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# An Empirical Relation Between SEP Proton Flux, CME Linear Speed And Flare Class

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***Abstract:*** *The effects of Solar Energetic Particle (SEP) events are well known in terms of the potential damages they can cause for space systems like satellites and space probes, health hazards to astronauts, electronic equipment on ground, the power grids, radio communication and more important to space weather. Earlier studies have indicated that the solar flares and Coronal Mass Ejections (CMEs) play a major role in producing SEP events where in high energy particles are involved. GOES satellites carry instruments to measure the proton flux of these SEPs in many ranges. Efforts were on to predict the SEPs early and give warning in advance so that preventive or protective actions can be initiated before the actual event occurs. A few operating systems are also available for the early prediction of SEPs each having a limited number of short falls in terms of probability of detection and false alarms. There are two aspects of predicting SEPs. One is to predict the occurrence early in time and the second is to predict the proton flux of the SEP event that is going to occur. In this paper an empirical relation is derived between SEP proton flux, CME linear speed and the flare peak intensity given by X-ray class. The first part is listing the associated CMEs and flares and the second part is finding the relation between them finally leading to the derivation of a simple empirical relation.*
***Key Words:*** *Solar Energetic Particle, SEP proton flux, CME, Flare class*

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## I. Introduction

Sun is a source of energy and energetic particles. It is also an efficient accelerator of energetic particles. The energetic particles ejected from Sun are omni-directional and some of them get connected to Earth through direct magnetic lines contact and through enhancement from Coronal Mass Ejections. It is widely believed that two events on Sun called flares and CMEs play a major role in Solar Energetic Particle events. Balch (1999) [1] defined a solar particle event to have occurred whenever the flux of energetic protons (greater than 10 MeV) at geosynchronous orbit exceeds 10 particles per square centimeter per second per steradian. The unit of measure that is called particle flux unit (pfu). SEPs can cause damage to the orbiting satellites by means of component failure and solar cell degradation. They can cause orbital decay and defective attitude control of satellites. They pose health hazards for astronauts. SEPs can also endanger costly electronic equipment on ground, cause partial or total failure of power grids, hamper radio communication and alter space weather [2].

Reames[3] observed that our ability to predict SEP events is almost nonexistent, but that does not prevent predictions from being made. He also observed that it should be possible to model the CME, the shock, and the acceleration and transport of particles sufficiently well to predict the peak intensity at shock passage and the event fluence. Kahler (2001) [4] summarized that the peak intensity of an SEP event observed at I AU depends on several factors, one of which is the speed of the CME driving the interplanetary shock. Park et al (2015) [5] found that the 6– 10 MeV SEP peak fluxes increase with the EUV wave speeds measured along the direction from the source regions to the foot points of the spacecraft. Dierckxsens (2014) [6] analyzed statistically the events of solar cycle. They have shown that the SEP occurrence probabilities generally increase significantly for events associated with large X-class flares, western solar longitudes, CMEs with high velocities and halo CMEs. Papaioannou (2016) [7] also reported in their study the dependence of the properties of SEPs on the flare and CME properties.

The earlier attempts were to establish a statistical relation between SEP properties to the properties of flares and CMEs. The mathematical formulations were very few and limited to relate only two parameters at a time. Linear speed of the CME is an important property and hence is likely to have more impact on the flux of the SEP. Similarly, the flare class is an important property which can have significant effect on SEP flux. The aim of the work presented here is to derive a comprehensive empirical relation between SEP proton flux, CME linear speed and flare class. The derived empirical formula is tested for the closeness of predicted SEP proton flux values with those actually measured.

## II. Data Used And Sources

GOES satellites, placed in geo-synchronous orbit at an altitude of 36,000 km, measure the high energy particles in several ranges. These measurements can be considered as measured at a distance of near 1 AU from Sun. Using the data from GOES instruments, the Space Weather Prediction Centre (SWPC) of National Oceanic and Atmospheric Administration (NOAA) maintains the list of SEP events. The SEP event data obtained from SWPC [8] contains, apart from other details, a list of SEP events with the starting time of the event, time at which the maximum proton flux occurred and the maximum proton flux. The Proton fluxes, listed in the table, are integral 5-minute averages for energies > 10 MeV, given in Particle Flux Units (pfu), where in 1 pfu is defined as 1 proton/sq. cm-s-sr.

