

# Ineffectiveness of Narrow CMEs for Cosmic Ray Modulation

Evangelos Paouris

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**Abstract** Monthly coronal mass ejection (CME) counts, – for all CMEs and CMEs with widths  $> 30^\circ$ , – and monthly averaged speeds for the events in these two groups were compared with both the monthly averaged cosmic ray intensity and the monthly sunspot number. The monthly  $P_1$ -index, which is a linear combination of monthly CME count rate and average speed, was also compared with the cosmic ray intensity and sunspot number. The main finding is that narrow CMEs, which were numerous during 2007–2009, are ineffective for modulation. A cross-correlation analysis, calculating both the Pearson ( $r$ ) product–moment correlation coefficient and the Spearman ( $\rho$ ) rank correlation coefficient, has been used. Between all CMEs and cosmic ray intensity we found correlation coefficients  $r = -0.49$  and  $\rho = -0.46$ , while between CMEs with widths  $> 30^\circ$  and cosmic ray intensity we found  $r = -0.75$  and  $\rho = -0.77$ , which implies a significant increase. Finally, the best expression for the  $P_1$ -index for the examined period was analyzed. The highly anticorrelated behavior among this CME index, the cosmic ray intensity ( $r = -0.84$  and  $\rho = -0.83$ ), and the sunspot number ( $r = +0.82$  and  $\rho = +0.89$ ) suggests that the first one is a very useful solar–heliospheric parameter for heliospheric and space weather models in general.

**Keywords** Coronal mass ejections · Solar cycle · Space weather · Cosmic ray modulation

## 1. Introduction

It is well known that coronal mass ejections (CMEs) are solar magnetized structures which are ejected from the solar upper atmosphere with velocities sometimes over  $2500 \text{ km s}^{-1}$ . CMEs drive interplanetary (IP) shocks (Sheeley *et al.*, 1985), and can consequently produce solar energetic particle (SEP) events. When a fast CME reaches Earth, it may produce a

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E. Paouris (✉)

Department of Astrophysics, Astronomy and Mechanics, Faculty of Physics, National and Kapodistrian University of Athens, Panepistimiopolis, Zografos, 15783 Athens, Greece  
e-mail: [evpaouris@phys.uoa.gr](mailto:evpaouris@phys.uoa.gr)

temporary disturbance in the Earth's magnetosphere, resulting in a magnetic storm. Generally, a connection between CMEs and space weather exists (see, *e.g.*, Allen *et al.*, 1989; Gosling, 1993; Brueckner *et al.*, 1998). These facts are of great interest, as the effects on satellites or space missions, communications, and electrical networks could be catastrophic. Thus, it is more important than ever to understand these phenomena. CMEs are also important for understanding the long-term solar interplanetary magnetic field evolution, as they remove significant amounts of magnetic flux along with material (see, *e.g.*, Low, 2001).

Forbush (1954, 1958) discovered that the cosmic ray intensity observed on Earth is inversely proportional to the sunspot number. Within the last decade, the importance of CMEs for cosmic ray modulation, as proposed by Newkirk, Hundhausen, and Pizzo (1981), has received major attention (Cane, 2000; Cliver and Ling, 2001; Lara *et al.*, 2005; Mavromichalaki, Paouris, and Karalidi, 2007; Paouris, 2007; Cliver, Richardson, and Ling, 2011).

In this paper we examine the effect of CME width on cosmic ray modulation for a sample of 15 508 CMEs. Their properties, such as the number of CMEs per month ( $N_c$ ), the mean linear speed ( $V_p$ ) per month, and the apparent angular width ( $w$ ), from January 1996 to October 2010 are studied. These properties are examined in order to find a reliable CME data set to work with and, then, to obtain the best expression for the CME index ( $P_i$ ) which can provide information for a whole solar cycle period. It is noticed that this index follows the behavior of the sunspot number very well, with a strong correlation, whereas it is in high anticorrelation with the cosmic ray (CR) intensity measured by neutron monitors. This fact again confirms the significant role of CMEs in cosmic ray modulation.

