# The Relationship Between Solar X-ray Flux and Coronal Mass Ejection Energy

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# Abstract

Solar flares and their associated coronal mass ejections (CMEs) are an integral part of solar weather that can have profound effects on Earth's atmosphere. The charged particles emitted by strong CMEs and strong x-ray fluxes produced by solar flares can cause damage to satellites, disrupt radio and GPS signals, and strain power grids (Siscoe, 2000). It is critical to understand how solar flare intensity influences the magnitude of CMEs so as to minimize and prevent these consequential negative effects. This study investigated the hypothesis that solar x-ray flux has a direct correlation to CME energy. Total daily x-ray flux was correlated with CME energy for the years 2000-2012. X-ray flux data consisted of background and solar flare flux obtained from the Geostationary Operational Environmental Satellites (GOES). CME energy was obtained by squaring the 2nd-order speed at 20 Rs (solar radii) and summing these squared values for each day of each year. CME speed data was obtained from the NASA Large Angle and Spectrometric Coronagraph (LASCO) located on the Solar and Heliospheric Observatory satellite (SOHO). Results indicate significant correlations between solar x-ray flux and CME energy for the years 2001, 2003, and 2012 (solar maxima). Weaker correlations for the entire time series, which includes both solar maxima and minima, were found.

# Introduction

Space weather refers to the phenomena that characterize the interaction between the sun and earth’s atmosphere. A significant aspect of space weather, the solar flare, is formed when strong magnetic fields of opposing poles form a pathway between the sun’s corona and core. These strong magnetic fields, a necessary component for solar flare formation, are typically found near sunspots (Murray, 2013). It has been well documented that a strong positive correlation exists between sunspot number and the magnitude and frequency of solar flares. Therefore, both follow the 11-year solar cycle, making it possible to help predict when strong solar flares will occur (Norton et al., 2013).

Solar flares are classified using a scale based on their peak x-ray flux. X-class flares, considered the strongest types of flares, are those whose peak x-ray flux is greater than $10^{-4}$ W/m$^2$. M-class flare flux ranges from $10^{-5}$ to $10^{-4}$ W/m$^2$, C-class flare flux ranges from $10^{-6}$ to $10^{-5}$ W/m$^2$, B-class flare flux ranges from $10^{-7}$ to $10^{-6}$, and A-class flares are those whose flux is less than $10^{-7}$ W/m$^2$. Strong solar flares have been associated with distinct effects on the Earth’s atmosphere. The electromagnetic radiation associated with flares have been known to interfere with radio transmissions and GPS signals, thereby causing communication problems. The most extreme solar flare to have been witnessed and recorded occurred in 1859. It is commonly referred to as Carrington’s flare. Telegraphs malfunctioned, and auroras, which were witnessed as far south as Cuba, were so bright that they reportedly provided enough light to read at midnight as if it were noon (Bell and Phillips, 2013). Carrington’s flare serves as an example of the magnitude of certain solar events and their potential negative effects on Earth. If such a flare were to occur today, it would take a decade to recover from the resulting damage . The significance of Carrington’s event spurred the study of solar weather.

