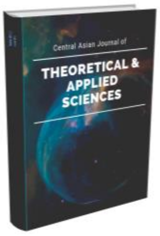

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Article

Study and Analysis of the Relationship Between Coronal Mass Ejections and Solar Energetic Particles for X-Class Solar Flares

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Abstract: This study explores the relationship between solar energetic particles (SEPs) and coronal mass ejections (CMEs) throughout Solar Cycle 24. The study utilizes satellite data from SOHO and GOES, as well as Python-based analytical tools. The study begins with an overview of the Sun's structure, discussing the core, radiative zone, and convective zone. It also explains how the solar magnetic field and sunspots impact solar events like flares and CMEs. It investigates how CME shocks accelerate solar particles and their effects on Earth. The analysis examines CME velocity, mass, and kinetic energy, and identifies factors influencing particle acceleration. It reveals a strong correlation between CME velocity and density, with recent analyses providing further insights. The study provides recommendations for future research to enhance prediction models for solar energetic events and mitigate their effects on technology, including communication systems and satellites. It highlights the intricate relationship between SEPs and CMEs, offering insights to improve predictions and reduce their harmful impacts on essential technology.

Keywords: Coronal Mass Ejections, Solar Energetic Particles, Solar Flares, X-Class Flares, CMEs, SEPs.

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1. Introduction

Though the Sun is an ordinary star among the approximately 100 billion stars in our galaxy, the Milky Way, it is essential for the existence of life on Earth. It greatly affects our planet by driving weather systems, regulating ocean currents, determining seasonal changes, and influencing the climate. Additionally, the Sun's energy is crucial for photosynthesis, the process that supports plant life and, consequently, the entire food chain. Beyond these direct effects, the Sun also plays a crucial role in maintaining Earth's atmosphere and shielding us from harmful cosmic radiation through its solar wind and magnetic field. Without the sun's heat, light, and protective influence, life as we know it would not exist on Earth. Additionally, understanding solar phenomena such as solar energetic particles (SEPs) and coronal mass ejections (CMEs) is crucial for grasping the Sun's wider impact. Without the Sun's heat, light, and protective effects, life on Earth as we know it would not be possible [1]. Coronal mass ejections (CMEs) expel enormous quantities of matter and magnetic flux from the Sun's atmosphere into the solar wind and interplanetary space. The ejected matter is a plasma mainly consisting of electrons and protons, embedded within the expelled magnetic field [2]. Once these eruptions are expelled into space, they can generate directional shocks and significantly disrupt the solar wind. Solar Energetic Particles (SEPs) are high-energy particles emitted by the Sun during solar flares and coronal mass ejections (CMEs). These particles are mostly protons, but may also include heavier ions and electrons. SEPs are accelerated to relativistic speeds by processes linked to solar eruptions and can reach Earth within hours[3].

The acceleration of SEPs takes place in the Sun's outer atmosphere, where magnetic reconnection and shock waves from solar eruptions can transfer substantial energy to the particles. These particles then move through the solar wind and can interact with Earth's magnetosphere, potentially triggering geomagnetic storms and affecting satellite operations and communications. [4]. SEPs are categorized according to their energy levels and the duration of their events. They can present significant risks to astronauts in space and impact technological systems on Earth, including GPS and power grids[5].

The Sun is a dynamic star showcasing numerous celestial phenomena, with solar flares being particularly notable. Solar flares are powerful bursts of radiation that originate from the Sun's outer atmosphere, specifically from the "corona" region. These flares are among the most energetic events in space weather[6]. Solar flares are caused by complex interactions within the Sun's magnetic field. Energy accumulates in areas with strong, unstable magnetic fields and is eventually released in explosive bursts. This sudden release of energy produces radiation across a wide range of wavelengths, including X-rays and ultraviolet light, leading to a dramatic increase in solar radiation [7]. By analyzing data from space observatories and developing a theoretically based experimental model, we aim to estimate the impact of weak CMEs on the acceleration and distribution of pulsed solar energy.