GOES satellites, also carry X-ray sensors to take measurements in the soft and hard x-ray bands of the electromagnetic spectrum. The X-Ray Sensor (XRS) on the Geostationary Orbiting Environmental Satellite (GOES) provides real-time monitoring for solar x-ray flares [9]. Solar flare data, as measured in the soft x-ray region, is taken from the yearly catalogs generated using XRS[10]instrument. The catalogs are compiled and archived by National Centers for Environmental Information (NCEI, formerly NGDC) of National Oceanic and Atmospheric Administration (NOAA), Department of Commerce[8]. This catalog gives information on date and time corresponding to the start, peak and end times of the flare as well as the class of the flare.

The Large Angle and Spectrometric Coronagraph (LASCO) on board the Solar and Heliospheric Observatory (SOHO) mission [11] provided very valuable data since 1996. The CME data is obtained from the catalog containing all CMEs manually identified since 1996. The CME Catalog derived from LASCO coronagraph on SOHO is used from CDAW Data Center by NASA and the Catholic University of America in cooperation with the Naval Research Laboratory. SOHO is a project of international cooperation between ESA and NASA. The catalog gives information on date and time of occurrence of CME in the Field of View of LASCO, the Central Position Angle (CPA), sky plane width of the CME, Linear Speed (LS), acceleration, mass, kinetic energy, Measured Position Angle (MPA) etc. CMEs of an apparent width of $360^o$ are marked as 'Halo' in the CPA. Partial Halo CMEs have a minimum angular width of $120^o$.

The common period of data for the present study reported here is from January 2002 to January 2016, that is for a period of 14 years. During this period a large number of SEP, flare and CME events are recorded. Table 1 gives the summary of the number of events.

**Table 1 Entries available from the Flare, CME and SEP catalogs**

| | |
|---|---|
| Period | 01-01-2002 to 02-01-2016 |
| Total number of flares | 23,660 |
| Total number of CMEs | 21,445 |
| Number of SEPs | 78 |

## III. Associating CMEs And Flares With SEPs

From table 1 it can be seen that a large number of flares and CMEs did occur during the period of 14 years under consideration. The number of SEPs during the same period are only 78. In order to associate the flares and CMEs with SEPs a lot of iterations were needed to select the flares and CMEs which are more likely to be associated with the SEPs. The description and number of the iterations are extremely large and beyond the space of this paper. Lot of qualifiers for important parameters of the CMEs and flares, and the time relations between them led to a very satisfactory association. Table 2 gives the list of final qualifiers and the selected criteria for each qualifier.

**Table 2 Qualifier parameters and the limits/ criteria**

| Qualifier | Criteria |
|---|---|
| Type of CME | Halo or Partial Halo |
| CME Linear Speed (km/s) | >850 |
| CME Angular width (deg.) | > 120 |
| CME CPA (deg.) | >240 |
| Flare duration (minutes) | > 10 |
| Class of flare | ≥ C1 |
| Time delay between CME and Flare | ± 2 hours |
| Time delay between SEP and CME | < 4 days |

Applying the criteria for the qualifiers as shown in table 2 resulted in great reduction of CMEs and flares to be associated with SEPs. But this also resulted in 10 out of the 78 SEPs not being associated with any CME, flare combination. The result is worth considering because of the reason that a data set of 68 associated events is good for deriving the relation between associated events. In a few cases of SEP events, more than one set of CME and flare were found. In such cases the most probable combination is selected. The results of this study are listed in table 3. SEP maximum time, proton flux, associated flare peak time, class of flare, associated CME time and linear speed of time are listed in table 3. The entries in red font are the SEPs which have no associated flare and CME. It is to be noted that only class of the fare and linear speed of the CME, as the aim is to generate relation between these parameters and proton flux leading to an empirical relation between them.

