A new statistical index (P_i) for coronal mass ejections

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Abstract – **In this work we are trying to understand statistically the coronal mass ejections through time and improving the previous P_i–index which is a monthly parameter, defined in this work, from the equation: $P_i = 0.68N_c + 0.32V_p{}^2$ where Nc is the total number of CMEs per month and Vp^2 is the square of mean plasma velocity of CMEs per month. As we know solar flares or CMEs are events related with magnetospheric events on Earth's atmosphere. The fluctuations of P_i index, for the years 1996-2007, seems to be strongly related with the fluctuations of cosmic rays intensity, especially in periods of violent phenomena. This index is very interesting as can explain the high solar activity even when the sunspot number is almost in the minimum, in the declining phase of the 11 year solar cycle, as it is happens in the very peculiar 23rd solar cycle with a lot of extreme events.**

***Key Words*—Coronal mass ejections (CMEs), Sunspot number, Cosmic rays, Solar activity.**

I. Introduction

A lot of physical phenomena are related with the solar activity such as solar flares, coronal mass ejections (CMEs) or prominences. For many years there has been debate on whether a solar flare causes a CME or vice versa. After a lot of observations and theoretical models, it is now clearer that neither flares nor CMEs cause the other, but that they are caused by changes driven by the same magnetic activity [1]. Flares also often occur in association with CMEs but they are not necessary and are certainly not the instigator of mass ejection, see [2], as has been sometimes assumed. Flares are believed to be generated by the heating resulting from reconnection of field lines blown open by the CME. Flares and prominence eruptions are different phenomena but often occur simultaneously [3].

High flow speeds and strong magnetic fields, often with strong southward components, are particularly found in interplanetary disturbances driven by fast coronal mass ejections. Thus, the most important link between solar activity and large, non–recurrent geomagnetic storms are CMEs [4]. CMEs are spectacular manifestations of solar activity in which 10^{12} – 10^{13} kg of solar material are suddenly propelled outward into interplanetary space [5], [6] and [3]. A vast magnetic bubble of plasma erupts from the solar corona and travels through the interplanetary space at a speed often well above that of the ambient solar wind [7], with speeds ranging from only a few km/sec to nearly 3000 km/sec. When these energetic solar particles reach the Earth's magnetosphere we have as a result geomagnetic storms, generally CMEs are related to very strong, short-lived Forbush decreases [8] of cosmic-ray intensity at Earth. Reference [9] was among the first to suggest that CMEs might play a role in long-term modulation of cosmic rays [10].

In this work we suppose that CMEs are the most important effect of solar activity and as a result our improved index P_i can gives us more information for the solar activity for the 11-year solar cycle, in opposition with the sunspot number, even when we are in the minimum of the cycle, which is the minimum of sunspot number. As a result for our index we are using only two parameters: the total number of CMEs per month and the square of mean plasma velocity also per month, as a meter for their energy, kinetic energy, as a CME travels from Sun to Earth and sometimes causing catastrophic results.

II. DATA ANALYSIS – THE FORMATION OF THE PI-INDEX

The data for coronal mass ejections are increasing rapidly as now we are using the observing power of three spacecrafts: SOHO, TRACE and Yohkoh. In this work we are using data from Solar and Heliospheric Observatory coronagraphs (SOHO/LASCO) studying the period 1996-2007. So, we can have access in very detailed data for a coronal mass ejection such as the central position angle measured from Solar North in degrees (counter-clockwise), linear speed in km/sec, 2nd-order speed at final height or at 20 R_{SUN} (km/sec), acceleration (km/sec^2) and other measurements. In this work we are using only the number of CMEs per month and their mean linear speed (km/sec), per month, but we should mention that there are no data for CMEs for the months of July, August, and September of 1998 and January of 1999. We introduced the P_i index in a previous work [11] as a relation of two factors, the total number of CMEs (*Nc*) and their mean plasma velocity (*Vp*) per month. It is well known that the rate of CMEs varies and the reason is that it is strongly related with the minimum or maximum of solar activity. The rate of CMEs using pre-SOHO observations has been summarized by [12]. They found a rate of about 0.25 CME/day at solar minimum rising to about 2.5-3 CMEs/day at solar maximum. Furthermore the [13] study obtained a CME rate of 0.7 CMEs/day during three months in early 1997 using LASCO data. It was about a factor of 3 higher than the [12] solar minimum rate. This was because of the increased sensitivity of LASCO compared to previous coronagraphs [3]. The second factor in our relation it was the mean plasma velocity as a meter of their kinetic energy. According to [14] another CME attribute linked with solar activity is the mean speed, which doubled from minimum to maximum. In *Figure 1* we can see the CMEs number per month and the mean linear speed.

