SCIENTIFIC DISCUSSION ON THE RELATIONSHIP BETWEEN THE SOLAR WIND SPEED AND THE GEOMAGNETIC ACTIVITY

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INTRODUCTION

A paper by myself, accepted for publication in November 2001 and printed in September 2002 [Ballatore, P., Effects of fast and slow solar wind on the correlation between interplanetary medium and geomagnetic activity, *Journ. Geophys. Res.*, 107(A9), 1227, 2002; paper B02], has received particular attention from the scientific community. Many people were very positively impressed by the original and innovative results and sent messages of congratulations. Few people have interpreted the results in the wrong sense that the fastest solar wind does not importantly affect the terrestrial system. The key for the correct interpretation is to give attention to the fact that my results highlight that linear (or with a relatively weak departure from linearity) transfer functions between the interplanetary and the geomagnetic system are efficient until a certain level of solar wind speed, being non linear factors dominant during the fastest solar wind. In any case, possibly due to some typing errors which might have made the paper more difficult to be understood, the scientists Wang and Chao (who wrote many good papers on space physics subjects) from the space physics community of Taiwan and China wanted to publish their attempt to demonstrating that my results were not based on correct calculations. However they claim to contradict paper B02 because of differences in the correlation coefficients of the order of 0.01, evidently not relevant. In addition, they use a statistical test that is indented for contradicting the smaller statistical significance of interplanetary-geomagnetic correlations during the fastest solar wind speeds, as reported in B02. Actually, it can be demonstrated that their test is wrongly applied and its proper use indicates the correctness of B02 data analysis and deductions.

A very interesting result is that Wang and Chao show some new calculations (not considered in the paper B02) suggesting a clear scientific innovative result: the relationship between the Dst index derivative and the interplanetary space is definitely less linear that the Dst index itself. They could not recognize this important finding of their. The only reason for which they showed those data was to contradicting B02: they suggest that it was better to use the time derivative of Dst instead of Dst itself in B02 because the time derivative of Dst would better correlate (linearly) with the interplanetary parameters. This is very clearly contrary to their Figures 1 and 4.

The Editor of the Journal of Geophysical Research-Space Physics, Dr. L.C. Lee (Taiwan), who published the Comment by Wang and Chao on my B02 paper, allowed me to submit a Reply. My observations above are detailed in this Reply, which has been accepted by the referees for publication in June 2003.

This ISTI/CNR Internal Report contains my Reply (Section I), the Comment by Wang and Chao (Section II) and my original B02 paper (Section III).

SECTION I

Reply to 'Comment on Effects of fast and slow solar wind on the correlations between interplanetary medium and geomagnetic activity' by C.B. Wang and J.K. Chao

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Abstract. The paper B02 (the paper commented) shows that the statistical significance of the correlations between the interplanetary parameters and the geomagnetic indices (*Kp* or *Dst*) is, generally, less significant during the fastest solar wind. On the other hand, at these fast solar wind periods, the significance of the *Kp vs. Dst* correlation is equal to or higher than during slower solar wind. These results, together with further observations related to substorm periods and with previously published findings, are interpreted in terms of a difference in the interplanetary-magnetospheric coupling for solar wind faster or slower than a certain threshold (identified between about 500 and 600 km/s). Specifically, it is suggested that a possible linear approximation of the geomagnetic-interplanetary coupling is more appropriate during solar wind speed (Vsw) slower than this threshold, being non linear processes more dominant during the fastest speeds. This Reply highlights that the correlation coefficients shown by Wang and Chao are in agreement with these findings. In addition, Wang and Chao show that the statistical significance of the difference between the correlation coefficients for $Vsw \geq 550$ km/s and those for $Vsw < 550$ km/s would indicate that the interplanetary-geomagnetic correlations during the fastest speeds are not significantly different from those at slower Vsw ranges. Here we give evidence of the fact that, according to the common definition of this parameter, the calculation of the significance of the difference between two correlation coefficients made by Wang and Chao is wrong. Moreover, Wang and Chao re-calculate the correlations between the interplanetary parameters and the ΔDst, instead of *Dst*, in fact they note that the time derivative of this index (not the index itself) is driven by the interplanetary medium. Here we note that, on the contrary, they show that the correlation coefficients between interplanetary parameters and *Dst* are larger than those obtained using *ΔDst* and we suggest a possible interpretation in terms of non-linearity.

1. Introduction

The comments by Wang and Chao about the paper B02 (Ballatore, 2002) are based on a re-calculation of correlation coefficients and a statistical test indicating the significance of the difference between the correlation coefficient for $Vsw \geq 550$ km/s and the correlation coefficients obtained for *Vsw* ranges of slower speeds. From their work, Wang and Chao conclude that they cannot obtain the same results presented in B02 and that the interplanetary-geomagnetic correlations during the fastest *Vsw* are not significantly different from those at whatever other *Vsw* range. On the contrary, the correlation coefficients that they show are in good agreement with those reported in B02, regardless the different data analysis routines and the different data point numbers. In fact, the statistical significances (see following paragraph) of their interplanetary-geomagnetic correlations are the smallest for $Vsw \geq 550$ km/s, with a different *Vsw* trend compared with the correlations *Kp vs. Dst.* Moreover, regarding Wang and Chao's statistical test, it is evident (from the equation Eq. 3 in the following) that the values shown in the Comment are not the significances of the differences between correlations for $Vsw \geq 550$ km/s and those at slower *Vsw* (Press et al., 1992; and references therein). This is clear at first look because of the crucial importance of the data point numbers in Eq. 3 in the following and not in the Comment's results.

One more observation by Wang and Chao is that it is better to consider *ΔDst,* instead of *Dst* (as in B02), for the linear interplanetary-geomagnetic correlations, since that is the *ΔDst* (not *Dst*) which is driven by the interplanetary medium. On the contrary, the total all-data correlation coefficients shown in their Figure 4 (horizontal solid lines) are smaller than the corresponding ones in their Figure 1 (horizontal dashed lines). More about this is reported in the following paragraph 2.2.

Regarding minor differences between data points and correlation coefficients in B02 and in the Comment, it is worth noting that these kinds of differences may occur in different data analyses. In any case, here it is not of interest to discuss which is the best number of data points (or coefficient) because these minor differences are not driving significantly different results. For example, in Figure 1 by Wang and Chao, for the *Dst vs. VswBs* correlation at *Vsw*=[450, 550) km/s (the square parenthesis means the inclusion of the extreme and the round parenthesis means the exclusion of the extreme), they have a coefficient about 0.59 with 2011 data points; in B02 the corresponding coefficient is about 0.62 with 2045 data points. As verified in details, the reason for this is that Wang and Chao have not considered data with B_Z=0.0 nT, while in B02 these data were included with *Bs*=0. nT (*VswBs*=0).

2. Statistical significance of correlations among interplanetary parameters and geomagnetic indices

2.1 Significance of linear correlations and significance of their difference

The statistical significance of the correlation coefficient *R* is indicated by the probability (*PROB*) that correlation coefficients equal to or higher than *R* can be obtained for uncorrelated variables. Smaller *PROB* corresponds to better correlations, in fact commonly the statistical significance, or the statistical confidence level, is defined by *(1-PROB)*. It is easy to verify that between two equal correlation coefficients, it is more significant that corresponding to larger *N*. This can be done by using the subroutine 'PEARSN' in Numerical Recipes (Press et al., 1992: paragraph 13.7) or just looking at the approximation of *PROB* in case of large *N*

$$PROB = erfc(\frac{|R| \cdot \sqrt{N}}{\sqrt{2)}}) \qquad [1]$$

where *erfc* is the complementary error function (Eq. 6.2.8 in Numerical Recipes)

$$erfc(x) = \frac{2}{\sqrt{\pi}} \int_x^\infty e^{-t^2} dt \qquad [2]$$

For larger *N*, the argument of the complementary error function in Eq. 1 is larger and the function is smaller. Therefore, it is evident that results about the statistical significance of the correlation coefficients by Wang and Chao are in agreement with considerations in B02.

The parameter used by Wang and Chao to show that the statistical significance for *Vsw* ≥ 550 km/s is not different from that at other *Vsw* ranges is named in the Comment paper 'significance of the difference between two correlations'. They don't give its equation and refer to Numerical Recipes. According to this reference (paragraph 13.7), the definition of the significance of the difference between two correlations:

$$PROB1 = erfc(\frac{|z1 - z2|}{\sqrt{2}\sqrt{\frac{1}{N1-3} + \frac{1}{N2-3}}}) \qquad [3]$$

Where z1 and z2 are the Fisher's z for the two correlations (returned by the same PEARSN subroutine)

$$z = 0.5 \cdot \ln(\frac{1+R}{1-R}) \qquad [4]$$

Where R is the coefficient of the specific correlation. Under certain hypothesis about the distributions of the variables for which the correlation is computed, *PROB1* indicates the statistical level at which a coefficient *R1* differs from another one *R2*. For two correlations having fixed *N1* and *N2* data points, the argument of *erfc* in Eq. 3 is larger for larger difference between *z1* and *z2*, so that smaller *PROB1* corresponds to larger difference between two correlations. *PROB1* has to be applied with several cautions, which are detailed in Numerical Recipes and references therein.