**Table 3 List of SEP events with associated flares and CME events**

| Sl. No. | SEP maximum | Proton Flux (pfu) | Flare peak | Flare | CME | CME speed |
|---|---|---|---|---|---|---|
| | dd/mm/yyhh :mm | | dd/mm/yyhh :mm | Class | dd/mm/yyhh :mm | Km/s |
| 1 | 11/01/02 05:30 | 91 | 08/01/02 17:25 | C 7.2 | 08/01/02 17:54 | 1794 |
| 2 | 15/01/02 20:00 | 15 | 14/01/02 06:27 | M 4.4 | 14/01/02 05:35 | 1492 |
| 3 | 20/02/02 07:55 | 13 | 20/02/02 06:12 | M 5.1 | 20/02/02 06:30 | 952 |
| 4 | 17/03/02 08:50 | 13 | 15/03/02 23:10 | M 2.2 | 15/03/02 23:06 | 957 |
| 5 | 19/03/02 06:50 | 53 | 18/03/02 02:31 | M 1.0 | 18/03/02 02:54 | 989 |
| 6 | 20/03/02 15:25 | 19 | 19/03/02 11:44 | M 1.0 | 19/03/02 11:54 | 885 |
| 7 | 23/03/02 13:20 | 16 | 22/03/02 11:14 | M 1.6 | 22/03/02 11:06 | 1750 |
| 8 | 17/04/02 15:40 | 24 | 17/04/02 08:24 | M 2.6 | 17/04/02 08:26 | 1240 |
| 9 | 21/04/02 23:20 | 2520 | 21/04/02 01:51 | X 1.5 | 21/04/02 01:27 | 2393 |
| 10 | 23/05/02 10:55 | 820 | 22/05/02 03:54 | C 5.0 | 22/05/02 03:50 | 1557 |
| 11 | 07/07/02 19:55 | 22 | 07/07/02 11:43 | M 1.0 | 07/07/02 11:30 | 1423 |
| 12 | 17/07/02 16:00 | 234 | 15/07/02 20:08 | X 3.0 | 15/07/02 20:30 | 1151 |
| 13 | 19/07/02 15:15 | 13 | 18/07/02 07:44 | X 1.8 | 18/07/02 08:06 | 1099 |
| 14 | 23/07/02 10:25 | 28 | 23/07/02 00:35 | X 4.8 | 23/07/02 00:42 | 2285 |
| 15 | 14/08/02 16:20 | 26 | 14/08/02 02:12 | M 2.3 | 14/08/02 02:30 | 1309 |
| 16 | 22/08/02 09:40 | 36 | 22/08/02 01:57 | M 5.4 | 22/08/02 02:06 | 998 |
| 17 | 24/08/02 08:35 | 317 | 24/08/02 01:12 | X 3.1 | 24/08/02 01:27 | 1913 |
| 18 | 07/09/02 16:50 | 28 | 05/09/02 17:06 | C 5.2 | 05/09/02 16:54 | 1748 |
| 19 | 10/11/02 05:40 | 404 | 09/11/02 13:23 | M 4.6 | 09/11/02 13:31 | 1838 |
| 20 | 29/05/03 15:30 | 121 | 28/05/03 00:27 | X 3.6 | 28/05/03 00:50 | 1366 |
| 21 | 31/05/03 06:45 | 27 | 31/05/03 02:24 | M 9.3 | 31/05/03 02:30 | 1835 |
| 22 | 19/06/03 04:50 | 24 | 17/06/03 22:55 | M 6.8 | 17/06/03 23:18 | 1813 |
| 23 | 26/10/03 22:35 | 466 | 26/10/03 18:19 | X 1.2 | 26/10/03 17:54 | 1537 |
| 24 | 29/10/03 06:15 | 29500 | 27/10/03 08:33 | M 2.7 | 27/10/03 08:30 | 1322 |
| 25 | 03/11/03 08:15 | 1570 | 02/11/03 17:25 | X 8.3 | 02/11/03 17:30 | 2598 |
| 26 | 05/11/03 06:00 | 353 | 04/11/03 19:50 | X 2.8 | 04/11/03 19:54 | 2657 |
| 27 | 22/11/03 02:30 | 13 | - | - | - | - |
| 28 | 02/12/03 | 86 | 02/12/03 | C 7.2 | 02/12/03 | 1393 |