The anticorrelation between sunspot number and cosmic ray intensity (Forbush, 1954; Mavromichalaki, Paouris, and Karalidi, 2007) and the correlation between sunspot number and CME rate (Webb and Howard, 1994) are already well-known results. Previous works have considered the relationship between CMEs and cosmic ray intensity. Newkirk, Hundhausen, and Pizzo (1981) suggested that CMEs might be effective modulators, and both Cliver and Ling (2001) and Lara *et al.* (2005) investigated the relationship between CMEs and cosmic ray intensity. Cliver and Ling (2001) suggested that the anticorrelation between low-latitude open flux and cosmic ray intensity occurs because CMEs bring new flux to the interplanetary medium. Lara *et al.* (2005) suggested that all CME properties show some correlation with the galactic cosmic ray intensity, although there is no specific property (width, speed, or a proxy for energy) that definitely has a higher correlation with galactic cosmic ray intensity.

## 2. Data Collection

In this work, data from the *Large Angle and Spectrometric Coronagraph* (LASCO) on-board the *Solar and Heliospheric Observatory* (SOHO) were used. In particular, data for the CMEs were taken from the SOHO/LASCO CME catalog ([http://cdaw.gsfc.nasa.gov/CME\\_list/](http://cdaw.gsfc.nasa.gov/CME_list/)). A detailed description of this database can be found in Gopalswamy *et al.* (2009). As the SOHO database has large data gaps for July, August, and September 1998, and January 1999, a smoothing method was applied. Data for the monthly sunspot number are taken from the National Geophysical Data Center (<ftp://ftp.ngdc.noaa.gov/index.html>). Monthly values of cosmic ray intensity are obtained from the Moscow Neutron Monitor station (<http://www.nmdb.eu>). The solar wind velocity data are taken from the OMNI database (<http://omniweb.gsfc.nasa.gov/>).

### 3. CMEs and Their Angular Width

#### 3.1. Total Number of CMEs

There is a new perspective in this work: the use of the apparent angular width of CMEs as the main criterion. First, the total number of CMEs with widths from  $1^\circ$  up to  $360^\circ$  (halo CMEs) is determined. The cross-correlation values, Pearson's  $r$  and Spearman's  $\rho$ , between the number of CMEs ( $N_c$ ) and cosmic ray ( $CR$ ) intensity values from the Moscow Neutron Monitor station gave values of  $r = -0.49$  and  $\rho = -0.46$ ; between  $N_c$  and sunspot numbers ( $R_z$ ) they gave  $r = +0.59$  and  $\rho = +0.55$ .

Lara *et al.* (2005) showed that generally the anticorrelation between galactic cosmic ray intensity and CME rate was relatively high ( $-0.88$ ), for the period of January 1996–December 2003. This anticorrelation was also high ( $-0.78$ ) using data up to 2006 according to Mavromichalaki, Paouris, and Karalidi (2007). Using data for all the CMEs from January 1996 up to October 2010, we show that the correlation coefficients significantly changed ( $r = -0.49$  and  $\rho = -0.46$ ).

During our data analysis, we noticed that the number of narrow CMEs (with widths  $< 30^\circ$ ) formed a relatively large fraction of all CMEs during the low solar activity (sunspot number) years of 2007–2009. Thus, in this study, we decided that a further analysis should be made to separate the narrow CMEs from the data set.

