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WBVR Standards in the Northern Sky. Analysis of Variability Using $\mathcal{MZ}$ Technique

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From our comparison of magnitudes of bright stars in the Hipparcos catalogue and in the Tien-Shan catalogue of *WBVR* magnitudes, we compiled a list of stars that could be candidate photometric standards in the northern sky. The selected stars were tested for variability using the $\mathcal{MZ}$ technique. The result is a list of 6484 stars recommended as standards.

1 Introduction

Kornilov et al. (1991) published "The Catalogue of *WBVR* Magnitudes of Bright Northern Stars". The catalog was based on observations in the *WBVR* photometric system acquired in the high-altitude observatory of the Sternberg Astronomical Institute (SAI) of the Lomonosov Moscow State University (MSU). This observatory was located in Trans-Ili Alatau mountains (near the city of Alma-Ata) at an altitude of about 3000 meters above the sea level. The catalog is often called the Tien Shan Sternberg catalog. It was demonstrated in several subsequent papers (Zakharov et al. 2000; Krutyakov et al. 2000; Mironov and Zakharov 2002; Zakharov et al. 2004), from comparison to Hipparcos Hp magnitudes (ESA, 1997), that the rms error of magnitudes in the Tien Shan Sternberg catalog was about $0\overset{\mathrm{m}}{.}003$.

This comparison was performed using a special algorithm, so that coefficients of the non-linear polynomial relating the $(Hp-V)$ difference to $W-B$, $B-V$, and $V-R$ color indices were calculated. The comparison proved that the difference of the observed $(Hp-V)_{obs}$ and that calculated using the polynomial, $(Hp-V)_{calc}$, namely $\Delta(Hp-V) = (Hp-V)_{obs}-(Hp-V)_{calc}$ did not exceed $\pm 0\overset{\mathrm{m}}{.}02$ for 8766 stars. The frequency distribution of the differences is shown in Fig. 1. The rms deviation is $0\overset{\mathrm{m}}{.}005$.

Obviously, the spectral energy distributions of these stars give a possibility to calculate magnitudes in one catalog (Hipparcos) from magnitudes in the other catalog (*WBVR*) rather accurately. This property allows us to consider the stars of this sample as candidate photometric standards in the northern sky. Since common stars in the two catalogs were observed at different times, using completely different methods, and from different positions (in space and on the Earth), the close agreement between calculated and observed values indicates that these stars are not variable or, at least, have low variability amplitudes. However, to be valuable standards, the stars should be carefully examined for variability.

Observations obtained during the Hipparcos mission and contained in the "Hipparcos Epoch Photometry Annex" and "Tycho Epoch Photometry Annex" lists provide such

