841 M-class solar events for 23rd solar cycle, while 24th solar cycle show 49 X-class and 500 M-class solar events. The highest violent solar flare of 23rd solar cycle was on November 4, 2003 with X28 (28×10^{-4} W/m^2), and solar event was on September 6, 2017 with X9.3 (9.3×10^{-4} W/m^2) of 24th solar cycle. The solar wind speed data from the Advanced Composition Explorer (ACE) was studied. It was found that, the highest solar wind speeds in 23rd and 24th solar cycle were 1020.9 km/s and 750.6 km/s, respectively. The position of solar flare and sunspot of each solar flare for both of solar cycles was analysed. It was found that they are corresponding to the Sun's magnetic field flip for every 11 year. The effect to the Earth's magnetic field of Kp-index from NOAA: SWPC (the National Oceanic and Atmospheric Administration: Space weather Prediction Centre) was analysed. The results from all analysed data for the space environment correspond to solar flare and the effects to the Earth's magnetic field during in 23rd and 24th solar cycles comparing with the violence between 2 solar cycles and the Sun's magnetic pole flip for every 11 years.
In this work, we choose the solar flare events on November 4, 2003 during of 23th solar cycle for study the propagation of particle from the Sun to the Earth. The solar flare information of solar event is shown in table 1.

Table 1. The solar flare information for solar event.

Date	Position	X-ray class	Solar wind speed (km/s)	Shock wave	Duration time (min)	Max Kp index
4 Nov. 2003	S17W78	X28	594	/	35	7

The SEP transport equation was solved by the numerical technique of finite different method. The simulation results are the He 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 χ^2. The χ^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, σ_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 find the injection duration of the interested solar event in the term of full width at half maximum of the injection function [8].

4. Result

In this research, the solar flare data was analyzed. The space environment from spacecraft during in the 23rd and 24th solar cycles was compared with the violence of both solar cycles. The analyzed data consists of the number of solar flares, the violence of X-ray class, solar wind speed, Kp-index, and position of solar flares for 1515 solar events from both solar cycles. The results from analysis were shown as Figures 1 - 3.

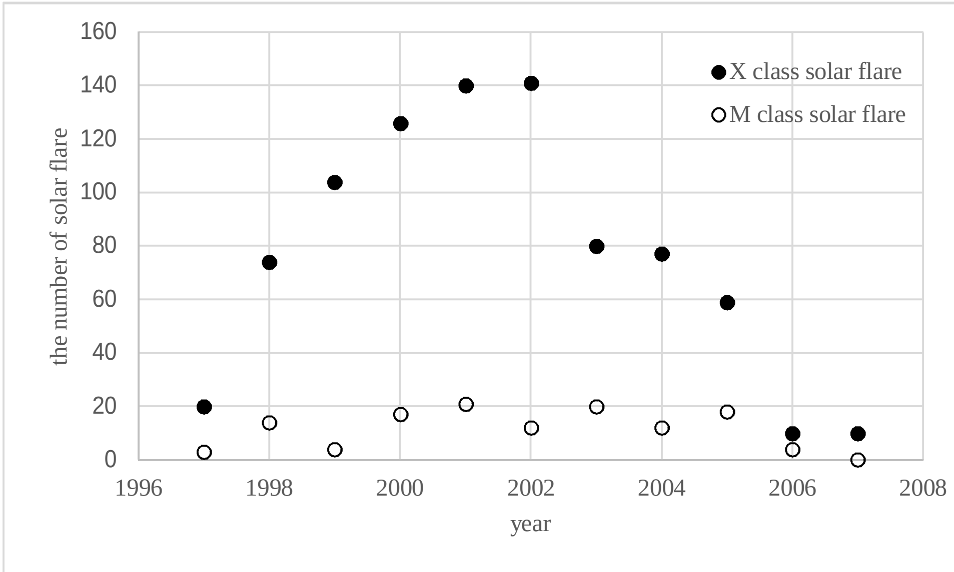

Figure 1. The number of solar flares for X-class in black dot and M-class in white dot for 23rd solar cycle.