In any case, in the results by Wang and Chao, it is evident at first look that they do not show the significance of the difference between each correlation and the corresponding correlation for $Vsw \geq 550$ km/s. For example, in Figure 1 for the case of *Kp vs. Em*, they have that the significance of the difference between the correlations for $Vsw < 350$ km/s and $Vsw \geq 550$ km/s is 0.50 and that between the correlations for *Vsw* =[350, 450) km/s and $Vsw \geq 550$ km/s is 0.51. This does not correspond to Eq. 3. In fact, being *N2* (1245) the data points for $Vsw \geq 550$ km/s, we have *N1*=14111 in one case and *N1*=4032 in the other case, giving significantly different complementary errors (see Eq. 2 and 3). Simply recalculating the three values of the significance of the difference for the case *Kp vs. Em* in Figure 1 (the four Wang and Chao's coefficients are read/approximated, respectively, as 0.64, 0.67, 0.64 and 0.61), Eq. 3 gives: $9.61 \cdot 10^{-2}$, $5.257 \cdot 10^{-4}$, 0.129 for *Vsw*, respectively, in the ranges < 350 km/s, [350, 450) km/s, [450, 550) km/s. This is in agreement with scientific discussion and observations in B02 and not with the comments by Wang and Chao.

In all the other panels in Figure 1 and 3, the significance of the differences between the correlations considered are similar to the three given above. Specifically, the correlation which is less significantly different from that at $Vsw \geq 550$ km/s is that for *Vsw* =[450, 550) km/s. This can be noted also qualitatively looking at the number of data points and at the coefficients in each *Vsw* sub-set.

The different *Vsw* trend between the correlation coefficients in Figure 1 and Figure 2 of the Comment is, again, in agreement with B02 paper. In particular, note the important difference between correlation coefficients in Figure 1 and 2 for *Vsw* < 350 km/s.

2.2 On the use of ΔDst instead of Dst

Differently from Wang and Chao's expectations, the global correlations of interplanetary parameters with *Dst* (Figure 1 of the Comment, dashed lines) are larger than those with *ΔDst** (Figure 4 of the Comment, solid horizontal lines). In the case of *Em*, these results are in agreement with previous findings showing that the best fits between Q and *Em* and between τ and *Em* are not-linear functions (Ballatore and Gonzalez, 2002). Similarly, non-linearity may affect the *VswBs* vs. *ΔDst** correlations. In fact, although the best fit between Q and *VswBs* is linear, the one between τ and *VswBs* is found to be a non linear function (O'Brien and McPherron, 2000). In any case, non linearity is also affecting the correlations related to *Dst* itself, but the total linear correlations in Figure 1 are higher than those in Figure 4 for the same intervals of all *ΔDst**. Therefore, the experimental results reported in the Comment paper would show that the interplanetary parameters drive more linearly *Dst* itself than *ΔDst**.

In agreement with Wang and Chao's observations, the intervals with *ΔDst** < 0 are periods when the ring current injection (Q) is dominant compared with the ring current decay. We recall that Q is generally approximated to be zero during northward IMF and for $|VswBs| < 0.49$ mV/m (O'Brien and McPherron, 2000; and references therein). Although relatively weak ring current injection may be observed, at times, during positive *IMF Bz* (Ballatore and Gonzalez, 2002), periods of *ΔDst** < 0 are above all periods of southward *IMF*. On the other hand, the occurrence of closer interplanetary-geomagnetic relationship during southward than during northward *IMF* (or during larger interplanetary-geomagnetic reconnection processes) is well-known. Therefore it is not surprising that for negative *ΔDst** the correlation coefficients between *ΔDst** and *Em* or between *ΔDst** and ε are slightly larger than those reported in Figure 1, which are calculated for all the data, independently of *ΔDst** and *IMF* orientation. For only southward IMF intervals, Wang and Chao show that the total correlation coefficient of *VswBs* with *Dst* (bottom middle panel in Figure 1) is about 0.68 and it is equal (again about 0.68) with *ΔDst** < 0 in Figure 4 (dot-dashed horizontal line in middle panel), when fewer data with larger ring current injection are considered. In this case, the total correlation coefficient in Figure 1 might have been expected to be smaller.

In summary, the direct comparison between results obtained for *Dst* and *ΔDst** can be done only when the same intervals are considered in both cases. Therefore, the Figure 1 and 4 by Wang and Chao can be compared only in their total correlations (for all *ΔDst**), which are higher for *Dst* than for *ΔDst**. Specifically, the fact that possibly larger correlation coefficients are found considering only periods of $\Delta Dst^* < 0$ cannot be interpreted in the sense that this *ΔDst** is a better indicator of the interplanetary parameters than *Dst* is.

2.3 On the global correlations

In order to contradict that the correlations for $Vsw < 450$ km/s are equal to or slightly better than the global correlations, Wang and Chao should calculate the correlations for the whole range $Vsw < 450$ km/s, grouping together the three separate bins considered for these speeds.

Regarding the comparison between global interplanetary-*Kp* correlations in B02 and in Figure 1 of the Comment (horizontal dashed lines in the three top panels), we note that the maximum difference is about 0.02. About the comparison between the global interplanetary-*Dst* correlations in B02 and in Figure 1 of the Comment (horizontal dashed lines in the three bottom panels), we note: (1) for *Dst vs. Em* the coefficient in the Comment is about 0.04 larger than in B02; (2) for *Dst vs. VswBs* the coefficient in the Comment is about 0.08 larger than in B02; (3) for the case *Dst vs.* ε, the correlation coefficients are both about 0.55 in B02 and in the Comment. Specifically, in case (2) for *VswBs*, Wang and Chao calculate a coefficient about 0.68 in Figure 1 and about 0.51 in Figure 4 (solid horizontal line), related to the use of *ΔDst** instead of *Dst* for the same intervals. Eventually, this relatively large difference (about 0.17) might have been affected, in part, by possible computational errors.

2.4 Differences in some of the correlation coefficients given in B02 and in the Comment

Few differences between correlation coefficients by Wang and Chao and those reported in B02 appear at times. For example, the results shown in the top panels of Figure 3 of the Comment are in agreement with those reported in the top panels in Figure 5 of B02, except for the coefficient of the correlation *Kp vs.* ε for *Vsw* $\geq$ 550 km/s: this is about 0.08 higher than in B02. In particular, this coefficient is also about 0.03 higher than the coefficient in the same panel of Figure 3 of the Comment for *Vsw* =[450, 550) km/s, suggesting to Wang and Chao that this 'is contrary to the results in B02'. First of all it is important that the reader realises that the differences of correlation coefficients discussed here are of the order of 0.01, which is not common in these kinds of linear correlation studies. Secondly, it can be worth noting that the number of data points in each correlation is slightly different in B02 and in the Comment. If the exclusion of one or two data points can cause an increase or a decrease in the coefficients, it has to be taken into account that these data are spurious, even if not labelled as missing measurements. For example, possible exceptional spurious data may appear as consequences of the data binning according to an interplanetary-geomagnetic delay of 1-h, which is valid on average but may be not appropriate at times.

A decrease of correlation significance associated to a threshold somewhat smaller than 550 km/s, and affecting the range of speed *Vsw*=[450, 550) km/s, does not contradict results in B02, where the 'threshold' was approximately indicated as a value between 500 and 600 km/s.

3. Corrections and observations about B02

There are some errors in the printed version of B02 and some of these may be identified by a careful reading, comparing the several parts of the text and the figures. These are:

1) Figure 4, top panel: first top number on the left is 154 instead of 156;

2) Figure 4, second panel from the top: first top number on the left is 496 instead of 506 and the second top number on the left is 943 instead of 1187.

3) Figure 5, bottom panels: *Dst vs.* E_m is *Kp vs.* E_m, and *Dst vs.* ε is *Kp vs.* ε.

4) Page SMP 3-5, line 14th in the left column: $n > 10$ cm^{-3} is $n \leq 10$ cm^{-3}.

The correlation coefficient for 1995-1997 shown in Figure 4 for *Vsw* $\geq$ 550 Km/s has been recently recalculated (again with 29 data points) and it is 0.63 instead of 0.24. This change might, eventually, be due to the modification or the update of data in the OMNI/NSSDC database since beginning of 2001 until today. In any case, in B02 it was verified that this exceptional result was not affecting (due to fewer data points than during the other years) the rest of the correlation coefficients for *Vsw* ≥ 550 Km/s. Now, this is also confirmed by Wang and Chao's calculations.