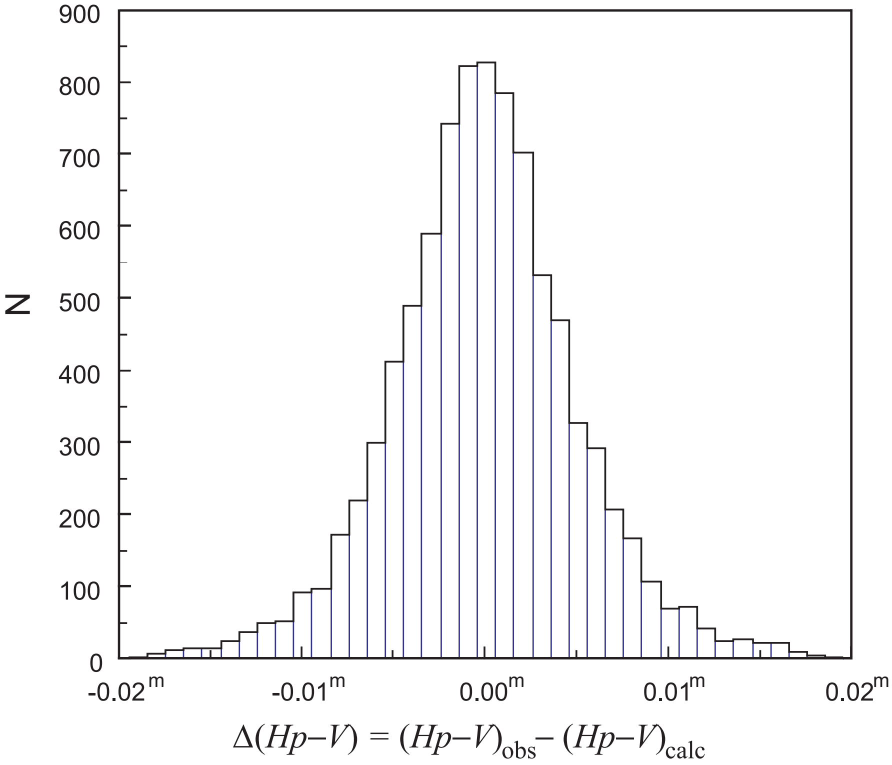

Figure 1. Frequency distribution of the $\Delta(Hp - V) = (Hp - V)_{obs} - (Hp - V)_{calc}$ differences.

an opportunity. A technique was developed in the SAI (Mironov et al. 2003) permitting to discover brightness variations of stars on the basis of simultaneous multichannel observations. According to this technique, an $\mathcal{MZ}$ parameter is calculated; this parameter evaluates the degree of correlation of individual magnitude measurements in several channels.

Suppose that, for a star with the number i in the pair of channels with numbers k and l, we have N simultaneous observations. Then we can calculate the linear correlation coefficient, assuming a normal distribution of the variables m_k and m_l, according to the formula:

$$\rho_{k,l} = \frac{\mathrm{cov}(m_k, m_l)}{\sigma_k \sigma_l}, \tag{1}$$

where

$$\begin{aligned} \mathrm{cov}(m_k, m_l) &= \tfrac{1}{N} \textstyle\sum_{j=1}^{N} (m_{jk} - \overline{m_k})(m_{jl} - \overline{m_l}) = \\ &= \tfrac{1}{N} \sum_{j=1}^{N} m_{jk} m_{jl} - \Big(\tfrac{1}{N} \sum_{j=1}^{N} m_{jk}\Big)\Big(\tfrac{1}{N} \sum_{j=1}^{N} m_{jl}\Big), \\ \sigma_k^2 &= \tfrac{1}{N} \sum_{j=1}^{N} (m_{jk} - \overline{m_k})^2, \quad \sigma_l^2 = \tfrac{1}{N} \sum_{j=1}^{N} (m_{jl} - \overline{m_l})^2. \end{aligned} \tag{2}$$

Magnitudes of different stars were measured unequal number of times, and thus the ratio of the correlation coefficient to its error should be used. An estimate of the correlation coefficient error is:

$$\sigma_{\rho(k,l)} = \frac{1-\rho^2_{k,l}}{\sqrt{N-2}}. \tag{3}$$

To search for variability of a star numbered i, we have suggested that the statistics $\mathcal{MZ}_{ikl}$:

$$\mathcal{MZ}_{i,k,l} = \frac{\rho_{i,k,l}}{\sigma_{\rho(k,l)}} \tag{4}$$

should be used.

Since there exist N_b channels, one can construct a vector $\mathcal{MZ}_{i,k,l}$ with $N_p = C^2_{N_b} = N_b(N_b-1)/2$ components being generally correlated. From components of the vector, one can calculate an integrated statistics $\mathcal{MZ}$ for every star:

$$\mathcal{MZ}_i = \frac{1}{\sqrt{N_p}} \sum_{k=l}^{N_b} \sum_{l=k+1}^{N_b} \mathcal{MZ}_{i,k,l} \tag{5}$$

reflecting all the channels that are generally correlated. It is easy to see that the integrated $\mathcal{MZ}$ is a projection of the N_p-dimensional vector $\mathcal{MZ}_{i,k,l,\ldots}$ onto the N_p-dimensional cube diagonal passing through the point of origin. We will call this diagonal the main diagonal. For the three channels, Hp, B_T and V_T:

$$\mathcal{MZ}_{Hp,BT,VT} = \frac{\mathcal{MZ}_{Hp,BT} + \mathcal{MZ}_{Hp,VT} + \mathcal{MZ}_{BT,VT}}{\sqrt{3}}. \tag{6}$$