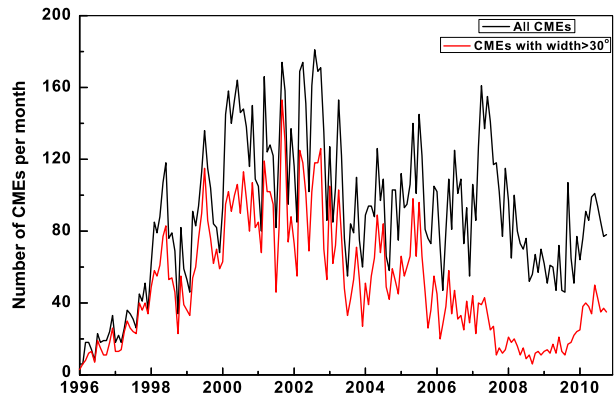
The mean linear speed ( $V_p$ ), which is the average speed of the CMEs per month, was also studied in relation to  $CR$  and  $R_z$ . We found values of  $r = -0.81$ ,  $\rho = -0.81$  and  $r = +0.72$ ,  $\rho = +0.81$ , respectively; these are very satisfactory correlation coefficients. Gopalswamy (2010) has also noticed that the average CME speed tracks the sunspot number.

#### 3.2. CMEs with Apparent Angular Width $> 30^\circ$

At this point CMEs with angular width  $> 30^\circ$  were considered, and the correlations between  $N_c$  and  $CR$ , and  $R_z$  were found to be  $r = -0.75$ ,  $\rho = -0.77$  and  $r = +0.85$ ,  $\rho = +0.89$ , respectively. These are the highest correlation values. These results suggest that narrow CMEs, which constitute the largest number of events (generally identified as “very poor events,” see Conclusions) during the years 2007–2009, are not effective for cosmic ray modulation; thus, we exclude them from our data set. CMEs with widths  $> 30^\circ$  include halo CMEs, whose importance for space weather has been well demonstrated. Many slow and narrow CMEs are spotted, especially in the descending phase of the solar cycle (Figure 1); as a result, the monthly number of CMEs,  $N_c$ , reaches higher values or stabilizes at higher values for the extraordinary solar minimum for the years 2007–2009. It seems possible that this increase in the number of narrow CMEs reflects a learning curve on the part of the catalog makers, makers, who, with time and experience were becoming more familiar with the narrow CMEs which are much more difficult to identify from the broader CMEs. Recently, researchers only trust CMEs with angular width greater than  $30^\circ$  because the manual detection of such events is highly subjective (Yashiro, Michalek, and Gopalswamy, 2008; Gopalswamy *et al.*, 2010).

We found that for  $> 30^\circ$  wide CMEs, the correlation coefficients for the mean linear speed ( $V_p$ ) and  $CR$  were  $r = -0.79$ ,  $\rho = -0.80$ , and for  $R_z$  they were  $r = +0.69$ ,  $\rho = +0.81$ , both slightly lower than those obtained for all CMEs. The correlation coefficients,  $r$  and  $\rho$ , between both categories, all CMEs and those with width  $> 30^\circ$ , and cosmic ray intensities and sunspot numbers are presented in Table 1. Table 1 clearly shows that the monthly number of CMEs – for all and for those with width  $> 30^\circ$  – is the most important

**Figure 1** Time profiles of the mean monthly number of CMEs using the total number of CMEs (black line) and those with angular width greater than  $30^\circ$  (red line) from the SOHO/LASCO CME catalog.



**Table 1** Pearson and Spearman cross-correlation coefficients,  $r$  and  $\rho$ .

Indices	Cosmic ray intensity ( $CR$ )		Sunspot number ( $R_z$ )	
	$(r)$	$(\rho)$	$(r)$	$(\rho)$
All CMEs (monthly counts)	-0.49	-0.46	+0.59	+0.55
CMEs with width $> 30^\circ$ (monthly counts)	-0.75	-0.77	+0.85	+0.89
Monthly averaged speed (all CMEs)	-0.81	-0.81	+0.72	+0.81
Monthly averaged speed (width $> 30^\circ$ )	-0.79	-0.80	+0.69	+0.81
$P_1$ -index (all CMEs)	-0.82	-0.82	+0.76	+0.84
$P_1$ -index (width $> 30^\circ$ )	-0.84	-0.83	+0.82	+0.89

factor as opposed to the mean linear speed, as the first shows a significant improvement while the second shows a small downturn, according to Pearson's correlation coefficient ( $r$ ).