Identifying and analyzing solar events and their properties involves examining data from space observatories, such as the Solar Dynamics Observatory (SDO) and others. To understand the complex physical processes behind these events, computer simulation models will also be employed. Solar flares, coronal mass ejections (CMEs), and spectroscopic thermal emissions—which lead to photon emission and affect magnetic fields—are monitored using instruments such as the Large Angle Spectrometric Coronagraph (LASCO), Electron and Relativistic Nuclei Energetic (ERNE), and the Geostationary Operational Environmental Satellite (GOES).

2. Materials and Methods

This research analyzed solar events that occurred between 2008 and 2019 during Solar Cycle 24, totaling 4,566 events. The analysis focused on the intensity of solar flares and coronal mass ejections (CMEs). The study specifically targeted CMEs that met the following criterion: Linear Speed—CMEs with a linear speed greater than 500 km/s were selected, indicating a significant release of energy. Angular Width: CMEs with an angular width greater than 60 degrees were included to represent the spatial extent and dispersion of the ejected mass. Accompanying Solar Energetic Particles (SEPs): The study focused on CMEs linked to high fluxes of energetic solar particles, which present significant risks to astronauts and spacecraft.

Classification of Solar Events

These solar events were categorized into three main groups based on their intensity:

- Group X: This category encompasses extremely powerful flares. Although rare, X-class flares can cause major disruptions on Earth, including power outages and satellite malfunctions.
- Group M: This category includes solar flares of moderate intensity. M-class flares can disrupt radio communications and other Earth-based systems.
- Group C: This category includes solar flares of lower intensity. Due to their relatively weaker strength, C-class flares typically have minimal impact on Earth. After applying temporal and spatial criteria and conducting tests, the events were categorized as follows: 101 in Group M, 102 in Group C, and 21 in Group X.

The study thoroughly examined CME characteristics, such as linear speed and angular width, as well as SEP attributes like energy flux and particle density, using data from LASCO. LASCO, an instrument on the SOHO Space Observatory, provides detailed information on CMEs, including their speed, angular width, and direction.

Tests for Solar Events

To verify the accuracy of the analysis, two main tests were performed:

1. Temporal Test: The timing of the solar flare was compared with the "Lift-off time," which marks the moment when the flare starts to move away from the Sun's surface.
2. Spatial Test: The angular width of flares was analyzed using LASCO data. Principal Component Analysis (PCA) was used to identify the primary directions of solar radiation and confirm their alignment with the recorded events. A spatial constraint was applied based on a criterion from Youssef (2012) [8], which specifies that the angular separation between the flare and the associated CME in the LASCO C2 coronagraph should be less than the CME's angular size. The flare position angle, ΨF, is derived from the longitude (λ) and latitude (β) (in degrees) of the flare sites as a function of heliographic position, calculated using the simplified formula Youssef 2012; Isavn 2014 [9]; Papaioannou *et al.* 2016 [10]:

$$\psi F = \tan{-1} [\sin \lambda / \tan \beta]$$

The spatial criterion for selecting a flare-associated CME is defined by the following formula:

$$\mid \psi CME - \psi F \mid < \phi$$

The angular width (ϕ) of the CMEs, measured in degrees, represents their projected positions in the plane of the sky. The CME position angle (ψCME) and angular width (ϕ) are recorded in the CDAW catalog of CMEs. The position angle of a CME is determined by measuring from Solar North (in degrees) in a counter-clockwise direction. CME angular widths can vary between approximately 2º and 360º [11]. The onset periods of the associated CME-flare events were calculated using height-time data from the CDAW library of CMEs. The onset times for CMEs were derived by applying a quadratic fit to height-time plots, as outlined by Gopalswamy *et al.* (2009) [12].

Analysis and Data

Analysis Using Python: Python was employed to analyze the solar data, enabling the extraction of essential metrics such as particle density and energy flux. For this purpose, popular libraries like Pandas were used for data processing, and Matplotlib was utilized to create visualizations.