If $\mathcal{MZ} > 3$, the star is variable with the probability 0.997. If $\mathcal{MZ} > 2$, the probability of the star being variable is 0.976.

Note that $|\mathcal{MZ}| < 3$ does not mean that the star cannot be considered variable. It only means that the Hipparcos material is not good enough to discover its variability. This is primarily due to the fact that the standard error of measurements in the B_T and V_T channels is large (about $0\overset{\mathrm{m}}{.}1$).

2 Taking into Account Correlation Between Channels

Initially, we selected 8766 stars with $\Delta(Hp - V) < 0\overset{\mathrm{m}}{.}02$. For 130 of them, either the "Tycho Epoch Photometry Annex" does not provide information about individual measurements in the B_T and V_T channels or the table of individual measurements contains very few reliable data points. For the remaining 8636 stars, the $\mathcal{MZ}$ statistics was calculated from the formula (6). These stars will be called "stars of our sample". The distributions of the $\mathcal{MZ}$ parameters for all stars of our sample and for all three pairs of channels: Hp and B_T, Hp and V_T, B_T and V_T are shown in Fig. 2.

Most stars of our sample are not variables; nevertheless, their distribution modes are not zero, as it should be for independent random variables. For the pair of Hp and B_T, the mode was found to be 0.11865; for the pair of Hp and V_T, 0.1672; and for the pair of B_T and V_T, 0.8047. Thus, all the channels are correlated. The same conclusion was earlier made from other considerations (Zakharov et al. 2000; Krutyakov et al. 2000). The correlation for the channel pairs Hp and B_T, Hp and V_T is poor, but for the pair of B_T and V_T it is strong enough. The presence of a correlation shifts the $\mathcal{MZ}$ parameter from