The sentences in B02 abstract "The correlation coefficients obtained for data points corresponding to solar wind slower than 550 Km/s are equal or slightly higher than the global correlations. The observations show generally lower correlation coefficients for solar wind speeds faster than 550 Km/s." were more appropriate to a previous version of the data analysis in which only the WIND satellite data were considered for the few years of availability. In that case, due to fewer data points, only two *Vsw* sectors were considered: *Vsw* < 550 Km/s and *Vsw* ≥ 550 Km/s, and the decrease of interplanetary-geomagnetic correlation coefficients at the fastest solar wind speeds were much larger than in B02. In the final version of B02, where four *Vsw* ranges are considered, those sentences would be better modified into "Generally these correlations are statistically less significant during the fastest solar wind, in particular for speeds faster than about 550 Km/s. On the other hand, for the same fastest solar wind data, the significance of the correlation between *Kp* and *Dst* is equal to or higher than the correlations obtained during slower solar wind periods."

References.

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SECTION II

Comment on “Effects of fast and slow solar wind on the correlation between interplanetary medium and geomagnetic activity” by P. Ballatore

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Abstract. *Ballatore* [2002] has investigated the correlations between the interplanetary medium and the geomagnetic indices *Kp* and *Dst* for different ranges of solar wind speed. She found that the correlation coefficients obtained for data points corresponding to a solar wind slower than 550 km s^{-1} are equal to or slightly higher than the global correlations. The observations show generally lower correlation coefficients for solar wind speeds greater than 550 km s^{-1}. From these results, she verified that at high solar wind speeds the processes responsible for the energy transfer between the interplanetary medium and the magnetosphere saturate. We have recalculated the correlation coefficients using the most recent OMNI data, and found, contrary to her results, that the global correlation coefficients between *Kp*, *Dst* and the interplanetary parameters are generally higher than the correlations obtained for data points corresponding to different solar wind speed intervals. From statistical tests we demonstrate that the correlations for solar wind speeds greater than 550 km s^{-1} are not significantly different from the correlations in other solar wind speed intervals. There is insufficient evidence to show that, from an investigation of the correlation coefficients between the interplanetary medium and the geomagnetic indices *Kp* and *Dst*, a threshold exists at a solar wind speed of ~550 km s^{-1} for the coupling of the interplanetary-magnetosphere system. This conclusion is also supported by analysis of the correlations between the time derivation of *Dst* and the interplanetary medium.

1. Introduction

There are two main processes responsible for energy and particle transfer from the solar wind to the magnetosphere. One is the magnetic reconnection between the interplanetary magnetic field (IMF) and the geomagnetic field, which is thought to be important essentially for the southward IMF [e.g., *Russell et al.*, 1973; *Akasofu*, 1981]. The other is the occurrence of a Kelvin-Helmholtz (KH) instability due to velocity shears at the magnetopause, which is observed to take a significant role when the IMF is northward [*Fairfield et al.*, 2000]. An analysis of the correlations between the solar wind speed and the micropulsation power observed at ground-based observatories suggested that the KH instability become saturated when the solar wind speed exceeds a threshold between 500 and 600 km s^{-1} [e.g., *Yedidia et al.*, 1991, and references therein]. *Ballatore* [2002] (hereinafter referred to as B02) claims to have verified the existence of this threshold in the solar wind speed from a correlation analysis between the interplanetary medium and geomagnetic indices *Kp* and *Dst*. We have repeated her calculation based on the most recent OMNI database, but could not obtain similar results.

2. Correlations between *Kp*, *Dst* and solar wind

As in B02, the time interval we investigate is the period from January 1977 to December 2000. The interplanetary data and the geomagnetic indices *Kp* and *Dst* were downloaded from the National Space Science Data Center (NSSDC) OMNI database (ftp://nssdcftp.gsfc.nasa.gov/spacecraft_data/omni). The OMNI data include a compilation of hourly resolution IMF and plasma data, energetic particle fluxes, and some solar and geomagnetic activity indices. For each of the 3-hour intervals of the *Kp* indices, the same value was repeated three times. An hour delay is introduced between the ground-based geomagnetic indices and the interplanetary data. The following three interplanetary parameters, defined by

$$E_m = V_{sw} B_t \sin^2(\phi/2), \tag{1}$$

$$\varepsilon = V_{sw} B^2 \sin^4(\phi/2), \tag{2}$$

$$V_{sw} B_s = \begin{cases} |V_{sw} B_z| & B_z < 0 \\ 0 & B_z \geq 0 \end{cases}, \tag{3}$$

are compared with the geomagnetic indices where V_{sw} is the bulk speed of the solar wind, B_t is the projection of the IMF onto the solar magnetosphere *y-z* plane, ϕ is the clock angle [*Kan and Lee*, 1979; *Akasofu*, 1981], B is the strength of the IMF, and B_z is the *z* component of the IMF in the GSM coordinate system.

First, we recalculated the results shown in Figure 1 of B02. We find that there is no significant difference between our result and that of B02, though there are some differences between the number of data points obtained by us and hers during the years from 1995 to 1997. All data points with available solar wind speed are included in this calculation. However, in the following calculations, we only consider the data points when observations of both the moments of solar wind plasma and IMF exist.

Second, Figure 1 shows the linear correlation coefficients of *Kp* and *Dst* with three interplanetary parameters E_m, ε and $V_{sw}B_s$ separately for data points binned by V_{sw} (<350, $350 \le V_{sw} < 450$, $450 \le V_{sw} < 550$ and $V_{sw} \ge 550$ km s^{-1}) with an ion density of $n > 10$ cm^{-3}, which is similar to Figure 2 of B02. The numbers in the parentheses in each panel of Figure 1 indicate the statistical significances of difference between the correlation for $V_{sw} \ge 550$ km s^{-1} and the correlations in the other three intervals of solar wind speed from a statistical test [*Press et al.*, 1992], respectively. The highest correlation coefficient is in the solar wind speed interval $350 \le V_{sw} < 450$ km s^{-1}. Although the interplanetary-geomagnetic correlation generally becomes smaller for higher V_{sw}, this decease is very slow and not as "sharp" decreases as seen in Figure 2 of B02. In addition, the correlation coefficient between *Dst* and $V_{sw}B_s$ increases for $V_{sw} \ge 550$ km s^{-1}. In particular, excluding the correlation between *Kp* and ε, one finds that the global correlations are higher than the correlations obtained for data points corresponding to different solar wind speed intervals, which is contrary to the result of B02. This result can be partially explained in terms of the range of V_{sw} (as well as $V_{sw}B_s$, ε and E_m) in each sub-correlation interval, because a smaller range of V_{sw} is usually associated with a decrease in the range of *Dst* and *Kp* such that the signal relative to the noise is reduced resulting in smaller correlations. Thus, one does not know whether the change in correlation is real differences of the underlying physical interaction or simply changes in the noise amplitude in *Dst* and *Kp* with solar wind speed. Moreover, the significances of difference between the correlations for $V_{sw} \geq 550$ km s^{-1} and the correlations in other solar wind speed intervals are generally greater than 0.15 (a small numerical value of the significance (0.05 or 0.01) means that the observed difference is significant [*Press et al.*, 1992].). That is, the correlations for $V_{sw} \geq 550$ km s^{-1} are not significantly different from the correlations in other solar wind speed intervals.

Third, in Figure 2 we show the correlation coefficients between *Kp* and *Dst* with exactly the same data points considered in Figure 1, where the test of the significances of difference between correlations are also shown in the same format as Figure 1. It is clearly shown that the global correlation is also higher than the correlations obtained for data points corresponding to different solar wind speed intervals. The correlation coefficients seem to approach a constant value when the solar wind speed is greater than 450 km s^{-1}. These results are different from those in Figure 3 of B02.

Fourth, the results obtained separately for the IMF northward or southward are illustrated in Figure 3 (combining all the years of data together and for $n > 10$ cm^{-3}) for the two interplanetary parameters E_m and ε, and for the geomagnetic indices *Kp* and *Dst*, respectively. The significances of difference between the correlation for $V_{sw} \geq 550$ km s^{-1} and the correlations in other solar wind speed intervals is shown as the numbers in parentheses in each panel. Comparing our Figure 3 with Figure 5 of B02, excluding the correlation between *Kp* and E_m during northward IMF, one can find from our results that the correlation coefficients for $V_{sw} \geq 550$ km s^{-1} is slightly higher than the correlation coefficients of the interval $450 \leq V_{sw} < 550$ km s^{-1}, which is contrary to the results of B02. However, these differences are not statistically significant since the significances of difference from the statistical test are generally greater than 0.14. The correlations between *Kp* and *Dst* increase monotonously with increase of solar wind speed for different signs of B_z. As expected from our previous analysis, there is no clear evidence that the interplanetary-geomagnetic correlation is lower at a solar wind speed greater than 550 km s^{-1}. Finally, we also recalculated and re-plotted Figure 4 of B02. In our plot, we found one point which the correlation coefficient between *Kp* and E_m is about 0.65 for $V_{sw} \geq 550$ km s^{-1} during 1995 and 1997, not the extremely low value shown in B02.