In Figures 2 and 3 the scatter plots of each parameter,  $N_c$ ,  $V_p$ , and  $P_1$ -index, in relation to  $CR$  intensity and sunspot numbers  $R_z$ , respectively, are presented. The scatter plots of the left column are produced by the first data set (all CMEs), and those of the right column are produced by the second data set (width  $> 30^\circ$ ). The Pearson ( $r$ ) and Spearman ( $\rho$ ) correlation coefficients are also indicated.

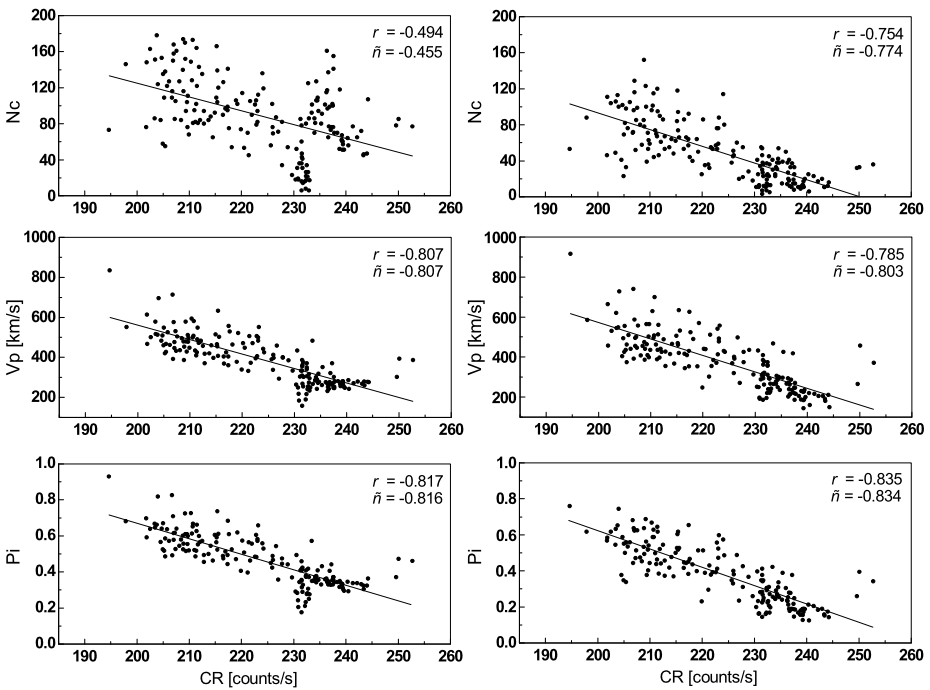
#### 4. The Expression for the $P_1$ -Index

In previous works (Paouris, 2007; Mavromichalaki, Paouris, and Karalidi, 2007) a CME index was defined using the empirical formula:

$$P_1 = \alpha \cdot N_c + \beta \cdot V_p, \quad (1)$$

where  $N_c$  is the monthly number of CMEs and  $V_p$  is the mean linear speed. For the  $\alpha$  and  $\beta$  factors we apply  $\alpha + \beta = 1$  and  $\alpha, \beta > 0$ . The factors  $\alpha$  and  $\beta$  are the values which give the best cross-correlation values between  $P_1$ -index and  $CR$  intensity. In this work we estimate the  $P_1$ -index using the previous data sets (all CMEs and CMEs with width  $> 30^\circ$ ) which were examined to find the best fit between  $P_1$ - $CR$  and  $P_1$ - $R_z$ . The new perspective in this work is the formation of this index using the formula:

$$P_1 = \alpha \cdot \frac{N_c}{N_{c_{\max}}} + \beta \cdot \frac{V_p}{V_{p_{\max}}}, \quad (2)$$



**Figure 2** Scatter plots between  $N_c$ ,  $V_p$ , and  $P_i$ -index in relation to the  $CR$  intensity, using data of all the CMEs (left column) and of the broader CMEs with width  $> 30^\circ$  (right column). The Pearson ( $r$ ) and Spearman ( $\rho$ ) correlation coefficients are also indicated.