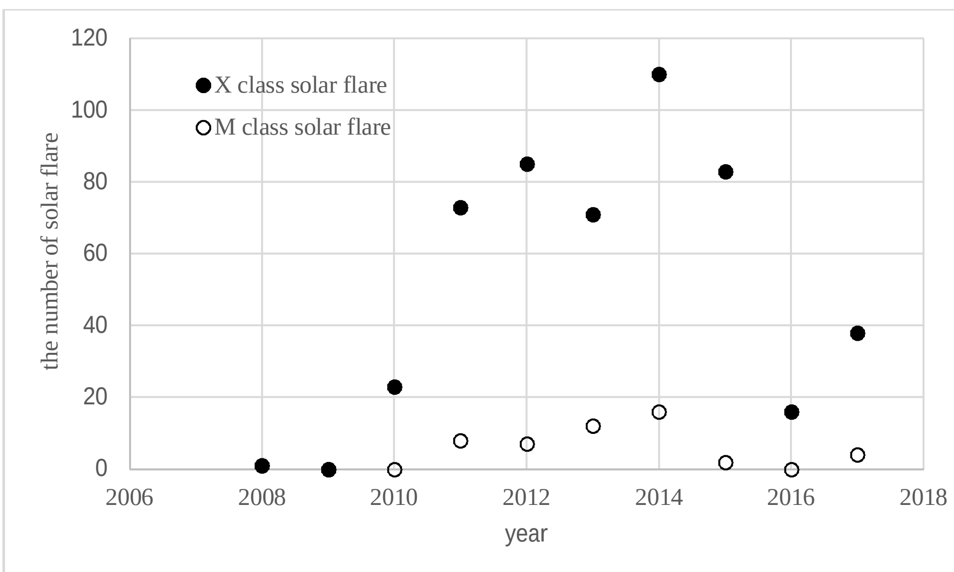

Figure 2. The number of solar flares for X-class in black dot and M-class in white dot for 24rd solar cycle.

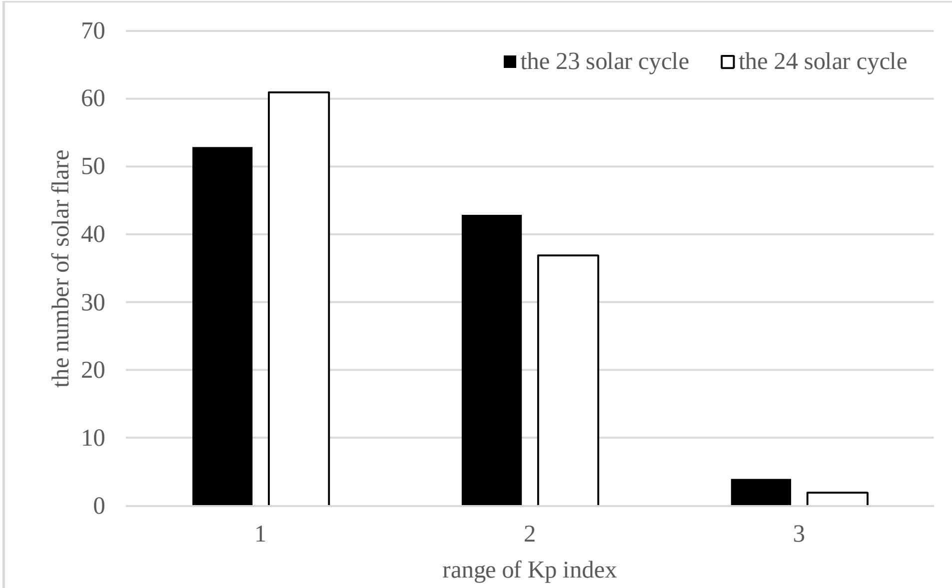

Figure 3. Percent of the number of solar flare on the range of the Kp-index for 23rd solar cycle in left side and 24th solar cycle in right side.

It was found that the 78% of the position of the violent solar flares occurred on the south part of the Sun for 23rd solar cycle, and 73% of the violent solar flares of 24th solar cycle occurred on the north part of the Sun .The violence of X-ray class of solar flares in the 23rd solar cycle (X28) was higher than that of the 24th solar cycle (X9.3). The rough solar wind speed of the 23rd solar cycle (1020.9 km/s) was higher than the 24th solar cycle (750.6 km/s).

In the part of solar energetic particle propagation, The fitting results between the transport equation simulation and the data from SIS instrument on ACE spacecraft for He at the energy range of 5.390-35.27 MeV/n shown in table 2.