3. Discussions

Because the distributions of *Dst*, *Kp*, $V_{sw}B_s$, ε and E_m are highly skewed, and because the relationships being tested are not thought to be linear, it is need to note that even the nominal rigorous statistical tests of significance can underestimate the uncertainty in the correlations and their differences [*Press et al.*, 1992]. Therefore, the significance of the trend and the threshold observed by B02 cannot be validated from results of the above analysis.

In addition, correlation between hourly *Dst* and *Kp* and the solar wind does not necessarily capture the physically relevant driving processes. The physical driver of *Kp* is generally not specified because *Kp* includes effects from several different geophysical current systems and responds to a variety of phenomena [*Mayaud*, 1980; *Huttunen* el al., 2002]. The physical driver of *Dst* is rather better known [*Burton et al.*, 1975; *Akasofu*, 1981; *O' Brein and McPherron*, 2000.], but it is poorly captured by the B02 analysis. During a magnetic storm, *Dst* and *Kp* rise relatively quick while $V_{sw}B_s$ is elevated, and then decay slowly after $V_{sw}B_s$ has diminished. The decay occupied a large portion of the time series of a storm period. Thus, one does not expect very good correlation between the indices themselves and the solar wind, except during the main phase of storms, which constitutes a very small portion of the historical record.

Moreover, we agree with the referee that it is the time derivative of *Dst* that is driven by $V_{sw}B_s$, ε or E_m according to the *Burton* equation [*Burton et al.*, 1975],

$$\frac{d}{dt}Dst^* = Q(t) - Dst^*/\tau . \qquad (4)$$

Here $Dst^* = Dst - 7.26\sqrt{P} + 11$ nT is the pressure corrected *Dst* [*O' Brien and McPherron*, 2000]. Q (≤ 0), τ and P are an injection term, the decay time and the solar wind dynamic pressure, respectively. The injection term Q has a negative contribution to ΔDst^* (the hourly difference of Dst^*), while the second term on the right has a positive contribution to ΔDst^* in most cases, since above eighty percent of Dst is negative and τ is positive.

In Figure 4, we show the correlation between ΔDst^* and the interplanetary medium for different signs of ΔDst^* corresponding to different intervals of solar wind speed with ion density $n > 10$ cm^{-3}. The solid lines show the correlation coefficients for all ΔDst^* data, while the results for positive (negative) ΔDst^* are shown by dashed (dot-dash) lines. The coefficients for data with negative ΔDst^* are much higher than those for all data, and the coefficients for data with positive ΔDst^* are generally less than 0.25. This is due to the fact that injection term Q is dominant on the right side of Equation (4) when ΔDst^* is negative, and it is commonly believed that Q is determined very well by solar wind conditions outside the magnetosphere, while τ may have some dependence on $V_{sw}B_s$ for the southward IMF [e.g. *O' Brien and McPherron*, 2000; *McPherron and O' Brien*, 2001]. The significances of difference from the statistical test between the correlations for $V_{sw} \geq 550$ km s^{-1} and the correlations for $350 \leq V_{sw} < 450$ km s^{-1} or $450 \leq V_{sw} < 550$ km s^{-1} are generally higher than 0.25 for all signs of ΔDst^*. Thus, there is no clear evidence that the coupling process between the interplanetary medium and magnetosphere becomes saturated for high solar wind speed.

4. Conclusions

Following an approach similar to that used in B02, we investigated the relationship between geomagnetic activity and the interplanetary medium for different ranges of solar wind speed using the most recent OMNI data. We recalculated the linear correlation coefficients between *Kp*, *Dst* and the three interplanetary parameters, divided into the same regimes of solar wind speed and ion density as B02, but we could not find any significantly lower correlation for speeds greater than 550 km s^{-1}. The global correlations are generally higher than the correlation obtained for data corresponding to different ranges of solar wind speed. The correlation coefficients between *Kp* and *Dst* increase monotonically with increasing solar wind speed for both southward and northward IMF; however, if we combine the data points for southward and northward IMF, the correlation coefficients seem to approach a constant value when the solar wind speed is greater than 450 km s^{-1}. Thus, it is important to investigate the correlation between *Kp* and *Dst* for southward IMF and northward IMF separately.

In summary, we suggest that there is insufficient evidence to show that, from an investigation of the correlation coefficients between the interplanetary medium and the geomagnetic indices using the most recent OMNI data base, a threshold of solar wind speed exists at ~550 km s^{-1} for the coupling of the interplanetary-magnetosphere system.

Acknowledgments

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Figure Captions

Figure 1. Correlation coefficients between the geomagnetic indices and the solar wind parameters for V_{sw} in the intervals indicated for interplanetary density $n > 10$ cm^{-3}. The error bar bans the standard deviation of correlation in each bin. The numbers of data for each correlation are shown on the top panel. The horizontal dashed lines indicate the global correlation coefficient for all V_{sw} values. The numbers in the parentheses in each panel indicate the statistical significances of difference between the correlation for $V_{sw} \geq 550$ km s^{-1} and the correlations in the other three intervals of solar wind speed from statistical test [*Press et al.*, 1992], respectively.

Figure 2. Correlation coefficients between *Kp* and *Dst* for the intervals of V_{sw} indicated. The error bar bans the standard deviation of correlation in each bin. The dashed line indicates the global coefficient. The data points considered are the same as in Figure 1. The numbers in the parentheses indicate the statistical significances of difference between the correlations as same as Figure1.

Figure 3. Correlation coefficients between the geomagnetic indices and the solar wind parameters for the intervals of V_{sw} indicated. The error bar bans the standard deviation of correlation in each bin. The top and bottom panels are for an IMF $B_z > 0$ and $B_z < 0$ respectively. The dashed line indicates the global coefficient. The numbers of data points in each correlation are given at the top of the respective right panel. The numbers in the parentheses indicate the statistical significances of difference between the correlations as same as Figure1.

Figure 4. Correlation coefficients between ΔDst^* and the solar wind parameters for V_{sw} in the intervals indicated for interplanetary density $n > 10$ cm^{-3}. The error bar bans the standard deviation of correlation in each bin. The horizontal lines indicate the global correlation coefficients, where the dashed, dot-dash and solid lines are the results for $\Delta Dst^* > 0$, $\Delta Dst^* < 0$ and all ΔDst^*, respectively. The numbers shown on the top and bottom panels are the data points of each correlation for $\Delta Dst^* > 0$ and $\Delta Dst^* < 0$, respectively. The numbers for the middle panel are data points for $\Delta Dst^* < 0$ and $B_z < 0$.