Aside from flares and other eruptive events, the magnetic field in the solar corona slowly evolves as changes in the surface field occur (Alexei A. Pevtsov, Luca Bertello, Andrey G. Tlatov, Ali Kilcik, Yury A. Nagovitsyn, and Edward W. Cliver, 2008). The energy released by solar flares (up to $6\times10^{25}$ J) may cause CMEs (Aulanier and Janvier, 2013). CMEs are bursts of solar wind from the sun's corona which consists of charged particles such as protons and electrons. Because these charged particles have mass, CMEs travel at slower velocities than do solar flares, whose radiation travel at the speed of light. CMEs are more likely to occur in the active regions of the Sun during the mature phase of their evolution (when they have complex magnetic field). CMEs also have a higher chance of occurring during a solar filament eruption. In fact, more than 80% of solar filament eruptions can cause a CME (B. Schmieder, P. Démoulin, G. Aulanier, 2013). The fastest CMEs can eject only from the most complex active regions (Grzegorz Michalek and Seiji Yashiro, 2013). Past studies have shown that as a solar flare's flux increases, so does the width of the associated CME (M.Youssef, R. Mawad, and Mosalam shaltout, 2012). The charged particles associated with CMEs are responsible for disruptions in the location and intensity of Earth's magnetic field. The change in the location of the magnetic field can result in the displacement of satellites that rely on the magnetic field for alignment. This magnetic field displacement also induces a geomagnetically induced current (GIC) which can strain the earth connections of power grid transformers (Thomson et al., 2011). This relationship between magnetic field variation and electric current is defined by Faraday's Law of Induction, where $\varepsilon = -N\frac{d\Phi}{dt}$. In this formula, ε refers to the induced electromotive force (EMF) that results from the negative change in magnetic flux with respect to time ($\frac{d\Phi}{dt}$). N refers to the medium in which this EMF is induced, in this case, air. Flares of higher classes (i.e. X- and M-class) are associated with faster and wider CMEs (M.Youssef, 2012). Studying CMEs can help in understanding the nature of the heliosphere and in the prediction of future geomagnetic activity.

To determine if a CME will be Earth-directed and therefore have a potential impact on its atmosphere, the triangulation method was used. The triangulation method is a multistep process that utilizes several NASA resources. The first step of the method is to determine where these satellites are located. This can be accomplished using one of NASA's websites which generates coronagraphs (Gurman, 2013). The triangulation method can be demonstrated by referring to a solar flare that occurred at approximately 3:00 A.M. (UT) on May 13, 2013.

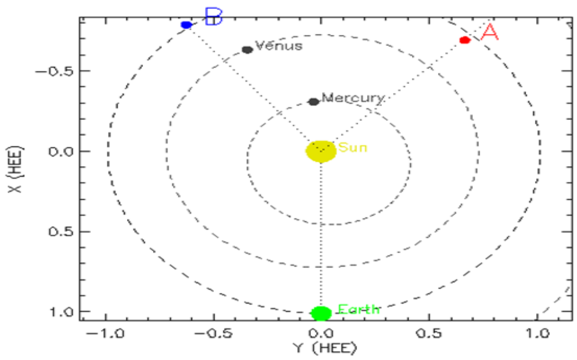


**Figure 1:** B represents Stereo B, A is Stereo A, and Earth represents the relative location of SOHO (Gurman, 2013).

Images of CMEs are recorded by the Solar and Heliospheric Observatory (SOHO), Solar Terrestrial Relations Observatory Ahead (STEREO A), and Solar Terrestrial Relations Observatory Behind (STEREO B) satellites. These images were taken from the Integrated Space Weather System (ISWA). Video displays of the CME were analyzed to determine its approximate direction. ("Available Cygnets.")