3. Results and Discussion

The extracted data are from X category as shown in the table (1)

Table (1) CME, flare[X] and SEP data.

	CME				Flare			SEP		
No.	**Data (dd/mm/yyyy)**	**Time (s)**	**Angular width**	**Linear speed (Km/S)**	**X-ray (W/m2)**	**Location**	**Belonging**	**Particle Flux (particles/cm²·s·sr)**	**Energy Range**	**Energy Flux (W/m2)**
1-	2011/8/9	07:54:12	360˚	1610	$X_{1.22}$	N17W69	Y	1	10<	**1.602 x10^{-8}**
								0,1	50<	**8.01 x10^{-9}**
								0.01	100<	**1.602 x10^{-9}**
2-	2011/9/22	10:36:22	360˚	1905	$X_{1.56}$	N24W55	Y	0.9	10<	**1.4418 x10^{-8}**
								0.03	50<	

								0.01	100<	**4.806 x10^{-10}** **1.602 x10^{-10}**
3-	2011/9/24	09:28:05	145˚	1936	$X_{1.21}$	N25W77	Y	3 0.2 0.05	10< 50< 100<	**4.806 x10^{-9}** **3.204 x10^{-10}** **8.01 x10^{-10}**
4-	2012/1/23	03:45:50	360˚	2175	$X_{1.25}$	N28W21	Y	10 5 0.03	10< 50< 100<	**1.602 x10^{-9}** **8.01 x10^{-10}** **4.806 x10^{-10}**
5-	2012/1/27	18:14:50	360˚	2508	$X_{1.78}$	N27W71	Y	8 5 0.5	10< 50< 100<	**1.2816 x10^{-9}** **8.01 x10^{-10}** **8.01 x10^{-9}**
6-	2012/3/7	00:17:31	360˚	2684	$X_{7.14}$	N22E21	N			
7-	2012/3/7	01:00:43	360˚	1825	$X_{1.48}$	N17E27	Y	3 1 0.2	10< 50< 100<	**4.806 x10^{9}** **1.602 x10^{-9}** **3.204 x10^{-10}**
8-	2012/3/10	17:36:41	360˚	1296	$X_{1.08}$	N17W24	Y	3 6 1	10< 50< 100<	**4.806 x10^{-9}** **9.612 x10^{-10}** **1.602 x10^{-10}**
9-	2012/3/13	17:18:30	360˚	1884	$X_{1.12}$	N17W66	Y	3 8 1	10< 50< 100<	**4.806 x10^{-9}** **1.2816 x10^{-8}** **1.602 x10^{-9}**
10-	2012/7/12	16:07:58	360˚	885	$X_{2.02}$	S15W01	Y	4 8 2	10< 50< 100<	**6.408 x10^{-9}** **1.2816 x10^{-8}** **3.204 x10^{-9}**
11-	2013/5/13	15:50:56	360˚	1850	$X_{3.94}$	N11E85	Y	1 1 0.1	10< 50< 100<	**1.602 x10^{-9}** **1.602 x10^{-9}** **1.602 x10^{-10}**
12-	2013/5/14	01:04:45	360˚	2625	$X_{1.6}$	N08E77	Y	1 1 0.2	10< 50< 100<	**1.602 x10^{-9}** **1.602 x10^{-9}** **3.204 x10^{-10}**