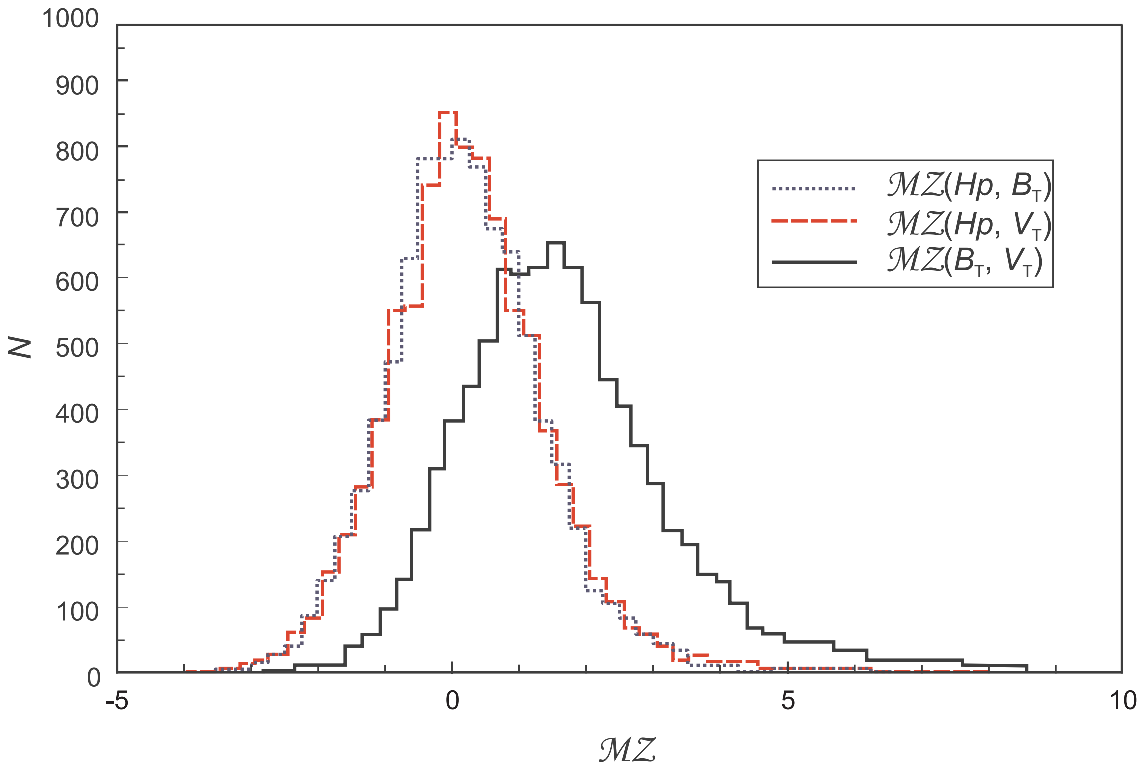

Figure 2. Histograms of the three $\mathcal{MZ}$ parameters, illustrating the shifts of distribution modes because of correlation between channels.

zero, even when there is no true variability. Before calculating the generalized statistics $\mathcal{MZ}$ according to formula (6), it is necessary to take into account the influence of the cross-correlation and to subtract corresponding values of the distribution modes, found for non-variable stars, from the obtained $\mathcal{MZ}_{Hp,BT}$, getting $\mathcal{MZ}0_{Hp,VT}$ and $\mathcal{MZ}0_{BT,VT}$. The corrected data points are denoted $\mathcal{MZ}0_{Hp,BT}$, $_{Hp,VT}$, $\mathcal{MZ}0_{BT,VT}$, and generalized as $\mathcal{MZ}0$.

3 Stars of Our Sample Listed as Variables in the GCVS and NSV Catalogs and the AAVSO VSX Database

An analysis of the $\mathcal{MZ}$ statistics for the stars identified as variables allows us to estimate the effectiveness of the $\mathcal{MZ}$ technique for discovering low-amplitude stars on the base of Hipparcos and Tycho data.

First, consider the stars with GCVS names. There are 181 of them in our sample of 8636 stars.

The fields H49–50 in the Hipparcos catalog contain respectively the 5th and 95th percentiles of the epoch photometry, i.e. $Hp(0.05)$ and $Hp(0.95)$. Thus, they provide an estimate of the magnitudes at maximum and minimum brightness detected during the time of observations.

We compared the $Ampl(Hp) = Hp_{min} - Hp_{max}$ differences to the $\mathcal{MZ}0$ parameter. The results for the 181 GCVS stars are shown in Figs. 3, 5, and 7.

Figure 3 shows that most points are grouped in an area where $\mathcal{MZ}0$ does not exceed 10 and the $Hp_{min} - Hp_{max}$ difference is not larger than $0\overset{\mathrm{m}}{.}1$. The highest values of $\mathcal{MZ}0$ were found for the stars TX UMa, V505 Per, and V2093 Cyg. TX UMa is an eclipsing