Table 2: The data fitting for the interested solar events on November 4, 2003 during 23rd solar cycle.

Solar event	Element	Energy (MeV/n)	λ (AU)	Duration time (min)
November 3, 2003	He	5.39	0.85	516.72
		11.66	1.57	418.65
		15.78	1.49	143.23
		35.27	1.57	135.43

We found mean free path is roughly constant as shown in Table 2. The injection duration of the higher energy is shorter than for the lower energy particles. This solar event is the gradual flare because we found the emission of type II radio (effect of CME in the interplanetary medium) after their explosion.

5. Conclusion

This research analyzes and compares the violence of solar flares, the space environment, and the effects to the Earth's magnetic field in the 23rd and 24th solar cycles. It was found that the 23rd solar cycle is violent explosion more than that of the 24th solar cycle because of the number of solar flares with X-class, the magnitude of the highest huge flare, the solar wind speed, and Kp-index value > 7. Overall, the 23rd solar cycle is more violent than the 24th solar cycle. The position of the solar flares for each solar cycle confirmed the Sun's magnetic field flip for every 11 year as solar cycle, corresponding to the occurring position of solar flare in the south of the Sun for the 23rd solar cycle, and in the north part of the Sun for the 24th solar cycle. These results correspond to the research work named "Solar energetic particle events during the rise phase of solar cycle 23 and 24", R. Chandra et al., 2013 [5].

The results of transport simulation of the solar energetic particles on November 4, 2003 show the trend of the mean free path is roughly constant. 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) [9] and Bieber et al. (1994) [10]. The injection duration depends on the energy level. The injection duration time from the data fitting of this solar event 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.

6. Acknowledgments

We are very grateful to the Department of Physics, Faculty of Science, Naresuan University, Thailand for computer supporting and budget for this research. I would like to thank to all organizations (NOAA, GOES, ACE) for the useful information.

7. References

1. Ruffolo D., Khumlumlert T., and Youngdee W. (1998). Deconvolution of interplanetary transport of solar energetic particles. Journal of Geophysical Research, 103, 20591.

2. Ruffolo D,. Tooprakai P, Rujiwarodom M., Khumlumlert T., Wechakama M.,. Bieber J.W, Evenson P., and Pyle R. (2006). Relativistic Solar Protons on 1989 October 22: Injection and Transport along Both Legs of a Closed Interplanetary Magnetic Loop. Astrophysical Journal, 639, 1186.

3. Aiemsa-ad N., Ruffolo D., Sáiz A., Mangeard P., Nutaro T., Nuntiyakul W., Kamyan N., Khumlumlert T.,. Krüger H, Moraal H., Bieber J.W., Clem J., Evenson P. (2015). Measurement and simulation of neutron monitor count rate dependence on surrounding structure. Journal of Geophysical Research a: Space Physics., 120, 5253-5265.

4. Khumlumlert T., Kanjanapa W., and Aiemsa-Ad N. (2017). The Information Study of Solar Flare Events on November 3, 2013 and August 9, 2011. Advanced Science Letter, 23, 1201-1204.

5. Chandra R. et al. (2013). Solar energetic particle events during the rise phases of solar cycles 23 and 24. (2013). Department of Physics, DSB Campus, Kumaun University, Nainital India., 263, 002.

6. Baisri P.,. Khumlumlert T, and Aiemsa-ad N. (2017). Solar energetic particle propagation from solar flare. Journal of Physics: Conference Series, 901 (1), 012015.

7. Paluk P., Khumlumlert T., Kanlayaprasit N., and Aiemsa-ad N. (2017). The solar energetic particle propagation of solar flare events on 24th solar cycle, Journal of Physics: Conference Series, 901(1), 012016.

8. Ruffolo D., Khumlumlert T.and Youngdee W. (1998). Deconvolution of interplanetary transport of solar energetic particles. Geophysical Research J., 103, 20591.

9. Palmer I.D. and Jokipii J.R. (1982). Interpretation of anisotropy in corotating events, Journal Geophysics Reserve Space Physics, 87(A8), 5991-6001.

10. Bieber J.W. et al. (1994). Proton and electron mean free paths: The palmer consensus revisited. 1994, Astrophys. J., 420, 294.