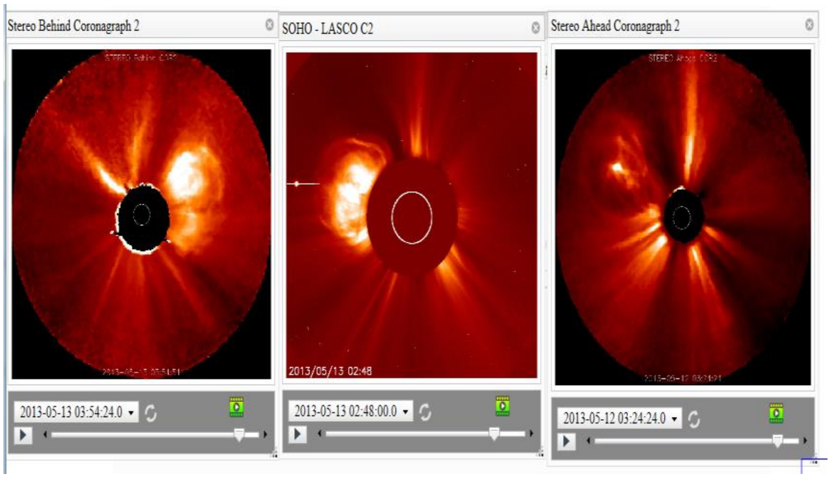
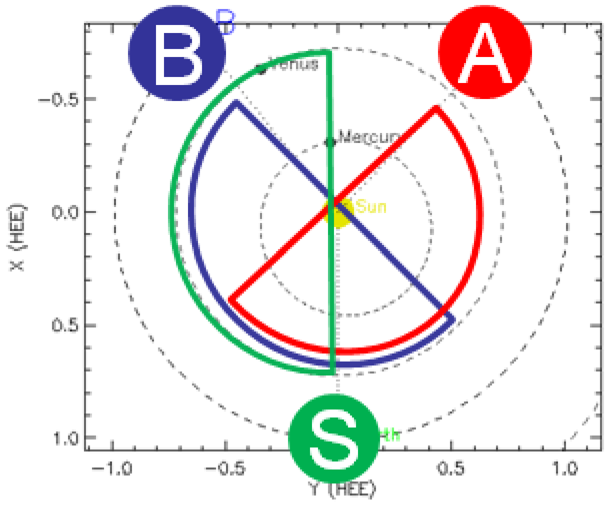


**Figure 2:** Several corona graphs of the Sun during a coronal mass

ejection. (From left to right the satellites that took the pictures are STEREO B, SOHO, and STEREO A).

**Figure 3:** Several views of the same CME taken from STEREO A (A), STEREO B (B), and SOHO (S).



From the viewpoint of STEREO B, **Figure 2** shows the CME being emitted from the right side of the sun, which places it somewhere in the blue outlined region of **Figure 3**. From the viewpoint of STEREO A, the image shows the CME being emitted from the left side of the sun, which places it somewhere in the red outlined region. From the viewpoint of SOHO, the image shows the CME being emitted from the left side of the sun which indicates that it occurred in the green outlined region. This data supports the conclusion that this CME was partially directed towards Earth. In addition, CMEs often emit in wedges and expand after ejection rather than in straight lines. This increases the possibility of a collision between a given CME and Earth's magnetic field.

The purpose of this study was to correlate solar x-ray flux, the defining characteristic of flare intensity, with CME energy, a way to quantify the CME's intensity. Previous research has shown that 40% of observed CMEs are associated with flares (Subramanian and Dere, 2001). Dr.

Yousef from the National Research Institute of Astronomy and Geophysics (NRIAG), in Cairo, Egypt, among other sources analyzed prior to this study, concluded that, "We found that there is a good relation between the solar flare fluxes and their associated CME energies, where R = 65%." Additionally, a positive correlation between flare flux and CME linear speed has been found (M. Youssef, R. Mawad, and Mosalam shaltout, 2012). However, the relative location of a CME and an associated flare is varying - the flare can be anywhere in the vicinity of the CME (R.A. Harrison, 1995).

## Materials and Methods

Data for x-ray flux from solar flares and daily background readings were obtained from the Geostationary Operational Environmental Satellites (GOES) using the National Oceanic and Atmospheric Administration's (NOAA) National Weather Service (NWS) Space Weather Prediction Center (SWPC) database. Total daily x-ray flux (watts/meter$^2$) was calculated for 2000-2012 by summing the x-ray flux from each solar flare event with the daily background x-ray flux. Time specific solar images from the SOHO, STEREO A, and STEREO B satellites from 2000-2012 were studied. SOHO, STEREO A, and STEREO B provided varying visual perspectives of the Sun used in the aforementioned triangulation method. This was done to predict if a CME was Earth-directed with the help of NASA's Stereo Analysis tool ("Stereo Analysis.").