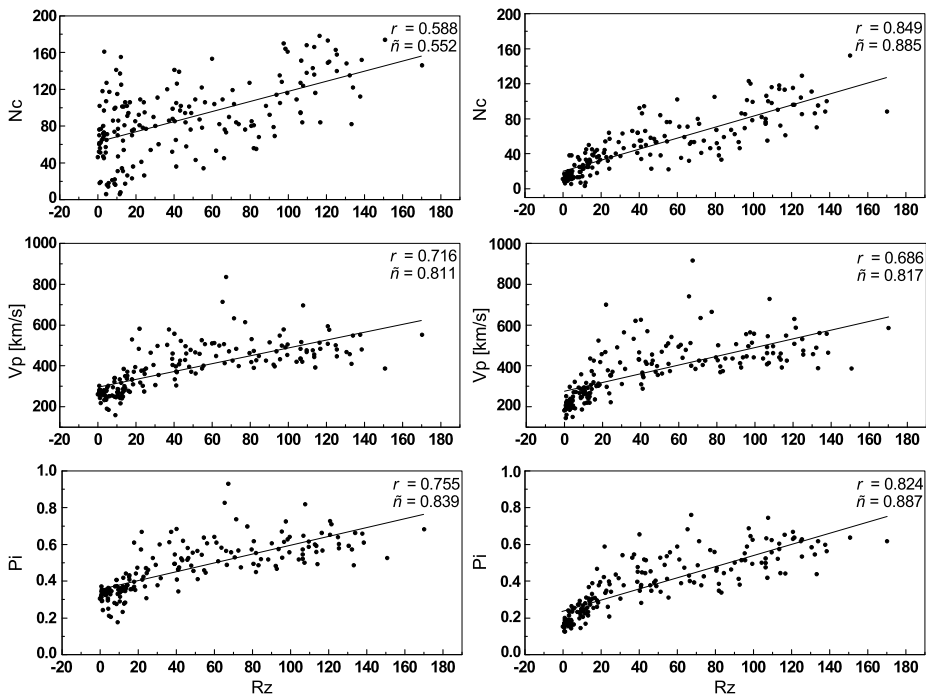
which makes this index dimensionless. Using the total number of CMEs the index was found to be:

$$P_i = 0.12 \cdot \frac{N_c}{N_{c_{max}}} + 0.88 \cdot \frac{V_p}{V_{p_{max}}}, \tag{3}$$

where  $N_{c_{max}} = 178$  and  $V_{p_{max}} = 834 \text{ km s}^{-1}$ . The correlation coefficients for  $P_i$ - $CR$  were  $r = -0.82$ , and  $\rho = -0.82$ , and for  $P_i$ - $R_z$  they were  $r = +0.76$ , and  $\rho = +0.84$ . Using CMEs with width  $> 30^\circ$ , the  $P_i$ -index is given by the expression:

$$P_i = 0.37 \cdot \frac{N_c}{N_{c_{max}}} + 0.63 \cdot \frac{V_p}{V_{p_{max}}}, \tag{4}$$

where  $N_{c_{max}} = 152$  and  $V_{p_{max}} = 915.6 \text{ km s}^{-1}$ . The correlation coefficient for  $P_i$ - $CR$  was  $r = -0.84$ , and  $\rho = -0.83$ , and for  $P_i$ - $R_z$  it was  $r = +0.82$ , and  $\rho = +0.89$ . The time profiles of the  $P_i$ -index calculated using Equation (4) with the  $CR$  values and  $R_z$  are presented in Figure 4. It is very interesting to see that the fluctuations of this index correspond to the  $CR$  variations and especially that the maximum of the CME index is exactly at the minimum of cosmic rays during October–November 2003, in opposition to  $CR$  and sunspot number. It is well known that the 11-year modulation of the cosmic ray intensity shows a time lag behind sunspot number; this is a kind of hysteresis effect which is different for even or odd solar cycles (Hatton, 1980; Nagashima and Morishita, 1980; Mavromichalaki, Paouris, and Karalidi, 2007; Paouris *et al.*, 2012). For the examined data sets there is no time lag between the  $P_i$ -index and  $CR$  intensity, but according to Paouris *et al.* (2012), between  $CR$  and  $R_z$  a time lag of  $13.6 \pm 0.04$  months is observed.