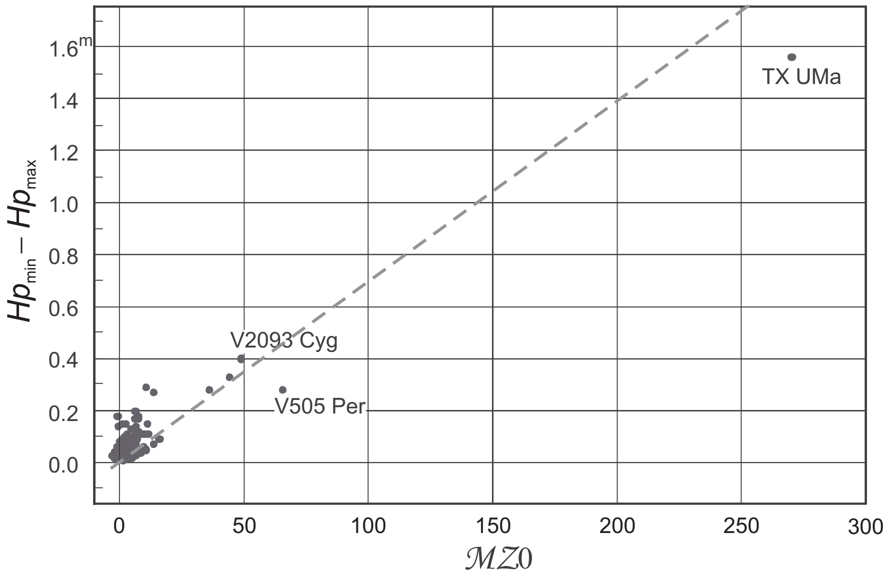

Figure 3. The relation between $\mathcal{MZ}0$ and the $Ampl(Hp) = Hp_{min} - Hp_{max}$ difference for the GCVS stars in our sample. The three stars with the highest $\mathcal{MZ}0$ values are marked.

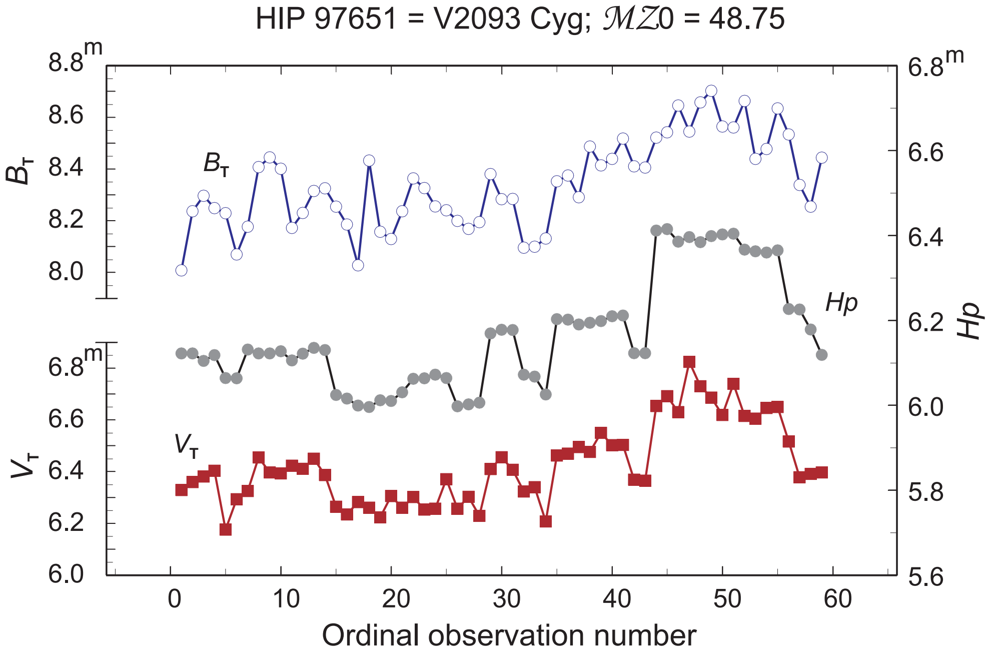

Figure 4. The light curves of the variable V2093 Cyg in the Hp, B_T and V_T bands. Hereafter, the figures showing light curves have B_T and V_T magnitudes labeled along the left ordinate axis, and Hp magnitudes, along the right one.