CME velocities were obtained from SOHO using the Coordinated Data Analysis Workshop (CDAW) Data Center at the Goddard Space Flight Center (GSFC). Daily CME energy was calculated by squaring their velocities (km$^2$/s$^2$) for 2000-2012. X-ray flux was statistically correlated to CME energy and graphed for the entire time series. Yearly correlations were conducted to better resolve the data for trends.

## Results

The graph in **Figure 4** illustrates the cyclic trend in annual solar flare frequency between the years of 1975-2012. The trend correlates with the 11-year solar cycle. The high points and low points in this graph correspond to the solar maxima and minima, respectively.

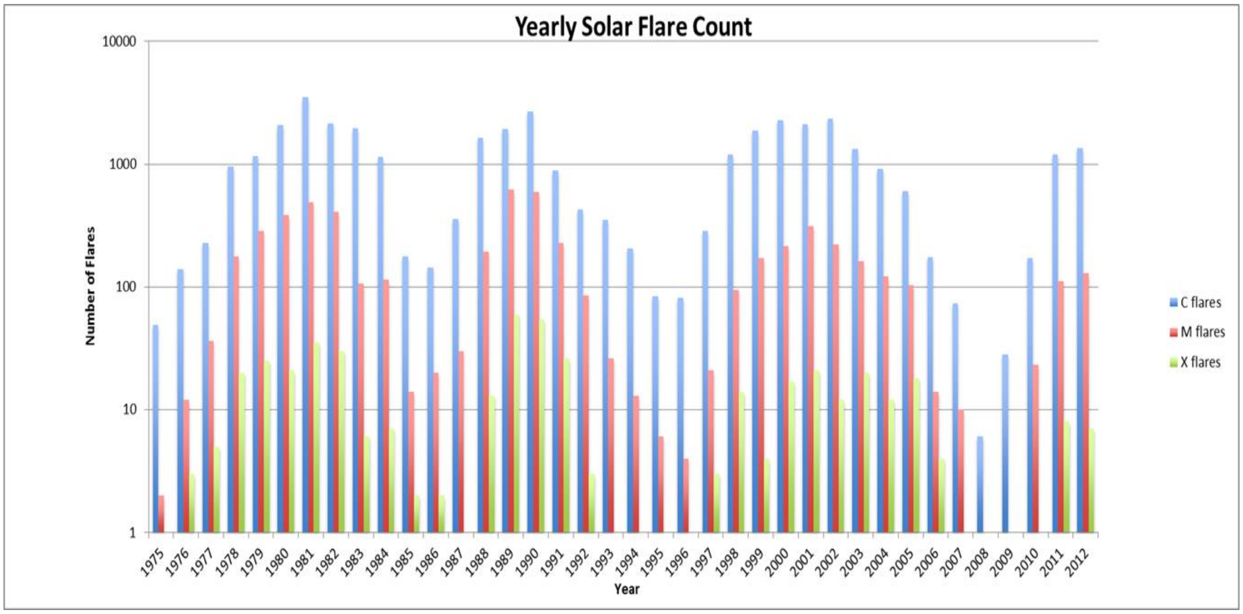


**Figure 4:** Annual solar frequency upon a log scale. While it is not uncommon for a year to contain hundreds of C-class flares, it is rare for a year to have more than a dozen X-class flares.

The graph in **Figure 5** depicts the annual background, flare, and total peak x-ray flux between the years of 2000 - 2012. This data was used to quantify the intensity of solar flares during this time period. The data is graphed upon the logarithmic scale to display background energy readings that are much less intense than the flare readings. The graph indicates that both types of solar x-ray flux, background and flare flux, vary in relation to the 11-year solar cycle. As can be seen, 2001 was a solar maximum and 2008 was a solar minimum. 2013, not graphed, is also considered a solar maximum