The empirical relation of the index was:

$$P_i = 0.65N_c + 0.35V_p \qquad (1)$$

where the Nc is the total number of CMEs and Vp is the mean plasma velocity, per month. The numbers 0.65 and 0.35 are the values as they occur for the best correlation coefficients between the index and the sunspot number and the cosmic-ray intensity [11]. In *Figure 2* we can see the P_i values in relation with the sunspot number, using monthly sunspot numbers from NGDC/NOAA and the normalized cosmic-ray intensity, using data from Oulu Neutron Monitor Station with cut-off rigidity 0.81GV, for the period 1996-2007. The pressure-corrected data for Oulu NM Station were normalized with the intensity taken equal to 1.00 at cosmic-ray intensity maximum at August 1997 and equal to 0.00 at cosmic-ray minimum at October 2003.

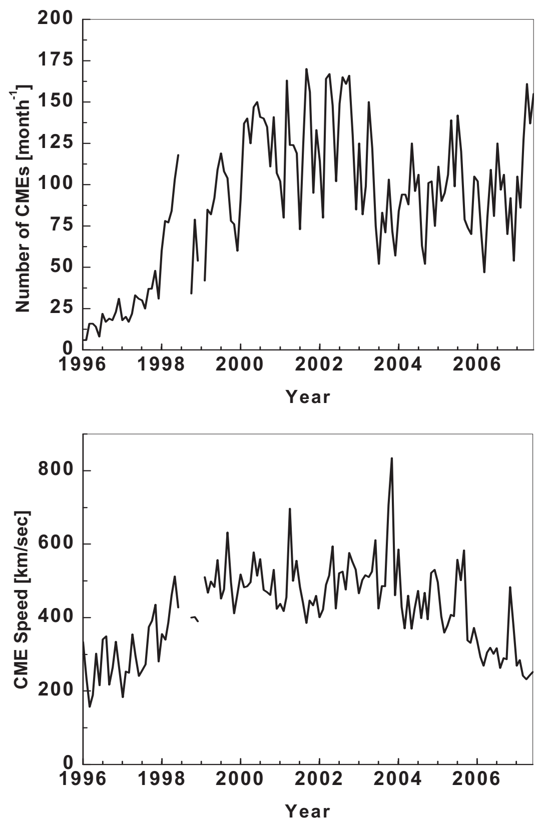

Fig. 1. The number of CMEs per month (up) and the mean linear speed (down). It is characteristic that for the period October-November 2003 we had a CME rate of 2.35-3.35 CMEs per day but in the same time we had extreme events which gave us the maximum for the speed and also for the P_i–index.

It is obvious that P_i shows a same behavior with the sunspot number and the most important result from this figure is that the fluctuations of the P_i–index are corresponding with the fluctuations of the cosmic-ray intensity, which is a strongly proof of the dependence of the cosmic-ray intensity by the solar activity as it is expresses through the P_i–index. Furthermore the study of the P_i–index in relation with the cosmic-ray intensity shows a very high cross correlation coefficient r = –0.82, when in the same time the cross correlation coefficient for the sunspot number in relation with the cosmic-ray intensity is r = –0.87 and for the number of CMEs per month Nc is r = –0.78 [15] which is also another fact for the reliability of the P_i–index.

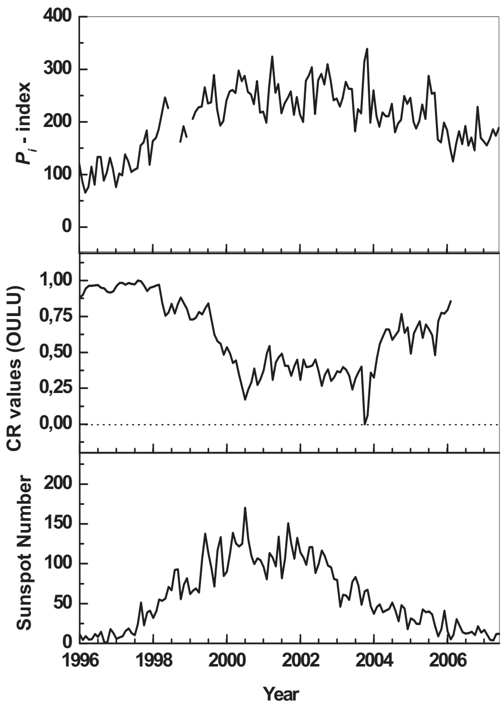

Fig. 2. P_i–index, normalized cosmic-ray values and sunspot number for 1996-2007. The minimum of the cosmic ray intensity –October-November 2003– it is obvious that occurs in the same time with the maximum of the P_i–index, when the sunspot number is in low values and could not justify this very violent period.