| Sl. No. | SEP maximum | Proton Flux (pfu) | Flare peak | Flare | CME | CME speed |
|---|---|---|---|---|---|---|
| | dd/mm/yyhh :mm | | dd/mm/yyhh :mm | Class | dd/mm/yyhh :mm | Km/s |
| | 17:30 | | 09:48 | | 10:50 | |
| 29 | 11/04/04 18:45 | 35 | 08/04/04 10:19 | C 7.4 | 08/04/04 10:30 | 1068 |
| 30 | 26/07/04 22:50 | 2086 | 25/07/04 15:14 | M 1.1 | 25/07/04 14:54 | 1333 |
| 31 | 14/09/04 00:05 | 273 | 12/09/04 00:56 | M 4.8 | 12/09/04 00:36 | 1328 |
| 32 | 20/09/04 01:00 | 57 | - | - | - | - |
| 33 | 01/11/04 08:05 | 63 | 01/11/04 04:22 | C 2.6 | 01/11/04 06:06 | 925 |
| 34 | 08/11/04 01:15 | 495 | 07/11/04 16:06 | X 2.0 | 07/11/04 16:54 | 1759 |
| 35 | 17/01/05 17:50 | 5040 | 15/01/05 23:02 | X 2.6 | 15/01/05 23:06 | 2861 |
| 36 | 15/05/05 02:40 | 3140 | 13/05/05 16:57 | M 8.0 | 13/05/05 17:12 | 1689 |
| 37 | 17/06/05 05:00 | 44 | - | - | - | - |
| 38 | 15/07/05 03:45 | 134 | 14/07/05 10:55 | X 1.2 | 14/07/05 10:54 | 2115 |
| 39 | 29/07/05 17:15 | 41 | 27/07/05 05:02 | M 3.7 | 27/07/05 04:54 | 1787 |
| 40 | 23/08/05 10:45 | 330 | 22/08/05 17:27 | M 5.6 | 22/08/05 17:30 | 2378 |
| 41 | 11/09/05 04:25 | 1880 | 09/09/05 20:04 | X 6.2 | 09/09/05 19:48 | 2257 |
| 42 | 07/12/06 19:30 | 1980 | 06/12/06 18:47 | X 6.5 | 06/12/06 20:12 | - |
| 43 | 13/12/06 09:25 | 698 | 13/12/06 02:40 | X 3.4 | 13/12/06 02:54 | 1774 |
| 44 | 14/08/10 12:45 | 14 | 14/08/10 10:05 | C 4.4 | 14/08/10 10:12 | 1205 |
| 45 | 08/03/11 08:00 | 50 | 07/03/11 20:12 | M 3.7 | 07/03/11 20:00 | 2125 |
| 46 | 22/03/11 01:35 | 14 | - | - | - | - |
| 47 | 07/06/11 18:20 | 72 | 07/06/11 06:41 | M 2.5 | 07/06/11 06:49 | 1255 |
| 48 | 05/08/11 21:50 | 96 | 04/08/11 03:57 | M 9.3 | 04/08/11 04:12 | 1315 |
| 49 | 09/08/11 12:10 | 26 | 08/08/11 18:10 | M 3.5 | 08/08/11 18:12 | 1343 |
| 50 | 26/09/11 11:55 | 35 | 24/09/11 13:20 | M 7.1 | 24/09/11 12:48 | 1915 |
| 51 | 27/11/11 01:25 | 80 | 26/11/11 07:10 | C 1.2 | 26/11/11 07:12 | 933 |
| 52 | 24/01/12 15:30 | 6310 | 23/01/12 03:59 | M 8.7 | 23/01/12 04:00 | 2175 |
| 53 | 28/01/12 02:05 | 796 | 27/01/12 18:37 | X 1.7 | 27/01/12 18:27 | 2508 |
| 54 | 08/03/12 11:15 | 6530 | 07/03/12 00:24 | X 5.4 | 07/03/12 00:24 | 2684 |
| 55 | 13/03/12 20:45 | 469 | 13/03/12 17:41 | M 7.9 | 13/03/12 17:36 | 1884 |
| 56 | 17/05/12 04:30 | 255 | 17/05/12 01:47 | M 5.1 | 17/05/12 01:48 | 1582 |
| 57 | 27/05/12 10:45 | 14 | - | - | - | - |
| 58 | 16/06/12 20:20 | 14 | 14/06/12 14:35 | M 1.9 | 14/06/12 14:12 | 987 |
| 59 | 07/07/12 07:45 | 25 | 06/07/12 23:08 | X 1.1 | 06/07/12 23:24 | 1828 |
| 60 | 12/07/12 22:25 | 96 | 12/07/12 16:49 | X 1.4 | 12/07/12 16:48 | 885 |
| 61 | 18/07/12 06:00 | 136 | - | - | - | - |
| 62 | 23/07/12 | 12 | - | - | - | - |