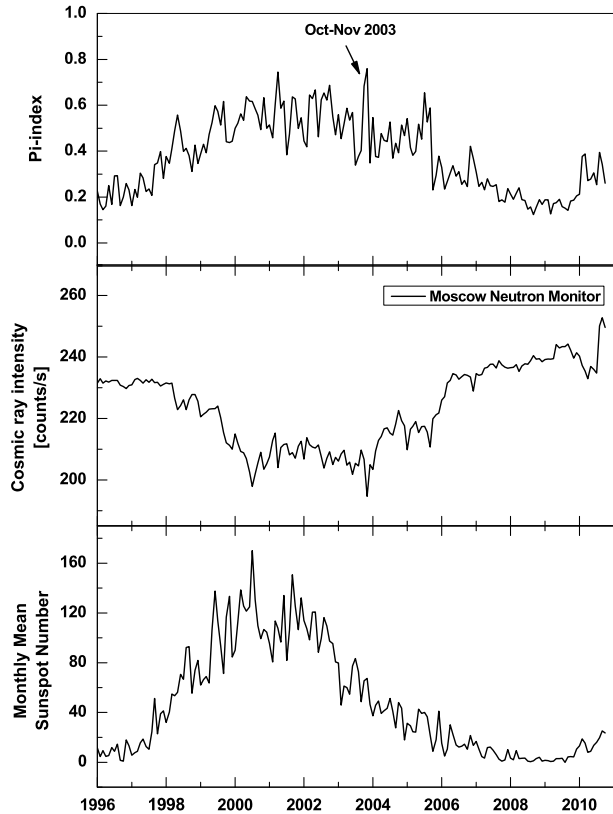
**Figure 3** Scatter plots between  $N_c$ ,  $V_p$ , and  $P_1$ -index in relation to the sunspot numbers  $R_z$ , using data of all the CMEs (left column) and of the broader CMEs with width  $> 30^\circ$  (right column). The Pearson ( $r$ ) and Spearman ( $\rho$ ) correlation coefficients are also indicated.

The correlation coefficients ( $r$  and  $\rho$ ) for the  $P_1$ -index using all CMEs and those with width  $> 30^\circ$  in relation to cosmic ray intensities and sunspot numbers are presented in Table 1.