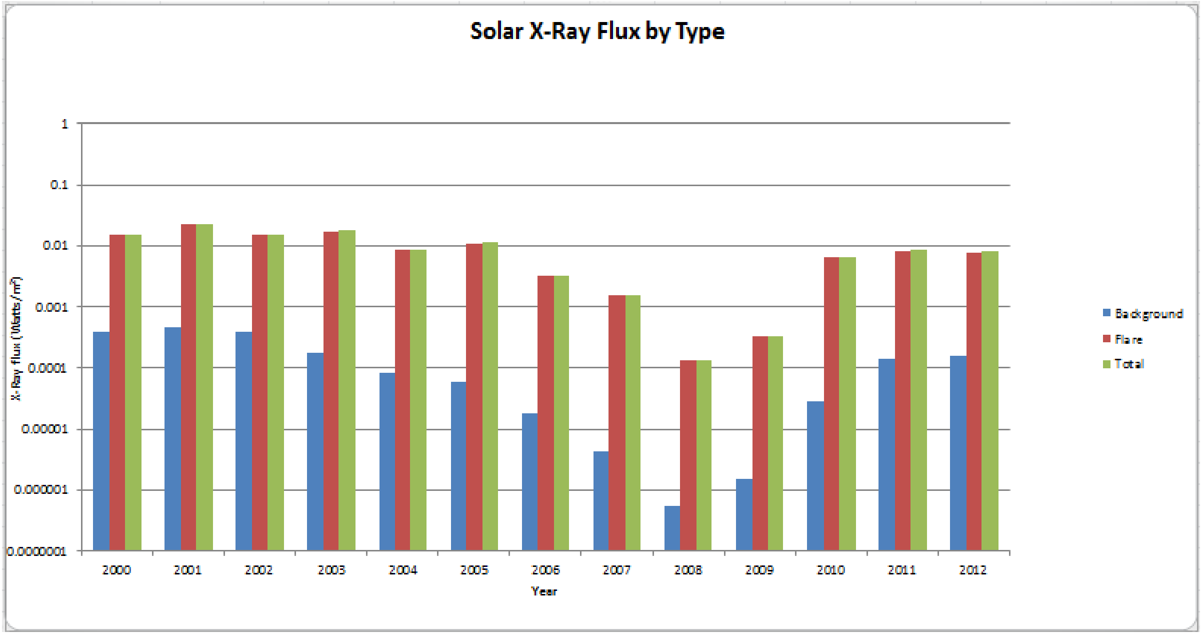


**Figure 5:** Background, solar flare, and total x-ray flux data graphed logarithmically for the years 2000-2012.

**Figure 6** shows the time-integrated solar x-ray flux, another way in which to quantify solar flare intensity, for 2000-2012. Since this data was integrated over time, the unit is joules/meter$^2$ as opposed to watts/meter$^2$ as it was for the regular solar x-ray flux data.