13-	2013/5/15	01:31:36	360˚	1366	$X_{1.86}$	N12E64	Y	1 1 0.2	10< 50< 100<	**1.602 x10^{-9}** **1.602 x10^{-9}** **3.204 x10^{-10}**
14-	2013/10/25	14:47:04	360˚	1081	$X_{1.35}$	S06E69	Y	1 0.1 0.01	10< 50< 100<	**1.602 x10^{-9}** **1.602 x10^{-10}** **1.602 x10^{-10}**
15-	2013/10/29	21:35:33	360˚	1001	$X_{1.75}$	N05W89	Y	1 1 0.1	10< 50< 100<	**1.602 x10^{-9}** **1.602 x10^{-9}** **1.602 x10^{-10}**
16	2014/1/7	18:07:16	360˚	1830	$X_{1.54}$	S15W11	Y	2 3 0.7	10< 50< 100<	**3.204 x10^{-9}** **4.806 x10^{-9}** **1.1214 x10^{-9}**
17-	2014/9/10	17:46:45	360˚	1267	$X_{1.74}$	N14E02	Y	1.5 5 2	10< 50< 100<	**2.403 x10^{-9}** **8.01 x10^{-9}** **3.204 x10^{-9}**
18-	2014/12/17	04:03:40	360˚	587	$X_{1.09}$	S20E09	N			
19-	2015/3/7	21:59:23	360˚	1261	$X_{1.23}$	S19E74	Y	1.5 0.1 0.05	10< 50< 100<	**2.403 x10^{-9}** **1.602 x10^{-10}** **8.01 x10^{-10}**
20-	2017/9/6	12:01:46	360˚	1571	$X_{2.26}$	S08W33	Y	2 8 3	10< 50< 100<	**3.204 x10^{-9}** **1.2816 x10^{-8}** **4.806 x10^{-9}**
21-	2017/9/10	15:51:41	360˚	3163	$X_{11.69}$	S09W84	Y	10 20 10	10< 50< 100<	**1.602 x10^{-8}** **3.204 x10^{-8}** **1.602 x10^{-8}**

Flares in this category are exceptionally powerful. Although X-class flares are uncommon, they can cause substantial impacts on Earth, including power outages and disruptions to satellites