| Sl. No. | SEP maximum | Proton Flux (pfu) | Flare peak | Flare | CME | CME speed |
|---|---|---|---|---|---|---|
| | dd/mm/yyhh :mm | | dd/mm/yyhh :mm | Class | dd/mm/yyhh :mm | Km/s |
| | 21:45 | | | | | |
| 63 | 02/09/12 08:59 | 59 | 31/08/12 20:43 | C 8.4 | 31/08/12 20:00 | 1442 |
| 64 | 28/09/12 04:45 | 28 | 27/09/12 23:57 | C 3.7 | 28/09/12 00:12 | 947 |
| 65 | 17/03/13 07:00 | 16 | 15/03/13 06:58 | M 1.1 | 15/03/13 07:12 | 1063 |
| 66 | 11/04/13 16:45 | 114 | 11/04/13 07:16 | M 6.5 | 11/04/13 07:24 | 861 |
| 67 | 17/05/13 17:20 | 41 | 17/05/13 08:57 | M 3.2 | 17/05/13 09:12 | 1345 |
| 68 | 23/05/13 06:50 | 1660 | 22/05/13 13:32 | M 5.0 | 22/05/13 13:25 | 1466 |
| 69 | 24/06/13 05:20 | 14 | - | - | - | - |
| 70 | 30/09/13 20:05 | 182 | 29/09/13 23:39 | C 1.2 | 29/09/13 22:12 | 1179 |
| 71 | 28/12/13 23:15 | 29 | - | - | - | - |
| 72 | 06/01/14 16:00 | 42 | 04/01/14 19:46 | M 4.0 | 04/01/14 21:22 | 977 |
| 73 | 09/01/14 03:40 | 1033 | 07/01/14 18:32 | X 1.2 | 07/01/14 18:24 | 1830 |
| 74 | 20/02/14 09:25 | 22 | 20/02/14 07:56 | M 3.0 | 20/02/14 08:00 | 948 |
| 75 | 28/02/14 08:45 | 103 | 25/02/14 00:49 | X 4.9 | 25/02/14 01:25 | 2147 |
| 76 | 18/06/15 14:45 | 16 | 18/06/15 01:27 | M 1.2 | 18/06/15 01:25 | 1714 |
| 77 | 29/10/15 10:00 | 23 | - | - | - | - |
| 78 | 02/01/16 04:50 | 21 | 02/01/16 00:11 | M 2.3 | 01/01/16 23:24 | 1730 |

## IV. Relation Between SEP Proton Flux, CME Linear Speed And Peak Flare Intensity

From table 3, 68 SEPs are found to be associated with flares and CMES. This set of 68 events is used for further analysis. The class of the flare measured in x-ray is determined by the peak intensity of the flare. The relation between the SEP proton flux and the peak flare intensity is shown by means of a scattered plot in figure 1. Both X and Y scales in the plot are logarithmic. A log-log relationship exists between the SEP flux and flare intensity with a reasonable correlation. The linear relation of the fit and the correlation factor are shown in the chart.