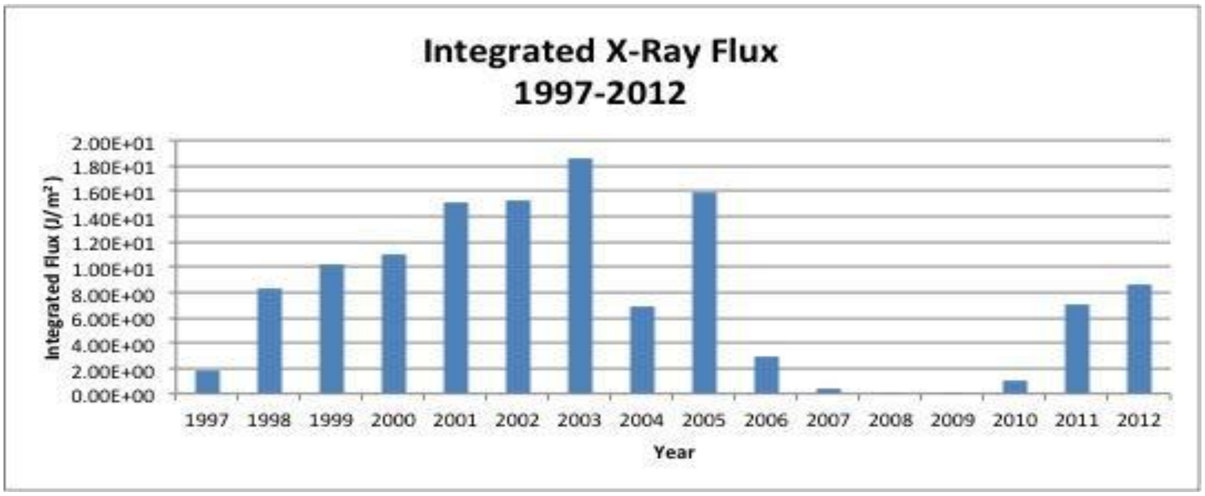


**Figure 6:** Integrated x-ray flux graphed from 1997 to 2012.

**Figure 7** shows the correlation of total solar x-ray flux and CME energy for the entirety of our time series, 2000-2012. A polynomial trendline has been superimposed for each dataset so as to identify relations between the two. A sparsity in x-ray flux data (red) can be seen for the time period around the 2008 solar minimum. The correlation coefficient for this data was 0.16.

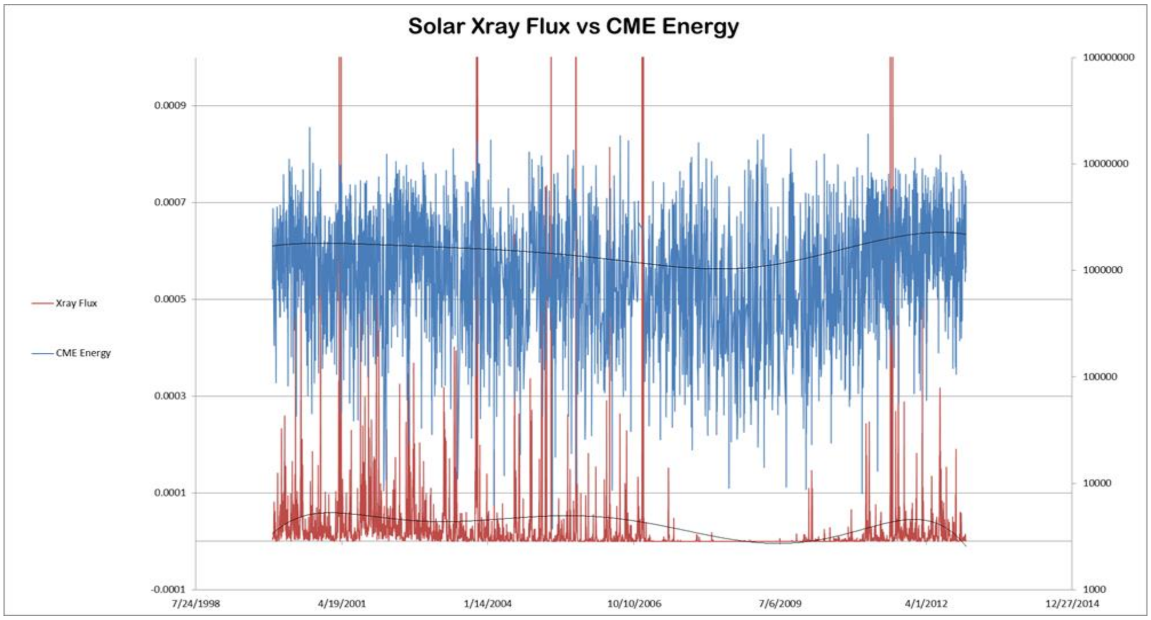


**Figure 7:** Solar x-ray flux vs. CME energy for 2000-2012.

**Figure 8** shows the solar x-ray flux and CME energy correlation for the year 2012, the year closest to the 2013 solar maximum. The correlation coefficient for this data was 0.31.

