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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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[1] *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. *INDEX TERMS:* 2784 Magnetospheric Physics: Solar wind/magnetosphere interactions; 2447 Ionosphere: Modeling and forecasting; 2164 Interplanetary Physics: Solar wind plasma; *KEYWORDS:* interplanetary-geomagnetic coupling, fast/slow solar wind, *Kp* and *Dst* index

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1. Introduction

[2] 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.

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2. Correlations Between *Kp*, *Dst*, and Solar Wind

[3] 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 (available at 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

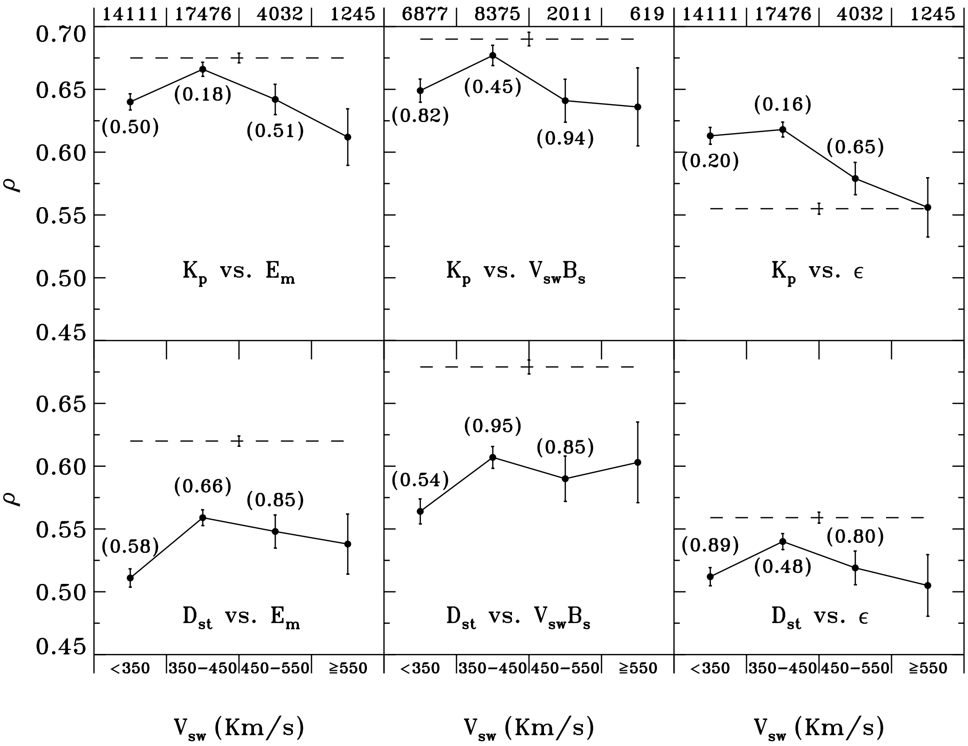

Figure 1. Correlation coefficients between the geomagnetic indices and the solar wind parameters for V_{sw} in the intervals indicated for interplanetary density $n > 10$ cm^{-3}. The error bar bans the standard deviation of correlation in each bin. The numbers of data for each correlation are shown 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.

three times. An hour delay is introduced between the ground-based geomagnetic indices and the interplanetary data. The following three interplanetary parameters, defined by

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

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

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

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.

[4] 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 her and us 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.

[5] 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 ≤ V_{sw} < 450, 450 ≤ V_{sw} < 550 and $V_{sw} \geq$ 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 $V_{sw} \geq$ 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 ≤ 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 $V_{sw} \geq$ 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 subcorrelation 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