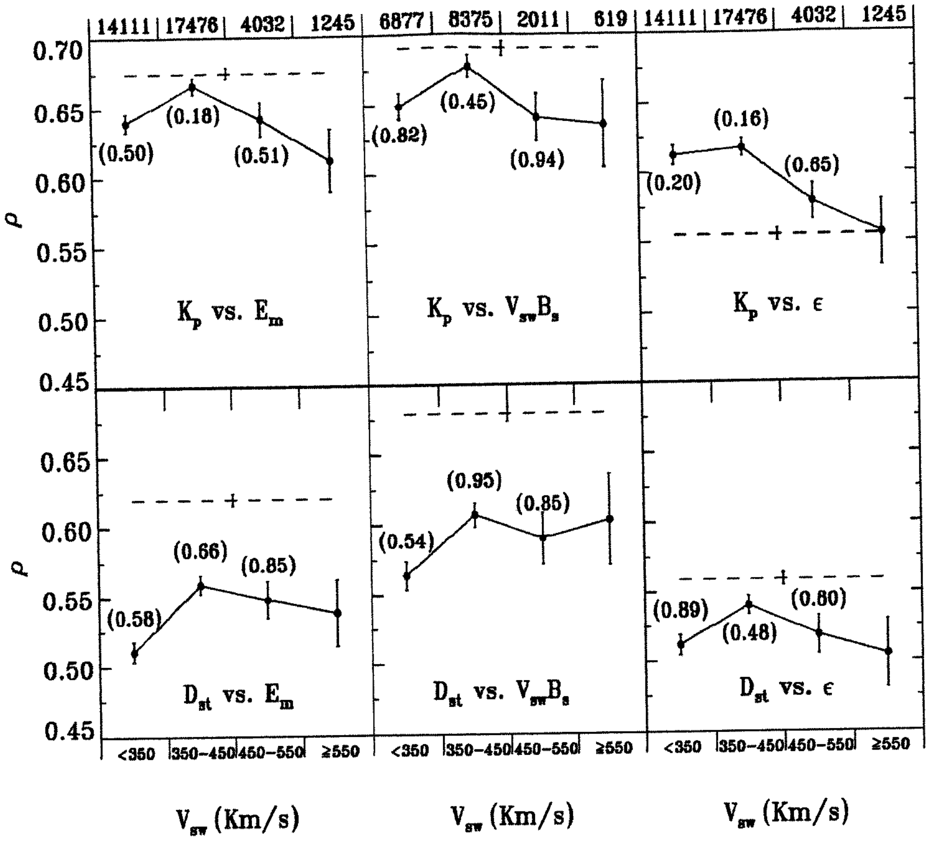


Figure 1. Correlation coefficients between the geomagnetic indices and the solar wind parameters for V_{sw} in the intervals indicated for interplanetary density $n > 10$ cm^{-3}. The error bar bans the standard deviation of correlation in each bin. The numbers of data for each correlation are shown on the top panel. The horizontal dashed lines indicate the global correlation coefficient for all V_{sw} values. The numbers in the parentheses in each panel indicate the statistical significances of difference between the correlation for $V_{sw} \geq 550$ km s^{-1} and the correlations in the other three intervals of solar wind speed from statistical test [*Press et al.*, 1992], respectively.

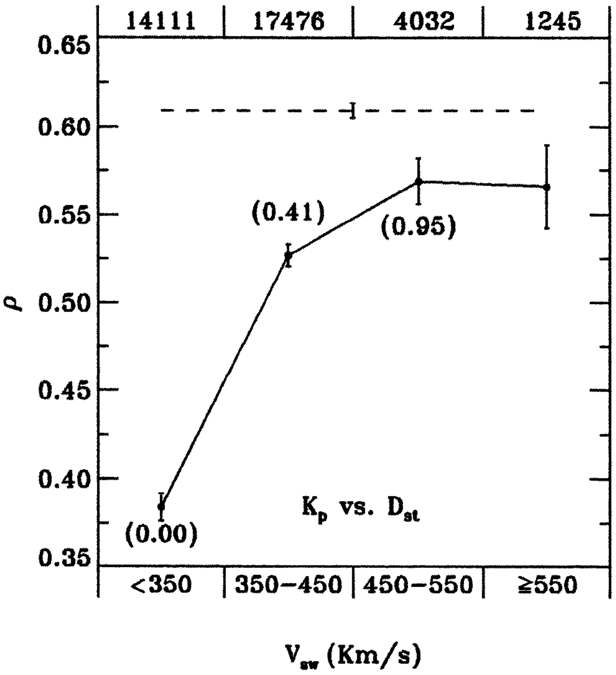
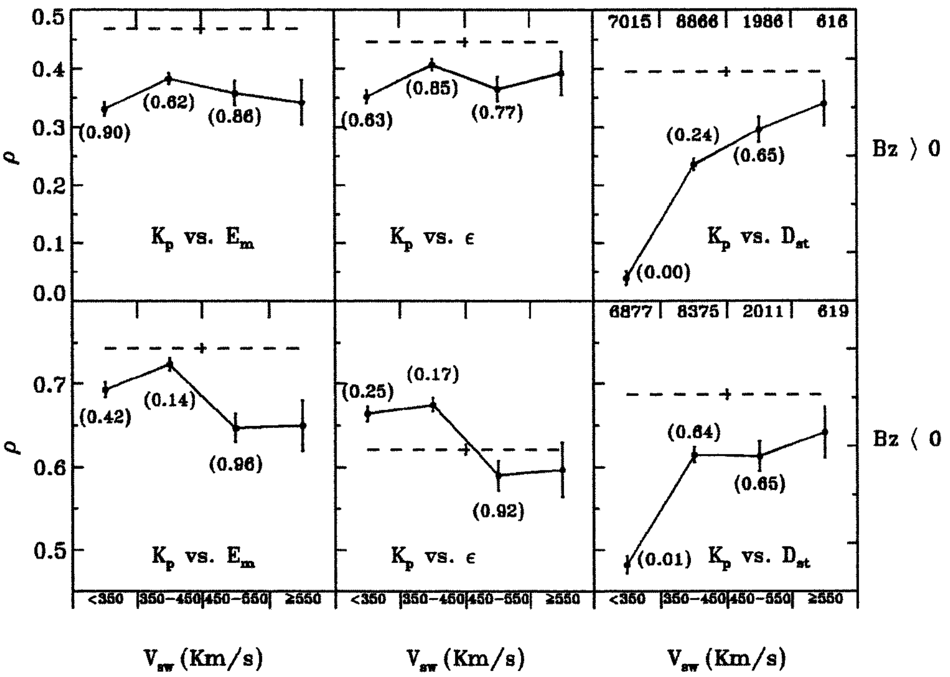


Figure 2. Correlation coefficients between *Kp* and *Dst* for the intervals of V_{sw} indicated. The error bar bans the standard deviation of correlation in each bin. The dashed line indicates the global coefficient. The data points considered are the same as in Figure 1. The numbers in the parentheses indicate the statistical significances of difference between the correlations as same as Figure1.



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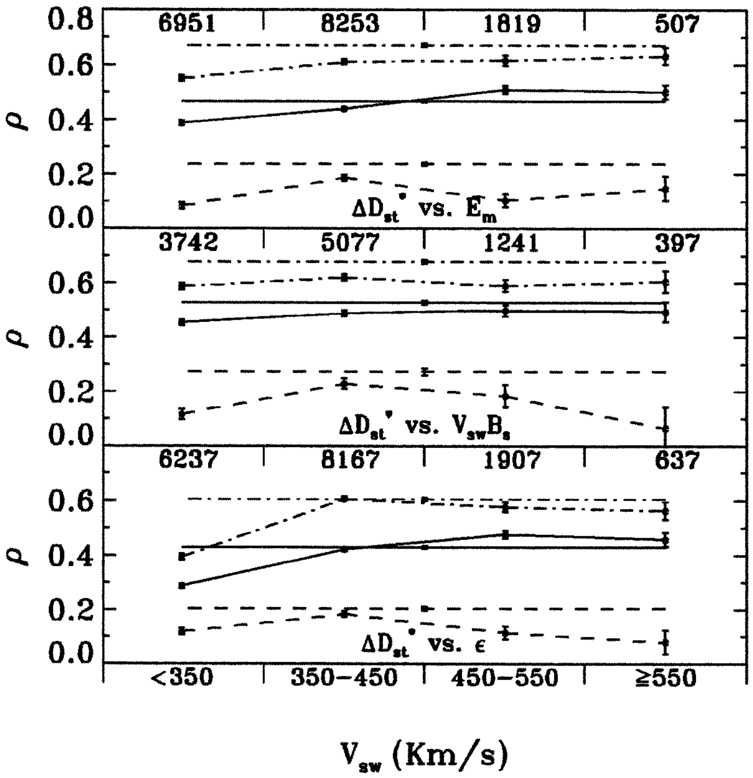

Figure 4. Correlation coefficients between ΔDst^* and the solar wind parameters for V_{sw} in the intervals indicated for interplanetary density $n > 10$ cm^{-3}. The error bar bans the standard deviation of correlation in each bin. The horizontal lines indicate the global correlation coefficients, where the dashed, dot-dash and solid lines are the results for $\Delta Dst^* > 0$, $\Delta Dst^* < 0$ and all ΔDst^*, respectively. The numbers shown on the top and bottom panels are the data points of each correlation for $\Delta Dst^* > 0$ and $\Delta Dst^* < 0$, respectively. The numbers for the middle panel are data points for $\Delta Dst^* < 0$ and $B_z < 0$.