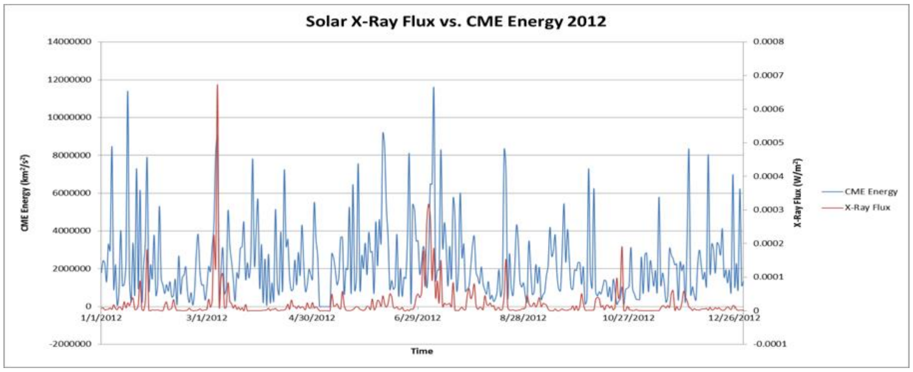


**Figure 8:** Solar x-ray flux vs. CME energy for 2012.

**Figure 9** shows the solar x-ray flux and CME energy correlation for the year 2003, just following the 2001 solar maximum. The correlation coefficient for this data was 0.48, the highest obtained within this study.

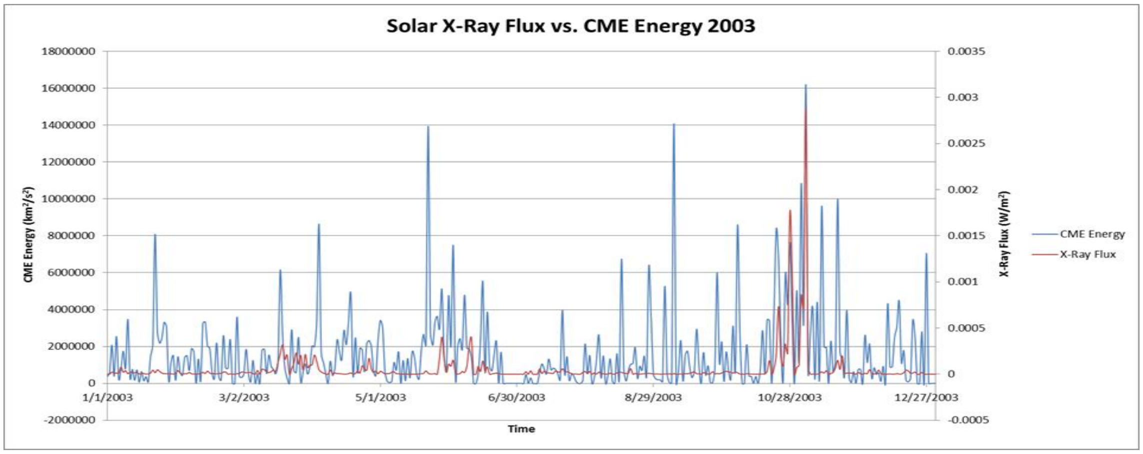


**Figure 9:** Solar x-ray flux vs. CME energy for 2003.

**Figure 10** shows the solar x-ray flux and CME energy correlation for the solar maximum year of 2001. The correlation coefficient for this data was 0.40.