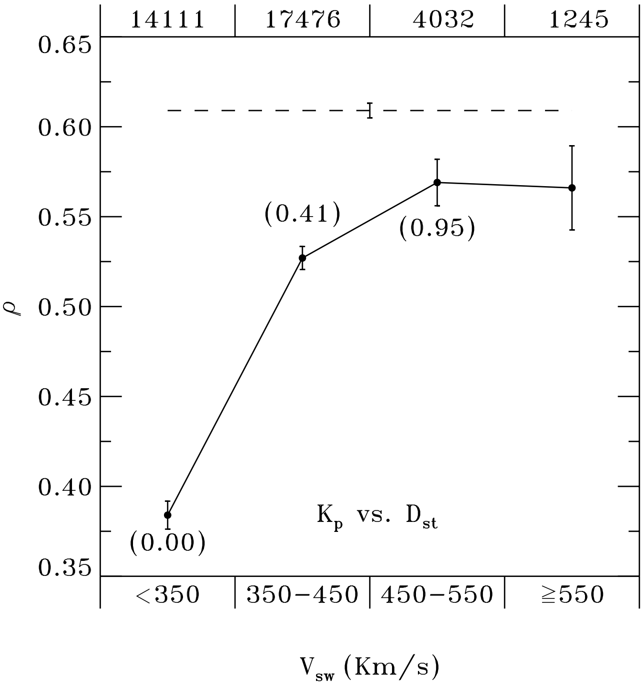

Figure 2. Correlation coefficients between *Kp* and *Dst* for the intervals of V_{sw} indicated. The error bar bans the standard deviation of correlation in each bin. The dashed line indicates the global coefficient. The data points considered are the same as in Figure 1. The numbers in the parentheses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

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.

[6] 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.

[7] 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,

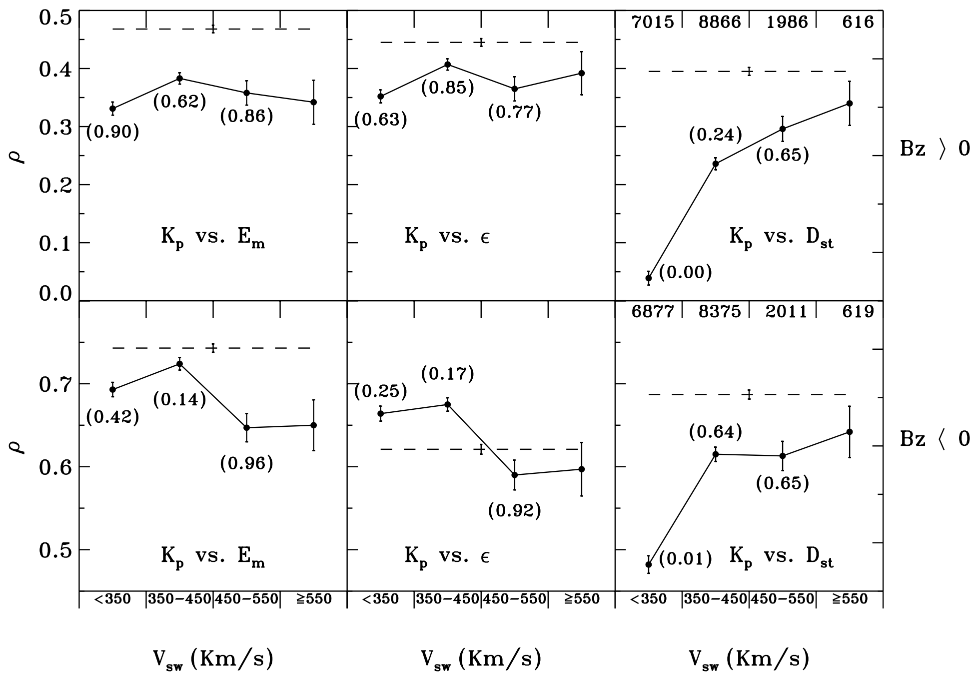

Figure 3. Correlation coefficients between the geomagnetic indices and the solar wind parameters for the intervals of V_{sw} indicated. The error bar bans the standard deviation of correlation in each bin. The top and bottom panels are for an IMF $B_z > 0$ and $B_z < 0$, respectively. The dashed line 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 Figure 1.

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

[8] 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 necessary 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.

[9] 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 et al.*, 2002]. The physical driver of Dst is rather better known [*Burton et al.*, 1975; *Akasofu*, 1981; *O'Brien 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.

[10] Moreover, we propose 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],

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

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 80 percent of Dst is negative and τ is positive.

[11] 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.