system of the EA/SD type. It has an amplitude of $1\overset{m}{.}74$ in V band and the period $3\overset{d}{.}06$. It is clear that the star was observed by Hipparcos in different phases and is easily detected by the $\mathcal{MZ}$ technique. The eclipsing variable V505 Per belongs to the EA/DM type, its amplitude being $0\overset{m}{.}59$. Hipparcos observed four eclipses, permitting the $\mathcal{MZ}$ technique to detect the variability reliably. V2093 Cyg has the type LB and an amplitude of $0\overset{m}{.}4$. As an example, the light curve of V2093 Cyg is shown in Fig. 4. Synchronous brightness changes in the three channels are clearly seen. $\mathcal{MZ}0$ is about 50; this value is very reliable

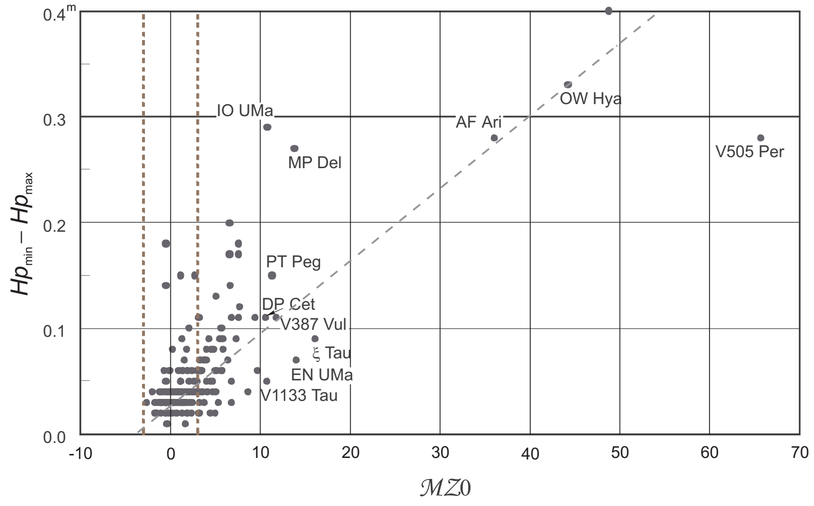

Figure 5. Same as in Fig. 3, for $\mathcal{MZ}0 < 50$. Variables in the $10 < \mathcal{MZ}0 < 50$ range are marked.