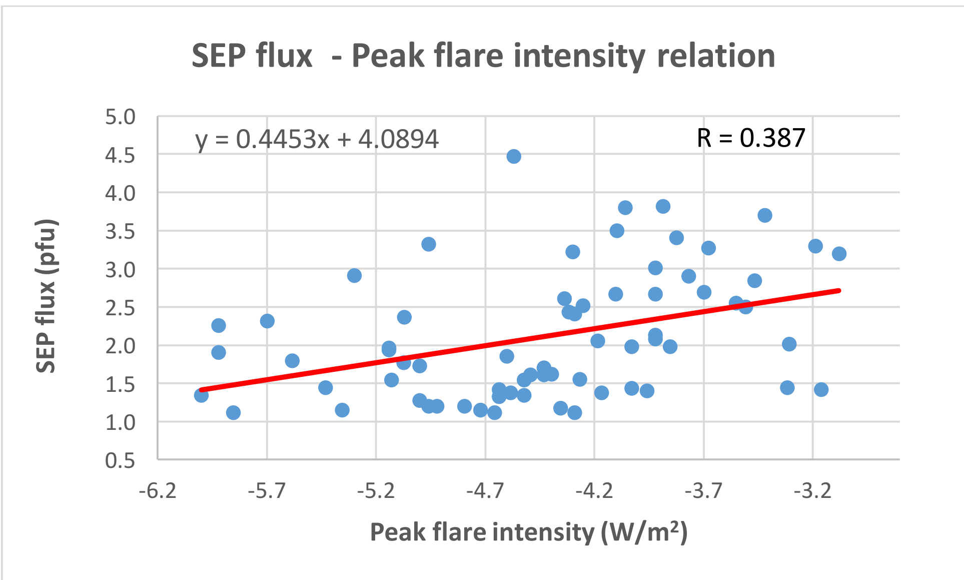


**Figure 1. Relation between log of SEP flux and Log of flare peak intensity**

The relation between the SEP flux and flare class is given by

**Log (SEP flux) = 0.4453 x Log (peak flare intensity) + 4.0894**

The relation between the SEP proton flux and the CME linear speed is shown by means of a scattered plot in figure 2. Both X and Y scales in the plot are logarithmic. A log-log relationship exists between the SEP flux and CME linear speed with a reasonable correlation. The linear relation of the fit and the correlation factor are shown in the chart. The correlation of the SEP flux with CME linear speed is better than that of with flare intensity.

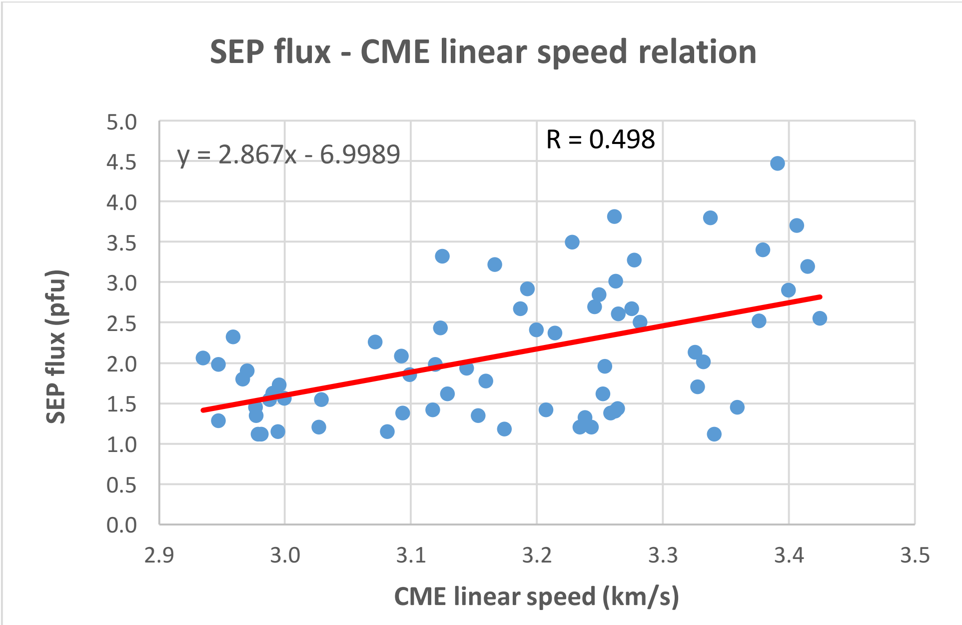


**Figure 2. Relation between SEP proton flux and CME linear speed**

The relation between the SEP flux and CME linear speed is given by

**Log (SEP flux) = 2.867 x Log (CME linear speed) – 6.9989**

From these two relations it is possible to derive an empirical relation between SEP flux, peak flare intensity and CME linear speed in the form of an equation as below.

**Log (SEP flux) = $A_1$ {0.4453 x Log (flare peak intensity) + 4.0894)} +**
**$B_1$ {2.867 x Log (CME Linear speed) -6.9989)}**

Where $A_1$ and $B_1$ are the normalization factors based the observed correlation of SEP flux with flare peak intensity and CME speed respectively. The observed correlation factors are given below.

Correlation factor between SEP flux and flare peak intensity $R_1 = 0.387$
Correlation factor between SEP flux and CME linear speed $R_2 = 0.498$
$A_1 = R_1/ (R_1 + R_2) = 0.387/ (0.387 + 0.498) = 0.4373$
$B_1 = R_2/ (R_1 + R_2) = 0.498/ (0.387 + 0.498) = 0.5627$

The empirical relational equation can be rewritten as

**Log (SEP flux) = 0.4373 x {0.4453 x Log (flare peak intensity) + 4.0894)} +**
**0.5627 x {2.867 x Log (CME Linear speed) -6.9989)}**
**Log (SEP flux) = 0.1947 x Log (flare peak intensity) + 1.6133 x Log (CME Linear speed) – 2.1500**