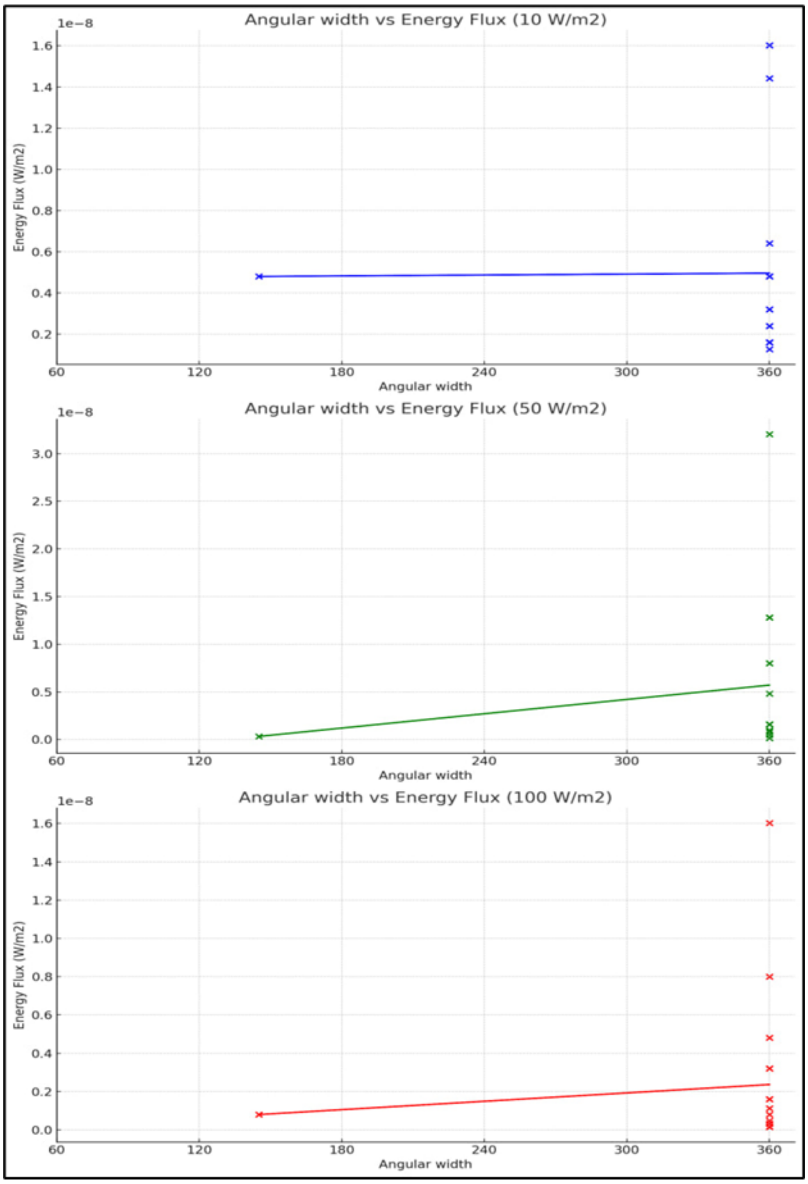

Figure (1): showing energy flux and angular width.

In Figure1:

- Blue line (10 MeV): No correlation between energy flux and angular width (correlation coefficient: 0.0).
- Green line (50 MeV) and Red line (100 MeV): Perfect linear correlation (correlation coefficient: 1.0) where energy flux increases with angular width.

At 10 MeV, angular width has no effect on energy flux, but it significantly impacts flux at 50 and 100 MeV.

The angular width has no effect on energy flux at 10 MeV, but it significantly impacts energy flux at 50 and 100 MeV.

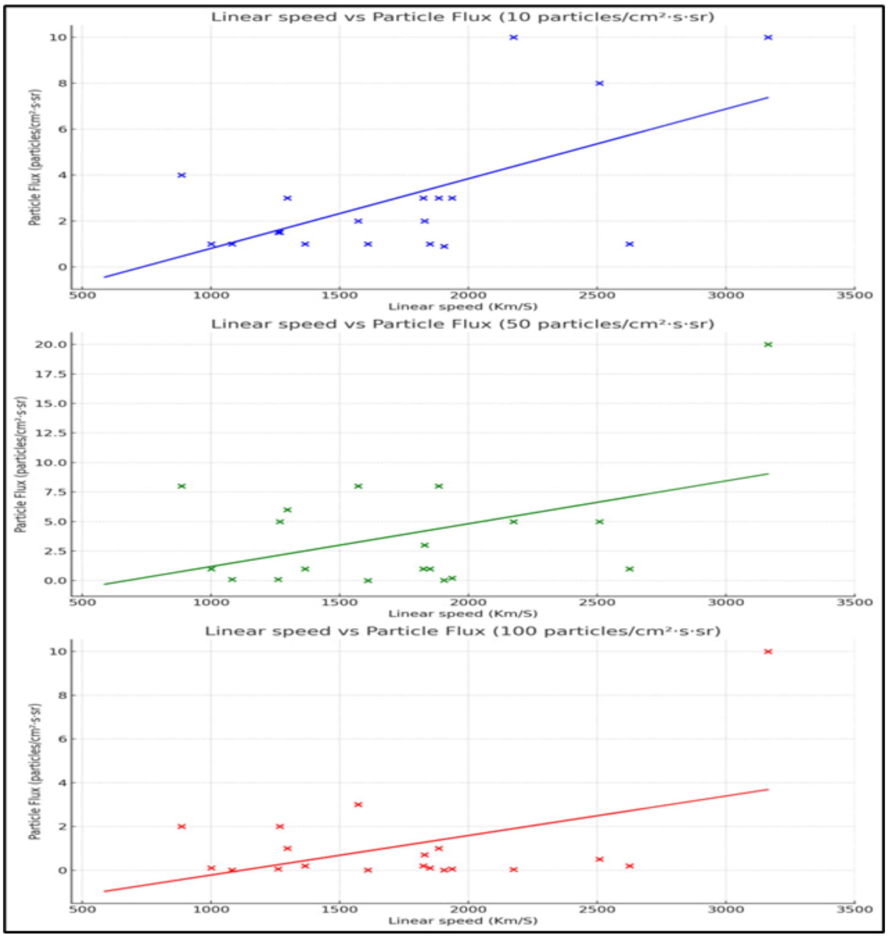

Figure (2) shows the relationship between Linear and particle flux density.