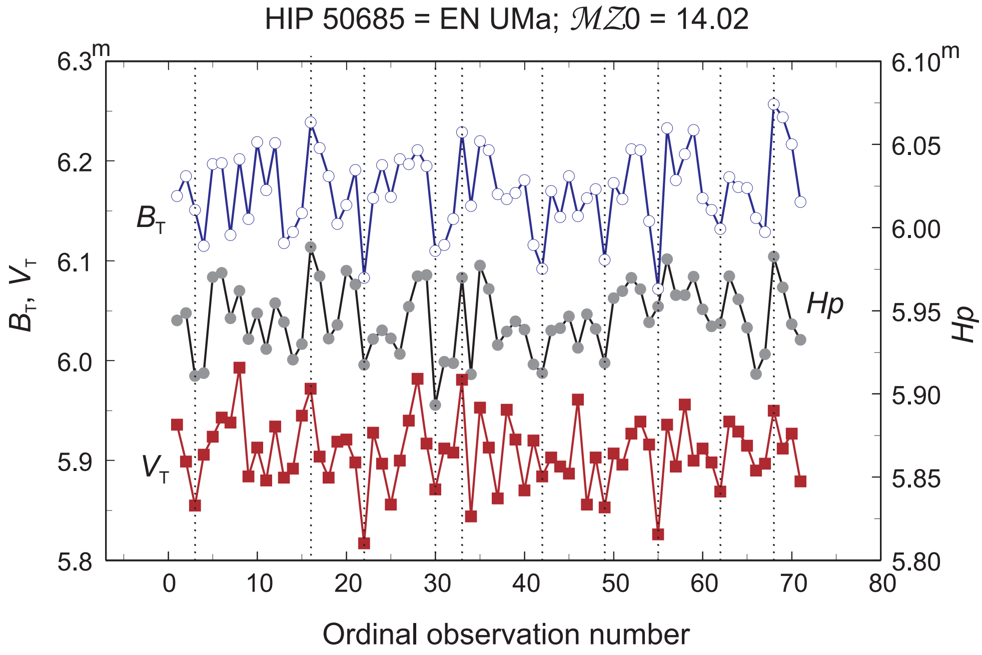

Figure 6. Brightness of EN UMa in the Hp, B_T, and V_T channels versus the ordinal number of observation. The vertical dashed lines mark the main correlated features of brightness variations that provided the high $\mathcal{MZ}$ value.

and indicates that the star is variable.

The area of $\mathcal{MZ}0 < 50$ is shown in more detail in Fig. 5.

The variables in the $10 < \mathcal{MZ}0 < 50$ range are marked in the figure. The figure convinces us that the $\mathcal{MZ}$-technique makes it possible to discover such variables as OW Hya, AF Ari, IO UMa, and MP Del without difficulties. These stars are eclipsing variables with amplitudes not exceeding $0\overset{\mathrm{m}}{.}25$. More interesting are the discoveries of EN UMa (DSCTC, amplitude $0\overset{\mathrm{m}}{.}05$) and V1133 Tau (LPB, amplitude $0\overset{\mathrm{m}}{.}04$). They confirm that the method is able to detect variability with amplitudes below the standard error in most channels. The light curve of EN UMa is shown in Fig. 6.

Figure 7 shows, in most detail, the area of the smallest $\mathcal{MZ}0$ values.

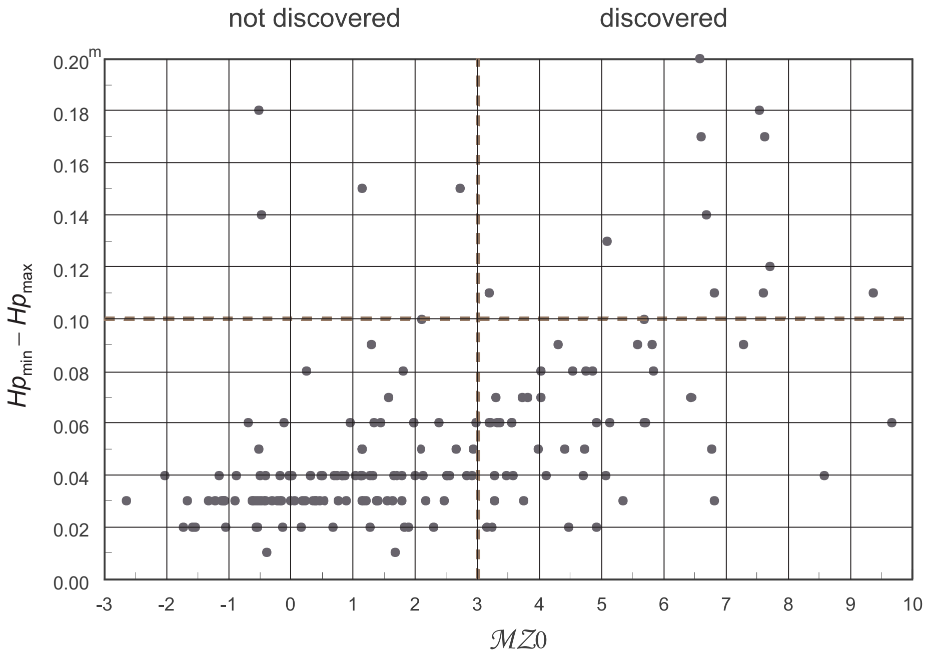

Figure 7. Same as in Fig. 3, for the $-3 < \mathcal{MZ} < 10$ range.