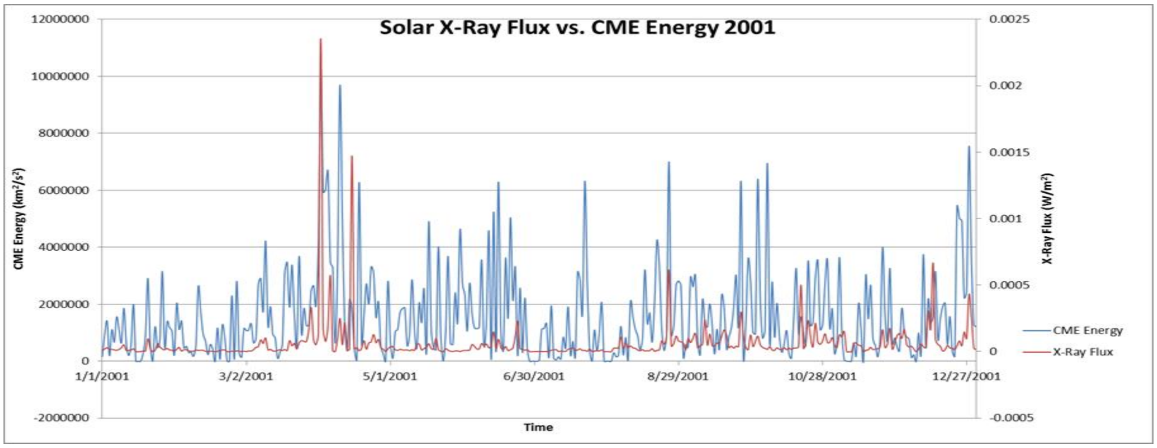


**Figure 10:** Solar x-ray flux vs. CME energy for 2001.

## Discussion

The first part of this study involved the identification of trends in solar flare occurrence and intensity for the recent time period. Correlations were found while analyzing the data. The main notable observation was a correlation of this data to the 11-year solar cycle. Upon inspection, **Figure 4** indicated varying amounts of flares (X-, M-, and C-class) that corresponded well to the solar cycle. Peaks of all three classes of flares typically occurred in years of solar maxima and the low-points of the data occurred during years of solar minima. Similar findings were observed in examining the solar flare intensity, characterized by x-ray flux emissions. In **Figures 5** and **6**, the maximum peaks for both regular x-ray flux and integrated flux occurred in 2001-2003, years close to the solar maximum, and the low-points in 2008, the year or the solar minimum. This initial study of solar flare frequency and intensity provided the context in which the rest of our study was performed.

The second part of this study involved correlating solar x-ray flux with CME energy. In **Figure 7**, the entire time series, trends can be seen by examining the polynomial trendlines. While the correlation coefficient for the entire time series is low (0.16), both trend lines decline, reaching a minimum around the year 2008, the solar minimum, and rise soon after. Correlations were then performed for individual years to see if coefficients would be higher when performed in a narrower time period. Correlations were higher for three of the 13 years examined. 2012 (**Figure 8**) had a coefficient value of 0.31, 2003 (**Figure 9**) had a value of 0.48, and 2001 (**Figure 10**) had a value of 0.40.

It is important to note that these correlations were performed without regard to the lag period that exists between the radiation emitted from solar flares and the massive charged particles that make up a CME. This is due to SOHO's, which measured CME velocity, and

GOES’s, which measured x-ray flux, different locations and distances from the Sun. In addition to the fact that CME speeds vary, a single lag period would be difficult to obtain. Another point to note is that correlations were higher near the years of upcoming solar maxima because of the increase and the higher fluctuation of x-ray flux and CME energy during these times. The sparsity of data around the solar minimum (2008) contributed to a coefficient value of virtually 0.

## Conclusion

The results of this preliminary study weakly support the hypothesis of a correlation between solar flare flux and CME energy for 2000-2012. Although the correlation coefficient calculated over the entire time series was 0.16, coefficients were greater in some cases when calculated by year, especially around the years of solar maxima. The highest correlation coefficient values obtained were 0.31, 0.40, and 0.48, which show distinct relationships between solar x-ray flux and CME energy for those particular years.

## Future Work

Future work will include further examining the correlation between these two data sets by studying specific periods in which high-intensity flare events occurred. In addition, the lag period between the two data sets will be investigated by taking into account satellite locations and CME velocities. Finally, a more comprehensive data set will be obtained for CME energy, since there were many days in which CME measurements were not available.

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