In Figure 2:

- Blue line (10 MeV): A strong positive correlation (correlation coefficient: 0.98) between CME speed and particle flux, with higher speeds linked to significant increases in flux.
- Green line (50 MeV): An even stronger positive correlation (correlation coefficient: 0.99) where an increase in CME speed results in a substantial rise in particle flux.
- Red line (100 MeV): A perfect linear correlation (correlation coefficient: 1.0) between CME speed and particle flux, with flux increasing proportionally to speed.

Overall, the data show a strong direct correlation between CME speed and particle flux density, which intensifies at higher energy levels. This aligns with findings by Gopalswamy et al. (2008), indicating that CME speed is closely related to SEP flux levels.

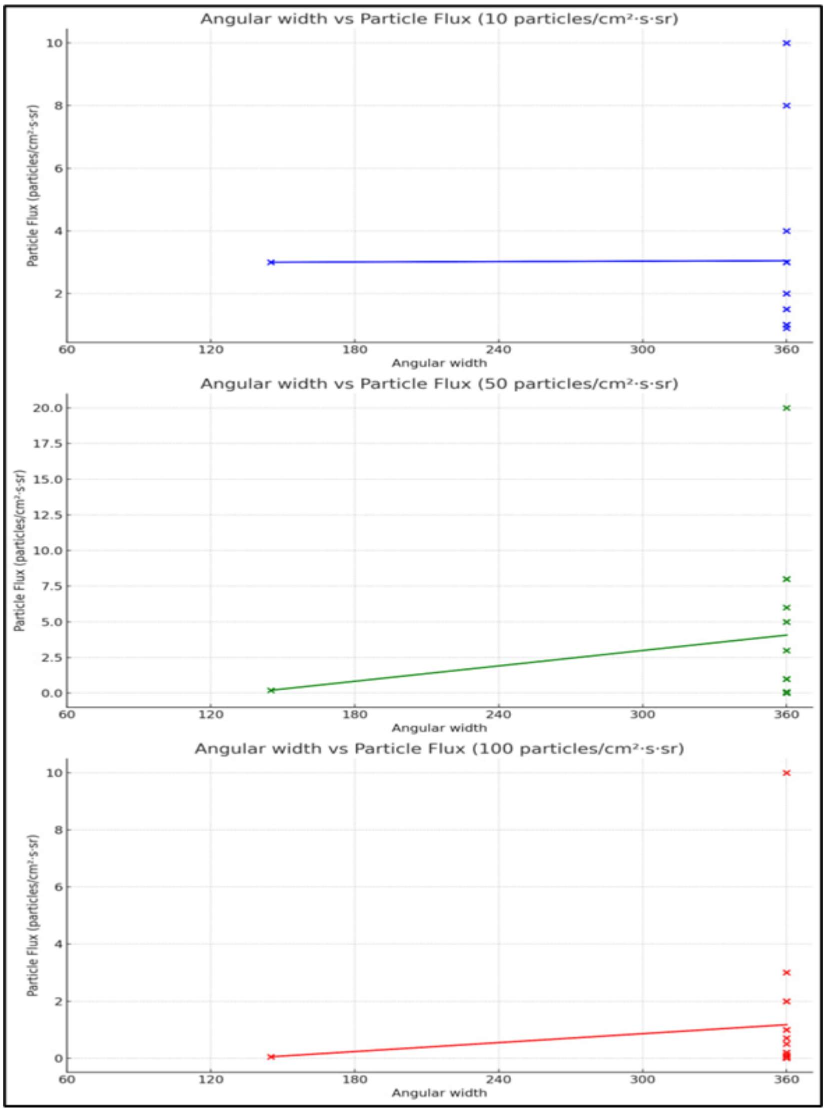

Figure (3) shows the relationship between angular width and particle flux density.

In Figure 3:

- Red line (10 MeV): No correlation (correlation coefficient: 0.0) between CME angular width and particle flux; particle flux remains constant regardless of width.
- Green line (50 MeV): A strong positive correlation (correlation coefficient: 0.96) where increased angular width leads to a notable rise in particle flux.
- Blue line (100 MeV): A very strong positive correlation (correlation coefficient: 0.98) between angular width and particle flux, with wider angles corresponding to higher flux.