III. The improved CME-index – Results

CMEs are now understood as large-scale magnetized plasma structures originating from closed magnetic field regions on the Sun: active regions, filament regions, active region complexes and trans-equatorial interconnecting regions [14]. As a result, continuing the previous work on this index, we want a relation between the energy of the magnetic fields on the active regions and plasmas in Sun's atmosphere. We suppose that when a CME erupts, the magnetic field energy of the active regions is changing to kinetic energy of the plasma, with a velocity which is the Alfvén speed, by the equation:

$$\frac{B^2}{8\pi} = \frac{1}{2}\rho V^2 \Rightarrow V^2 = V_A^2 = \frac{B^2}{4\pi\rho} \qquad (2)$$

From this equation it is obvious that the most important characteristic of the CME as a meter of their energy is the square of the velocity and not the first power of the linear speed. According to this result we have the new relation:

$$P_i = 0.68N_c + 0.32V_p^{\;2} \qquad (3)$$

and the results are much more better especially in periods of extra violent phenomena. The factors 0.68 for the number of CMEs per month and 0.32 for the mean plasma velocity are different from the previous factors (Eq. 1). These factors occur from the best cross correlation coefficients of the P_i–index in relation with the sunspot number and cosmic-ray intensity. Especially the cross correlation coefficient for P_i (using Eq. 3) in relation with sunspot number is r = 0.68 and the correlation coefficient factor between P_i and cosmic-ray intensity is r = –0.83, which are the best values. In *Figure 3* we can see the new values of linear speed in square: Vp^2 and P_i–index. To make this plot we divide the Vp^2 by a factor of 10^3 to take results to the same area from 0 to 400 as it was the previous index. As we said before P_i is a statistical index which help us to understand better the solar activity in opposition with the sunspot number which is now in the minimum for the current solar cycle and could not give us details for very violent periods with CMEs which can produce geomagnetic storms.

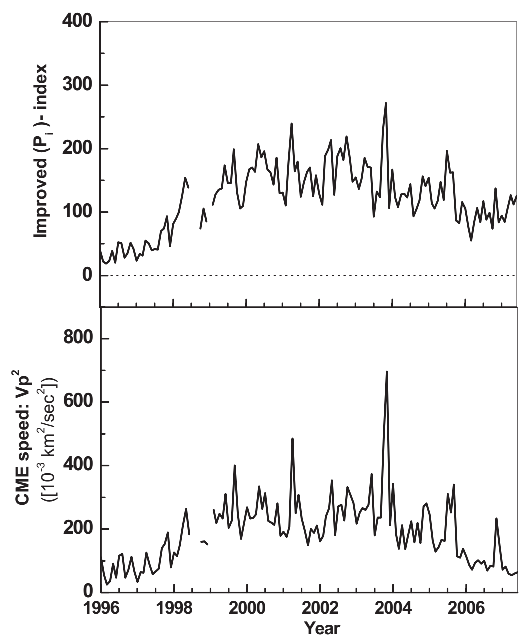

Fig. 3. The improved P_i–index with the square of the CME speed. This graph shows the importance of the CME index. The violent periods like April 2001, October-November 2003, July and September 2005 or November 2006 are easily spotted in opposition with the sunspot number which is in the declining phase (2003-2007).

It is very characteristic the maximum of the P_i–index in the period of October-November of 2003 when the sunspot number is in the declining phase and as a result we do not have the high values for the sunspot number as it is happens in the period 1999-2001. So, if we take in count only the sunspot number as a meter for the solar activity we haven't any further information for violent phenomena. Some periods which are known for the extra violent activity of the Sun such as April 2001, October-November 2003, July and September 2005 or November 2006 are difficult to explain with the sunspot number curve, but with the CMEs-index these periods are spotted easily because these events are strongly related with the solar activity and especially with the violent activity.

IV. Conclusions

Previous works [14] showed that CME speed, kinetic energy, seems to be an important parameter characterizing extreme events and if we take in count the fact that the free energy available from the Sun depends on the size of the active region magnetic field we made a very good approach for the improved P_i–index starting our project from the equilibrium of the magnetic field energy with the kinetic energy (Eq. 2). As a result we have the new index using the square of the CME speed and we have better results (Fig. 3) as we can notice now ascending, maximum and descending phases for the index for the years 1996-2007, which is the period of 23rd solar cycle. The 23rd solar cycle is a very peculiar cycle with activity also in the minimum of the cycle. This fact imposes the use of an index with information for the solar activity for the whole cycle and not only for the period of the maximum. The P_i-index could give us information for the whole cycle and especially in periods of extreme activity like October-November 2003.

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b) The Oulu Neutron Monitor research team for easy access in the cosmic ray data from: *http://cosmicrays.oulu.fi*, and

c) The National Geophysical Data Center (of NOAA) for sunspot number data from: ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA.

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