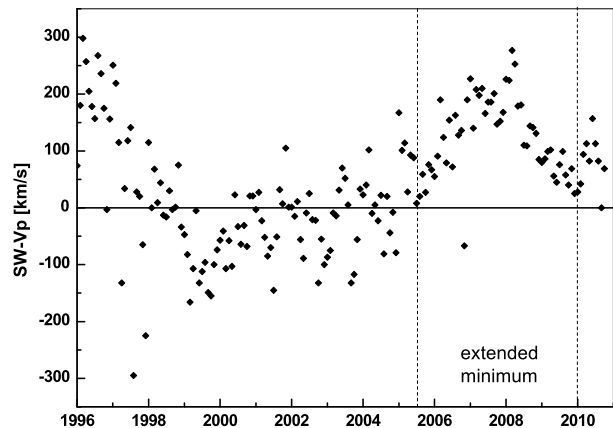
## 5. Conclusions

In this paper CME data sets were examined in relation to cosmic ray intensity values and sunspot numbers. We conclude that when cosmic ray intensity is compared to the monthly CME number ( $N_c$ ), narrow CMEs appear to be relatively ineffective modulators. The best correlation coefficients were found using CMEs with apparent angular width  $> 30^\circ$ . The correlation coefficients from linear fitting between cosmic rays and  $P_1$ -index from Equation (4) are highly anticorrelated and are found to be  $r = -0.84$  and  $\rho = -0.83$ . This is a very important result for short and/or long-term cosmic ray modulation studies or space weather studies in general, as this index is strongly connected to extreme events and not only to the overall solar activity as the sunspot number is. Cliver, Richardson, and Ling (2011) proposed that the main cause of cosmic ray modulation is the rise and fall of the amount of magnetic field transported to the heliosphere by CMEs over the solar cycle. The results of our work support this assumption, as the  $P_1$ -index is highly anticorrelated with the CR values. A very strong connection between this index and the sunspot numbers is also indicated by the high correlation coefficients,  $r = +0.82$  and  $\rho = +0.89$ . It is clear from Figure 1 that the monthly number of CMEs using the total number of CMEs in the catalog is much higher

**Figure 4** Time profiles of the CME  $P_1$ -index (upper panel), of the cosmic ray intensity from the Moscow Neutron Monitor Station (middle panel), and of the sunspot number (lower panel). The maximum of the CME index in the period October–November 2003 is also indicated.



**Figure 5** Time profiles of the variation of the difference between the mean monthly solar wind velocity and the mean monthly velocity of narrow CMEs ( $SW - V_p$ ). The extended solar minimum is also indicated.



than the monthly number of CMEs with width  $> 30^\circ$ , especially after 2005. These narrow CMEs (with width  $< 30^\circ$ ) are generally slow (very poor events), even slower than the mean monthly solar wind speed. As a result, they are not connected to space weather effects, as they possibly disperse in the interplanetary space before reaching Earth.

In Figure 5 we observe the variation between the mean monthly solar wind velocity and the mean monthly velocity of narrow CMEs. Each point corresponds to the result of the subtraction between the mean monthly solar wind velocity and the mean monthly velocity  $V_p$  of narrow CMEs. It is obvious that in the period of solar maximum the difference  $SW - V_p$  is negative; as a result, only a fraction of these narrow CMEs can reach Earth before dispersing. The opposite is obvious in the period of the extended solar minimum, especially after 2005. From Figure 1 the monthly number of CMEs clearly gives greater values than monthly numbers using CMEs with width  $> 30^\circ$ , without strong connection with space weather effects. This must be considered in order to calculate CME occurrence rates, and it is something that will be investigated in future work with CMEs properties in general.

While there is a significant increase in the correlations between the count rates of all CMEs and those with widths  $> 30^\circ$ , the difference in the correlations for the average speeds of the two groups is small and in the opposite direction; *i.e.*, considering only the CMEs with width  $> 30^\circ$  reduces the Pearson correlation coefficient. From the values of  $\alpha$ ,  $\beta$  in Equations (3) and (4) it is evident that the term  $V_p/V_{p_{\max}}$  contributes almost overwhelmingly (Equation (3)) or is dominant (Equation (4)) in determining the  $P_1$ -index values, which might suggest that the speed is the dominant parameter for modulation. In a future work the  $P_1$ -index will be investigated considering other parameters, such as the average magnetic field which was carried by CMEs in combination with the monthly CME number and their speed.

Our results indicate that narrow CMEs may have a different physical nature than broader CMEs. The model of Chen and Shibata (2000) is quite different from the standard CSHKP (Carmichael, 1964; Sturrock, 1966; Hirayama, 1974; Kopp and Pneuman, 1976) picture of an expanding magnetic bubble. A Chen and Shibata CME type might be expected to be narrower and more porous for cosmic rays, as it will have to propagate exclusively along the pre-existing heliospheric magnetic field lines and hence will not cause a major magnetospheric disturbance, and this is consistent with our results. Moreover, but equally important, they may well miss geospace as they are narrow and typically observed beyond the limb, as it is hard to detect such narrow CMEs against the disk.

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