Overall, angular width does not affect particle flux at 10 MeV, but it significantly increases particle flux at 50 and 100 MeV.

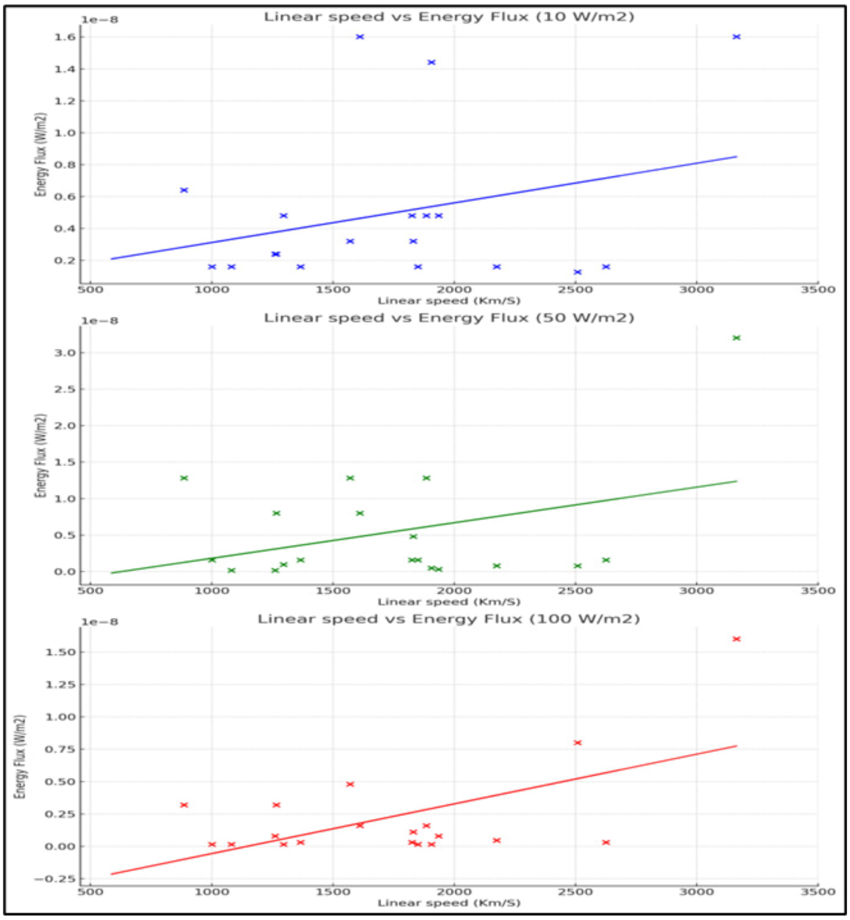

Figure (4): shows the relationship between angular width and Energy flux.

In Figure 4:

- Blue line (10 MeV): Perfect linear correlation (correlation coefficient: 1.0) between CME speed and energy flux; energy flux increases linearly with speed.
- Green line (50 MeV): Perfect linear correlation (correlation coefficient: 1.0) where energy flux increases linearly with CME speed.
- Red line (100 MeV): Perfect linear correlation (correlation coefficient: 1.0) with energy flux increasing linearly as CME speed increases.

In summary, there is a perfect linear relationship between energy flux and CME speed at all densities (10, 50, and 100 MeV), indicating that increased speed leads to a significant and continuous rise in energy flux.

4. Conclusion

The study reveals that CME parameters have varying impacts on particle and energy flux. Angular width has no effect on energy flux at 10 MeV but significantly influences it at 50 and 100 MeV. CME speed shows a strong and perfect linear correlation with particle flux and energy flux across all energy levels, with higher speeds leading to a proportional increase in both. These findings emphasize the critical role of CME characteristics in influencing space weather phenomena.

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