SECTION III

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Effects of fast and slow solar wind on the correlations between interplanetary medium and geomagnetic activity

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[1] The coupling between interplanetary parameters and geomagnetic activity has been investigated. In particular, the correlations between the interplanetary medium and the geomagnetic indices *Kp* and *Dst* have been calculated for different ranges of solar wind speed. The correlation coefficients obtained for data points corresponding to solar wind slower than 550 km/s are equal or slightly higher than the global correlations. The observations show generally lower correlation coefficients for solar wind speeds faster than 550 km/s. These results suggest that at high solar wind speeds the processes responsible for the energy transfer between the interplanetary medium and the magnetosphere saturate. In addition, the influence of internal magnetospheric plasma physics on the geomagnetic activity may be larger for the faster solar wind intervals. In the context of the deterministically chaotic approximations we discuss how the threshold at ~550 km/s might represent the break of the order in the interplanetary-geomagnetic coupling system, so that the linear correlations or the correlations with a relatively weak departure from linearity are significant mostly during the slower solar wind. *INDEX TERMS:* 2784 Magnetospheric Physics: Solar wind/magnetosphere interactions; 2447 Ionosphere: Modeling and forecasting; 2164 Interplanetary Physics: Solar wind plasma; *KEYWORDS:* fast/slow solar wind regimes, *Kp* and *Dst* indices, interplanetary-geomagnetic coupling, solar wind

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1. Introduction

[2] The interaction between the interplanetary medium and the terrestrial magnetosphere is one of the most important subjects of study in the context of Sun-Earth relations. It is well accepted that energy and particles can enter the magnetosphere when reconnection occurs between the interplanetary magnetic field (IMF) and the geomagnetic field. The low-latitude dayside reconnection normally takes place during southward IMF and reconnection at the magnetospheric lobes and/or at the high latitudes can occur during northward IMF [e.g., *Akasofu*, 1981; *Song and Russell*, 1992]. Moreover, the magnetic shears at the bowshock and magnetosheath can be associated with diffusion of particles [*Phan et al.*, 1997] and waves [e.g., *Yumoto and Saito*, 1983] into the magnetosphere. In addition, the velocity shears at the magnetopause are commonly associated with the occurrence of the Kelvin-Helmholtz (K-H) instability, which is thought to allow the entry of energy and momentum to the magnetosphere in the form of plasma waves [e.g., *Fujimoto and Terasawa*, 1995]. In particular, during times of northward IMF, entry of mass from the interplanetary to the magnetospheric system is observed to be due to the K-H instability [*Fairfield et al.*, 2000].

[3] The K-H instability has been invoked as the explanation for the significant correlations between the solar wind speed (V_{sw}) and the micropulsation power observed at ground-based observatories [e.g., *Odera*, 1986, and references therein]. However, further increases of solar wind speed above a threshold between 500 and 600 km/s do not provide any further increase in micropulsation power [*Junginger and Baumjohann*, 1988; *Yedidia et al.*, 1991; *Ballatore et al.*, 1996]. In the previous papers, this result was attributed to a possible saturation of the efficiency of energy transfer between velocity shears at the magnetopause.

[4] In the present paper, we verify the existence of a possible threshold in the solar wind speed, and we speculate about its interpretation in the context of the interplanetary-magnetospheric coupling.

2. Data Analysis and Experimental Observations

[5] The time interval under investigation is the period from January 1977 until December 2000. For this period the interplanetary data considered are the measurements of interplanetary magnetic field (IMF), solar wind speed (V_{sw}), and density (n) from the National Space Science Data Center (NSSDC) database. According to data availability, these measurements are from different satellites, mostly from IMP 8 before 1994 and from Wind since December 1994. Smaller amounts of data are from IMP 6,

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IMP 7, ISEE 3, PROGNOZ 10, and ACE. The 1-hour resolution interplanetary data have been used to calculate three parameters: the electric merging field (indicated by E_m), the parameter $V_{sw} \cdot B_s$ (indicated by $V_{sw}B_s$) and energy coupling between the solar wind and the magnetosphere (ε) [*Akasofu*, 1981]. In particular, the electric merging field is defined:

$$E_m = V_{sw} B_t \sin^2(\phi/2), \tag{1}$$

where B_t is the projection of the IMF on the Y-Z plane (in the GSM coordinate system) and ϕ is the clock angle between B_t and the Z axis [e.g., *Kan and Lee*, 1979]. In the parameter $V_{sw}B_s$, B_s defined as the component ($-Bz$) of the IMF during southward IMF, and it is zero during northward IMF ($V_{sw}B_s$ is considered only during southward IMF periods). The energy coupling, ε is defined:

$$\varepsilon = V_{sw} B^2 \sin^4(\phi/2), \tag{2}$$

where B is the module of the IMF and ϕ is the clock angle mentioned above [*Akasofu*, 1981].

[6] These interplanetary parameters have been compared with the geomagnetic indices *Kp* and *Dst*, respectively available at 3- and 1-hour resolution. However, the resolution considered in our case is 1 hour for both indices, by considering, for each one of the 3-hour intervals of the *Kp*, the same value repeated for each single hour.

[7] A delay is introduced between the ground-based geomagnetic indices and the interplanetary data. This delay is set equal to 1 hour because this value optimizes the correlation between ground-based and interplanetary measurements in our data set. In addition, the approximation of a 1-hour delay is in agreement with previous estimations of average delays between satellites and ground-based measurements [e.g., *Arnoldy*, 1971; *Ballatore et al.*, 2001]. The results that we obtain with this average delay are qualitatively similar to the results obtained with a slightly different delay or, in particular, to the results obtained with a more accurate calculation of the delays at specific times. For example, for Wind measurements during the year 1997 the propagation time has been approximated at each hour by taking into account the specific average solar wind speed and the Wind position in the interplanetary space with respect to the magnetospheric bowshock subsolar point. The results that we obtained for this test case are qualitatively similar to those using a 1-hour delay.

[8] The linear correlation coefficient between the geomagnetic indices *Kp* and *Dst* has been calculated over 3-year periods from 1977 until 2000 and these are respectively 0.57, 0.59, 0.57, 0.58, 0.66, 0.65, 0.61, and 0.57. These coefficients have been re-calculated considering the data for all the 24 years together but separately for data points corresponding to different intervals of solar wind speed. In particular, the results obtained for $V_{sw} < 350$ km/s, $350 \leq V_{sw} < 450$ km/s, $450 \leq V_{sw} < 550$ km/s, and $V_{sw} \geq 550$ km/s are reported in the Figure 1. The correlation coefficients obtained during faster solar wind speeds are equal to or higher than the coefficients obtained during the slower solar wind speeds. In addition, no time dependence for this result is shown.

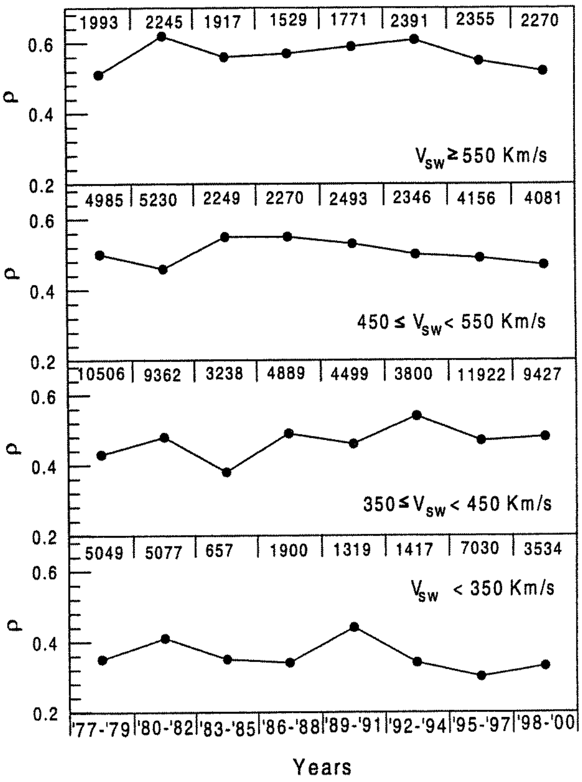

Figure 1. Correlation coefficients between *Kp* and *Dst* for the interval of years indicated on the *X* axis; each panel refers to the data corresponding to the V_{sw} interval indicated. On the top of each panel the numbers of data points for each correlation are shown.

[9] The linear correlation coefficients between the geomagnetic indices *Kp* and *Dst* and the interplanetary quantities, E_m, $V_{sw}B_s$, and ε, have been calculated. Several sources of error may be present. The upstream parameters observed may not be the same as those at Earth's magnetosphere [*Paularena et al.*, 1998; *Richardson et al.*, 1998, and references therein]. In particular, statistics shows that correlations among different spacecrafts are better for ion density $n > 10$ cm^{-3} [*Paularena et al.*, 1998, and references therein]. Taking into account these considerations, in order to minimize the effect of the variability in the interplanetary data, we consider only the data points corresponding to $n >$ 10 cm^{-3} in the following correlations of *Kp* and *Dst* with the interplanetary parameters.