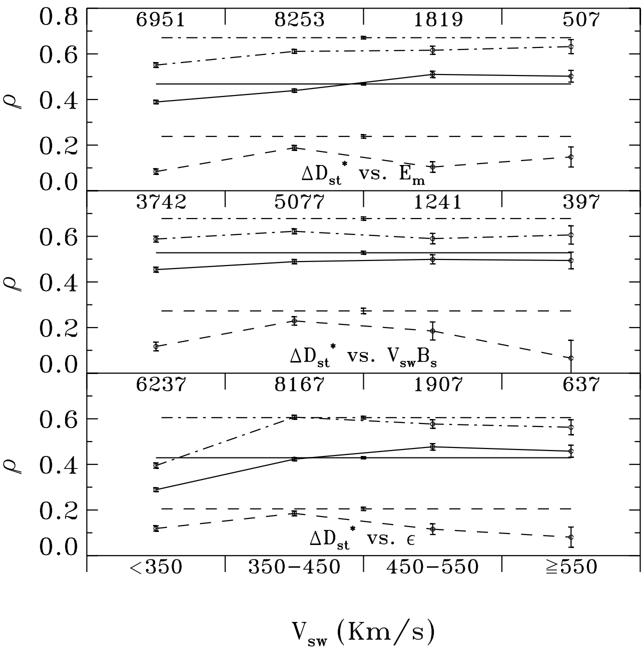

Figure 4. Correlation coefficients between ΔDst^* and the solar wind parameters for V_{sw} in the intervals indicated for interplanetary density $n > 10$ cm^{-3}. The error bar bans the standard deviation of correlation in each bin. The horizontal lines indicate the global correlation coefficients, where 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 $B_z < 0$.

4. Conclusions

[12] 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.

[13] 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 $\sim$550 km s^{-1} for the coupling of the interplanetary-magnetosphere system.

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References

Akasofu, S.-I., Energy coupling between the solar wind and the magnetosphere, *Space Sci. Rev.*, *28*, 121, 1981.

Ballatore, P., Effects of fast and slow solar wind on the correlations between interplanetary medium and geomagnetic activity, *J. Geophys. Res.*, *107*(A9), 1227, doi:10.1029/2001JA000144, 2002.

Burton, R. K., R. L. McPherron, and C. T. Russell, An empirical relationship between interplanetary conditions and Dst, *J. Geophys. Res.*, *80*, 4204, 1975.

Fairfield, D. H., A. Otto, T. Mukai, S. Kokubun, R. P. Lepping, J. T. Steinberg, A. J. Lazarus, and T. Yamamoto, Geotail observation of the Kelvin-Helmholtz instability at the equatorial magnetotail boundary for parallel northward fields, *J. Geophys. Res.*, *105*, 21,159, 2000.

Huttunen, K. E. J., H. E. J. Koskinen, and R. Schwenn, Variability of magnetospheric storms driven by different solar wind perturbations, *J. Geophys. Res.*, *107*(A7), 1121, doi:10.1029/2001JA900171, 2002.

Kan, J. R., and L. C. Lee, Energy coupling function and solar wind-magnetosphere dynamo, *Geophys. Res. Lett.*, *6*, 577, 1979.

Mayaud, P. N., *Derivation, Meaning, and Use of Geomagnetic Indices*, *Geophys. Monogr. Ser.*, vol. 22, AGU, Washington, D. C., 1980.

McPherron, R. L., and T. P. O'Brien, Predicting geomagnetic activity: The *Dst* index, in *Space Weather*, *Geophys. Monogr. Ser.*, vol. 125, edited by P. Song et al., p. 339, AGU, Washington, D. C., 2001.

O'Brien, T. P., and R. L. McPherron, An empirical phase space analysis of ring current dynamics: Solar wind control of injection and decay, *J. Geophys. Res.*, *105*, 7707, 2000.

Press, W. H., S. A. Teukolsky, W. T. Vetterling, and B. P. Flannery, *Numerical Recipes in FORTRAN*, Cambridge Univ. Press, New York, 1992.

Russell, C. T., R. L. McPherron, and R. K. Burton, On the cause of geomagnetic storms, *J. Geophys. Res.*, *78*, 92, 1973.

Yedidia, B. A., M. Vellante, U. Villante, and A. J. Lazarus, A study of the relationship between micropulsations and solar wind properties, *J. Geophys. Res.*, *96*, 3465, 1991.

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