Finally, normalization is to be done by matching the maximum and minimum values of the calculated SEP flux using this equation and those that are actually measured. This means the slope and offset are to be corrected by comparing the computed values and measured values. The final equation will be in the form of

**Log (SEP flux) = M x {0.1947 x Log (flare peak intensity) + 1.6133 x Log (CME Linear speed) – 2.1500}**
**+ C**

## V. Results

Based on the normalization process described in the previous chapter the components M and C are calculated to be

M = 0.5959 and C = 0.9158

Rewriting the equation once again using this M and C we get

**Log (SEP flux) = 0.5959 x {0.1947 x Log (flare peak intensity) + 1.6133 x Log (CME Linear speed) – 2.1500} + 0.9158**

The desired final empirical relation is

**Log (SEP flux) = 0.116{Log (flare peak intensity)} + 0.961{Log (CME linear speed)} + 0.596**

Using this formula, predictions are made for the proton flux of all the 68 SEP events. The predicted proton flux values are then compared with the actual measured values all the corresponding 68 SEP events. The comparison results in the form of a scattered plot with a linear fit superimposed are given in figure 3.

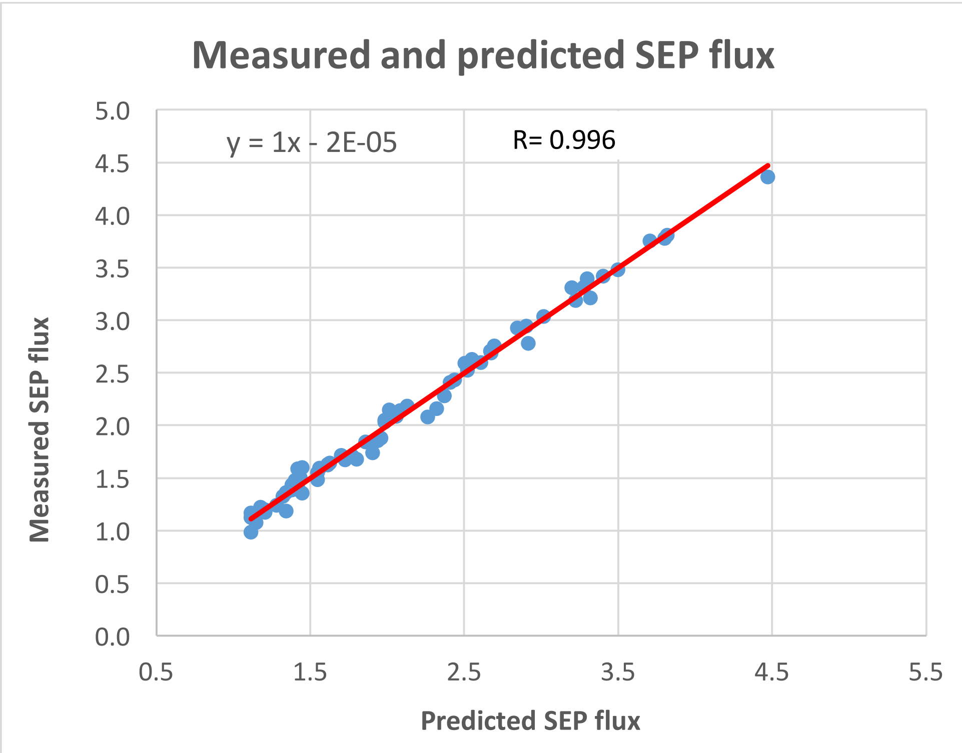


**Figure 3 Comparison of Measured and predicted flux for all predicted SEP events**

The results are extremely gratifying as can be seen from the chart with a linear relation of slope equal to 1 and offset equal to zero. The correlation between the two is also seen extremely high with a correlation factor of 0.996 almost near to unity.

## VI. Conclusion

The fact that the flares and CMEs greatly influence the SEP events led to this work for finding a simple empirical relation between them. The assumption that Halo and partial Halo CMEs are directed towards Earth and hence have to be associated with SEP events measured in geo-synchronous orbit near to Earth is proven by the fact that all associated CMEs are either Halo or Partial Halo. The linear speed of CMEs and the class of the flares are the two factors that are assumed to be having greater impact on the SEP flux. This is also proven by the effectiveness of the empirical relation derived. The aim of deriving a simple empirical relation between SEP proton flux, CME linear speed and flare class is accomplished successfully.


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