[10] In Figure 2 we show the linear correlation coefficients of *Kp* and *Dst* with the three interplanetary quantities considered, separately for data points binned by V_{sw} (< 350, $350 \leq V_{sw} < 450$, $450 \leq V_{sw} < 550$ and ≥ 550 km/s). In general, the data with faster solar wind speeds (in particular equal or faster than 550 km/s) are less correlated. In particular, considering two correlations with equal correlation coefficient value, the more significant is the one related to the larger number of data points. Therefore, in a condition of equal variability of the considered variables, the best correlations shown in Figure 2 are observed for $350 \leq V_{sw} <$ 450 km/s and the worst are observed for $V_{sw} \geq 550$ km/s. The significance of the smaller interplanetary-geomagnetic

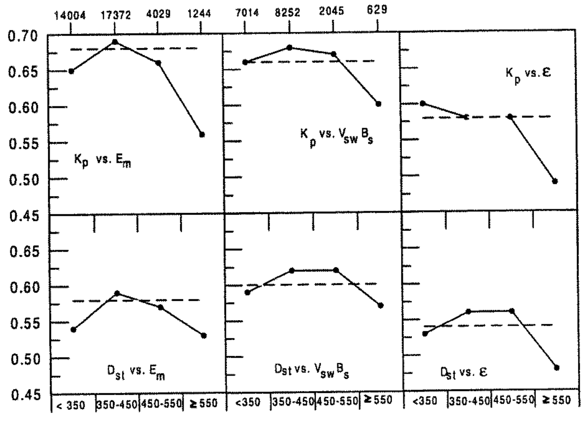

Figure 2. First-order correlation coefficients between the indicated parameters, separately for V_{sw} in the intervals indicated on the X axis. The data points considered correspond to interplanetary density $n > 10$ cm^{-3}. On the top of the left column the numbers of data points for each correlation are shown and these are the same for the panels in the first column on the right (for which no numbers on the top are specified). For the middle column, similarly, the numbers on the top specify the number of data points considered. In each panel, the horizontal dashed line indicates the total correlation coefficient for all the V_{sw} values.

correlation for solar wind speeds equal or faster than 550 km/s is also indicated by the consistence of the results in the different panels. In addition, for purposes of direct comparison, we showed in Figure 3 the correlation coefficients between *Kp* and *Dst* for, exactly, the same data points considered in Figure 2. Results in Figure 3 indicate that the decrease of interplanetary-geomagnetic correlation is associated with an increase of the correlation between the geomagnetic activity indices.

[11] The study of the interplanetary-geomagnetic correlation versus years, similarly to Figure 1, indicates no solar cycle or other systematic time dependence. For example, we show the case for *Kp* versus E_m in Figure 4. The two cases of $V_{sw} \geq 550$ km/s for 1986–1988 and 1995–1997 can be considered statistically less significant due to the relatively smaller number of data point involved.

[12] The results obtained separately for IMF northward or southward are illustrated in Figure 5 (combining all the years of data together and for $n > 10$ cm^{-3}) for the two interplanetary parameters E_m and ε and for the geomagnetic indices *Kp* and *Dst*. As expected [e.g., *Akasofu*, 1981, and references therein], the coefficients are higher during southward IMF than during northward. In particular, an interesting result shown in Figure 5 is that the decrease of interplanetary-geomagnetic correlation at faster solar wind speeds is observed for both orientation of IMF, associated with an increase of the *Kp* versus *Dst* correlation. In addition, during the quietest conditions (northward IMF and $V_{sw} < 350$ km/s), the correspondence between *Kp* and *Dst* is about null, while each one of them separately can be

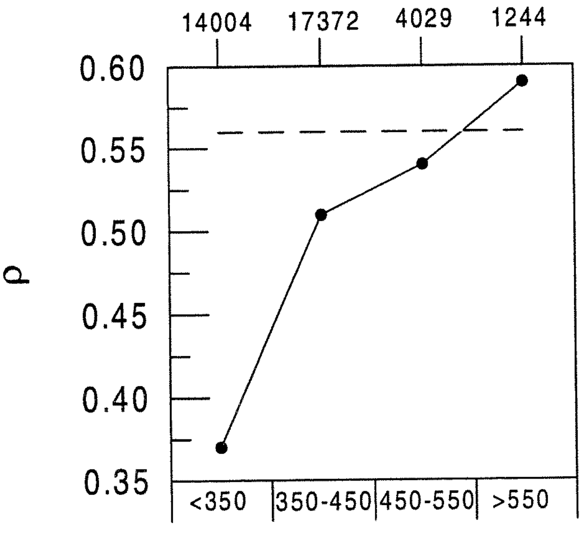

Figure 3. Correlation coefficients between *Kp* and *Dst* for the V_{sw} intervals on the X axis. The data points considered are the same as in Figure 2. The dashed line indicates the total correlation coefficient; the numbers at the top are the numbers of data points in each correlation.

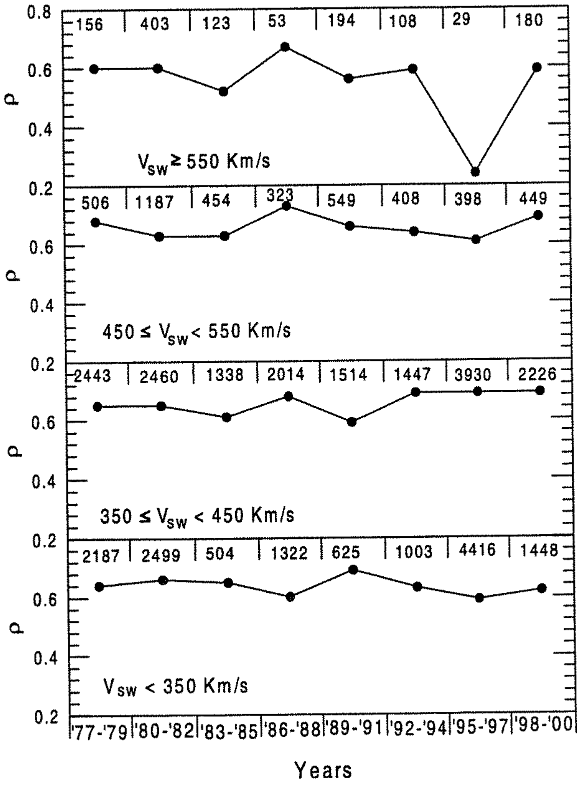

Figure 4. Correlation coefficients between *Kp* and E_m for the interval of years indicated on the X axis; each panel refers to the data corresponding to the V_{sw} interval indicated. On the top of each panel the number of data points for each correlation is shown.

are consistently slightly lower than the ones for slower speeds, indicating a smaller correlation at these times.

[17] Previous studies demonstrated the existence of an extreme variability in the interplanetary data measured by different satellites [*Russell et al.*, 1980; *Crooker et al.*, 1982]. However, rather little control on this variability could be attributed to the solar wind speed, at least in the range 300–500 km/s [*Crooker et al.*, 1982]. The most recent works on this subject have shown that the correlations among interplanetary measurements from different spacecrafts are 50% higher for density $n > 10$ cm^{-3} than for density $n < 4$ cm^{-3} [*Paularena et al.*, 1999, and references therein].

[18] This justifies our exclusion of data points with ion density $n > 10$ cm^{-3} for the interplanetary-geomagnetic correlations. In particular, rather similar results are obtained for $n > 4$ cm^{-3}, while, considering all n values, a slight decrease of the correlations for solar wind 350–450 km/s and a slight increase for $V_{sw} \geq 550$ km/s may be observed at times. In particular, if we consider only the Wind satellite data, for all n values together, over the years 1995–2000, we obtain that the decrease of interplanetary-geomagnetic correlation at high speeds is much more evident than in Figure 2 (for $V_{sw} \geq 550$ km/s the correlation coefficient is generally <0.4). Differently, considering the only data from IMP 8, for all n values and during the same period, the high-speed correlation is slightly higher than in Figure 2. This indicates the importance of selecting the highest solar wind density data in order to obtain a better reliability of the upstream parameters [*Paularena et al.*, 1999, and references therein].

[19] However, the solar wind density and speed are not just independent, but they correlate with correlation coefficients of the order of about −0.45 in our data set: the higher V_{sw} is statistically associated to a smaller density. Therefore an increase of interplanetary-geomagnetic correlations can be expected during slower solar wind associated with a higher reliability of upstream measurements. This is one more reason for restricting the variabiability of n ($n >$ 10 cm^{-3}) when studying the effects of V_{sw}.

[20] It is important to stress that since most high-speed solar wind intervals are low density, the condition $n > 10$ cm^{-3} is affecting the sector $V_{sw} \geq 550$ km/s more significantly than the rest of the V_{sw} intervals. This might indicate that the smaller interplanetary-geomagnetic correlation is just related to the occurrence of interplanetary structures of both high speed and density. In fact, the presence of high density associated with high speed can be related to the ejections of solar coronal mass (coronal mass ejections (CMEs)) or to the compression of the slow solar wind streams reached by faster streams in the interplanetary space (corotating interactions regions (CIRs)) [e.g., *Kivelson and Russell*, 1997, and references therein]. The implication that the decrease of interplanetary-geomagnetic correlation for $V_{sw} \geq 550$ km/s is not specifically related to the CME or CIR events is proved by the fact that a similar decrease is not found for intervals of higher solar wind pressure (nV_{sw}^2).

[21] In addition, in respect to spatial scale sizes of interplanetary medium variability [*Crooker et al.*, 1982] or IMF orientation [*Russell et al.*, 1980; *Crooker et al.*, 1982], we do not find a clear association between the satellite location and the observed decrease of correlation for $V_{sw} >$ 550 km/s.

[22] Results reported in Figure 2 combine together all data from the all years 1977 until 2000. However, considering each year or groups of years separately (an example is given in Figure 4), we see no systematic solar cycle effects.

[23] The interplanetary quantities considered are E_m, $V_{sw}B_s$, and ε because these parameters give the best correlations between the interplanetary medium and the magnetosphere, as expected from previous studies [*Akasofu*, 1981; *McPherron*, 1997a, and references therein]. However, we obtained similar results considering other interplanetary parameters (for example, IMF B_z, or $V_{sw}B_z$).

[24] The results above, related to the first order approximation, indicate that the mechanism responsible of the energy transfer between the interplanetary medium and the magnetosphere is different for V_{sw} faster or slower than a certain threshold between 500 and 600 km/s. This could be related to the saturation of the energy transfer processes that are active during the quieter conditions.

[25] As suggested by previous studies on micropulsations (see the introduction), the saturation of the K-H instability process is also expected to occur at ~500–600 km/s. We find that a decrease of linear correlation values at 500–600 km/s also occurs in the E_m, the ε and the $V_{sw}B_s$ correlations; these quantities are typically considered as indicators of the reconnection rate between the IMF and the magnetosphere [*Akasofu*, 1981, and references therein]. The entry of energy and plasma to the magnetosphere through reconnection is somehow seen as an alternative process with respect to the K-H instability. In fact, the former is considered to be mostly active during southward IMF, and the latter is usually invoked for IMF-magnetosphere coupling during northward IMF [*Fairfield et al.*, 2000, and references therein]. In particular, $V_{sw}B_s$ takes into account only reconnection for negative IMF B_z, while E_m is a more general parameter including also the effects of lobe reconnection during positive IMF B_z.

[26] Figure 5 shows the correlation coefficients versus V_{sw} considering separately the periods of northward and southward IMF: the change of the correlations as a function of V_{sw} is similar in the two cases considered and in agreement with results shown in Figure 2 and 3. Our results suggest that similar to the K-H instability, the ground-based effects of the merging between the IMF and the magnetosphere undergo a kind of saturation at $V_{sw} \sim 550$ km/s.

[27] A difference might be expected for the results related to higher-order correlations, e.g., these correlations could be definitely smaller for $V_{sw} < 550$ km/s than for the global case, or for $V_{sw} > 550$ km/s they could be higher than for $V_{sw} < 550$ km/s. In fact, the correlations between interplanetary quantities and geomagnetic indices are not expected to be only linear. One known explanation of the possible origin of the non-linear relationship between *Dst* and ε was given by *Akasofu* [1981], who invoked the fact that a more intense ring current tends to form at a closer distance to Earth. The correlation function estimated in that case was a second order polynomial function in the independent variable log(ε) [*Akasofu*, 1981].

[28] Therefore, in our case it is of interest to verify what happens by considering a departure from linearity. So we have calculated higher-order correlations up to the fifth order. We report in Table 1 results up to the third order:

for orders higher than this, no more increase in the significance of the correlations was observed.

[29] We also have considered a second order polynomial function in the variable log(ε). Use of this variable does not improve our results.

[30] Table 1 confirms the observations derived from the first-order approximation: the correlation coefficients for data corresponding to $V_{sw} < 550$ km/s are slightly higher than the for data with $V_{sw} \geq 550$ km/s. Therefore, similar to the linear case, the fast solar wind may be associated to a decrease of the correlations.

[31] This result confirms the different nature of the interaction between the interplanetary medium and the geomagnetic indices when the solar wind flow is faster or slower than ∼500–600 km/s.

[32] If we take into account the fact that the interplanetary medium affects the geomagnetic activity less during the faster solar wind, we may deduce that the causes of the observed geomagnetic activity are inside the magnetosphere itself at these times. This is also in agreement with the higher correlation between *Kp* and *Dst* at these times (see Figure 3).

[33] By analyzing some specific fast solar wind intervals we noted some occurrences of geomagnetic substorms at these times, with specific high correlation between *Kp* and *Dst* and small interplanetary-geomagnetic correlations.

[34] The mechanism producing the substorms is related to the continuous presence of the magnetospheric-ionospheric convection system that transports magnetic plasma flow from the dayside toward the geomagnetic tail. In this sense the substorms can be seen as a way to return the plasma energy and flow toward the dayside, as determined by the reconnection in the magnetotail [e.g., *McPherron*, 1997b, and references therein]. The primer of the tail reconnection is related to the fact that the electric fields between the plasma layers in the tail become so thin that the conductivity (generally infinite in these plasmas) becomes finite and plasma can move. This primer is due to the energy stored in the magnetosphere and/or to the geometry of interactions between the solar wind flow and the magnetosphere. The initial phase of the substorms (or of the storms, seen as larger substorm events) is impulsive as soon as the critical energy parameters are reached [e.g., *McPherron*, 1997b, and references therein].

[35] In the terms above, during the occurrence of the substorms (and we mean in particular during their initial phase), the geomagnetic activity is determined by processes related to the magnetospheric plasma and is not directly related to the interplanetary medium, although its primer is determined by the interplanetary medium.

[36] It is worth to specify that the results obtained for *Kp* and *Dst* in Figure 2 are similar also for the geomagnetic index *AE* (the standard *AE* is considered until 1988, after 1988 the provisional *AE* is considered, in agreement with public *AE* availability). This result is expected in association with the positive correlation between *AE* and V_{sw} (with correlation coefficients of the order of 0.5 in our data set). Since an increase of *AE* indicates an increase of substorm activity, during faster solar wind a larger substorm occurrence rate is expected in the *AE* values which may produce the decrease of the V_{sw} versus *AE* correlation.

[37] In we consider *Kp* and *Dst*, the statistical significance of their correlation with V_{sw} is not so directly implying a higher substorm occurrence during the faster solar wind. However, we recall that one of the causes of substorm occurrence is solar wind structures faster than the average solar wind speed (∼400 km/s). For example, fast CMEs are known to produce preceding shocks and compressed solar wind and IMF, and these elements are generally associated with the onset of geomagnetic storms [e.g., *Tsurutani et al.*, 1990a; *Gonzalez et al.*, 1994, and references therein].

[38] Although this observation, the decrease of interplanetary-geomagnetic correlation at $V_{sw} \sim 550$ km/s cannot be due to the substorms and storms occurrence solely. In fact, if we exclude the data corresponding to the substorm intervals (with $AE > 500$ nT in particular), the results shown in Figures 2 and 3 are still qualitatively observed in our data set. This result is in agreement with the previous finding relating solar wind speed to the low-frequency geomagnetic pulsation power. In particular, in the work of *Ballatore et al.* [1996] the SSC (sudden storm commencement) events were excluded from the data set considered. In addition, the ground-based data considered by *Yedidia et al.* [1991] were from only the dayside 0600–1800 LT interval and from a station located at middle latitude, so that the effects of both substorms and storms are expected to be excluded.

[39] In these studies the storms and substorms were excluded because, during these events, there is less order in the magnetosphere, so that linear correlations or correlations with a weak departure from linearity may fail in predictions. In particular, the magnetospheric system is not just random, but it seems deterministically chaotic so that, given the initial state, its evolution may be predicted [e.g., *Baker et al.*, 1990; *Tsurutani et al.*, 1990b]. In this context, our results can be interpreted as the fact that a general break of the magnetospheric order can occur, independent of the substorm or storm occurrence, in association with the increase of the solar wind speed above a certain threshold between 500 and 600 km/s.

4. Conclusions

[40] The relationship between the interplanetary medium and the geomagnetic activity is found to be different during periods of solar wind faster or slower than a threshold speed of about 550 km/s. We suggest that the processes responsible for the coupling between the interplanetary medium and the magnetosphere are different during different regimes of solar wind speed.

[41] In particular during the faster solar wind the correlation coefficients between the interplanetary quantities and the geomagnetic indices are smaller. On the contrary, for the same faster solar wind data, the coefficient of the correlation of one geomagnetic index with the other is higher. These results show that the geomagnetic variations at different latitudes of the terrestrial system are very well correlated, in particular during fast solar wind speed. This may suggest that the geomagnetic activity observed during the faster solar wind conditions can be more directly related to plasma processes inside the magnetosphere than to the interplanetary parameters.

[42] In the context of the treatment of the magnetosphere as a deterministically chaotic system, our results are interpreted in the sense that an order in the interplanetary-magnetosphere coupling is significant only until a certain threshold of solar wind speed, i.e., ~550 km/s. Above this speed, the correlations between interplanetary parameters and the geomagnetic activity are expected to be lower, both in linear and in higher-order approximations.

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