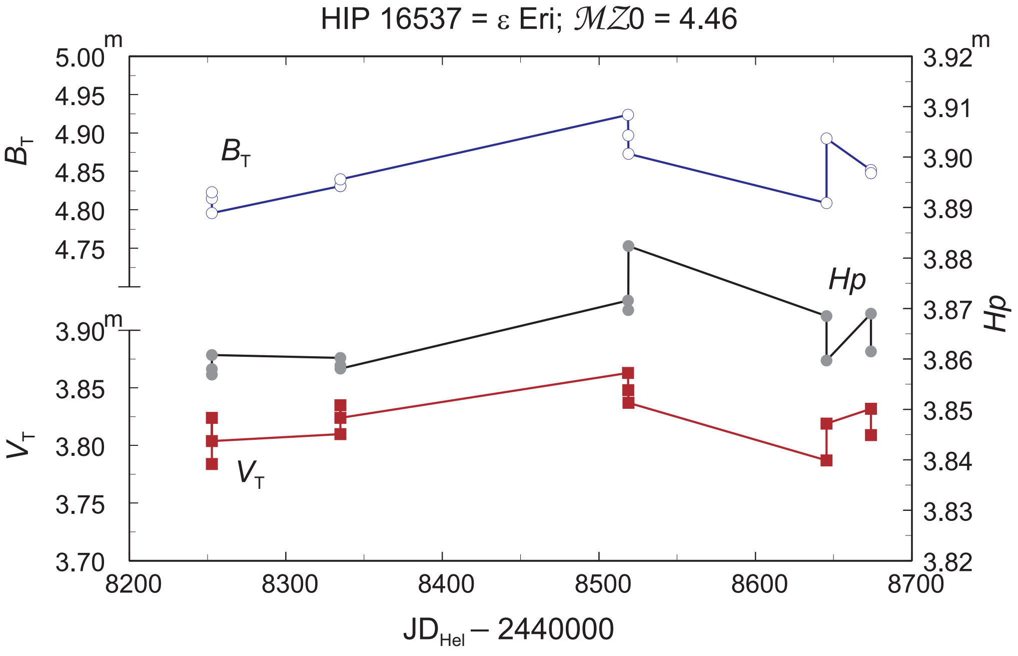

Figure 8. The light curves of HIP 016537 = ε Eri in the Hp, B_T, and V_T bands.

It follows from Fig. 7 that if $\mathcal{MZ}0 > 3$, then, according to the theory, we should expect the star to be variable. 54 stars are situated in the $3 < \mathcal{MZ}0 < 10$ range. The area of $\mathcal{MZ}0 < 3$ mainly contains variables with amplitudes of $0^{\rm m}_{.}05 <$ Ampl $< 0^{\rm m}_{.}08$. They are not detected, primarily because of large errors in the B_T and V_T channels.

Figure 8 shows the light curve of ε Eri. The star's variability type is BY. Despite the small number of observations (only 9 reliable simultaneous measurements in Hp, B_T, and V_T), there is a strong correlation.

Thus, on the base of simultaneous measurements in individual Hp, B_T, and V_T bands of the Hipparcos experiment, from 174 GCVS stars having $(Hp_{min} - Hp_{max})$ below $0\overset{m}{.}10$, the $\mathcal{MZ}$ technique found 43 variables (25%) at $\mathcal{MZ}0 = 3$ and 59 variables (34%) at $\mathcal{MZ}0 = 2$.

Consider now the stars of our sample contained in the NSV list. There are 504 such stars. They all lie in the $Hp_{min} - Hp_{max} < 0\overset{m}{.}1$ range. Their positions in the $\mathcal{MZ}$ vs $(Hp_{min} - Hp_{max})$ diagram are shown in Fig. 9. The following distribution of $\mathcal{MZ}0$ was found for these 504 stars:

$\mathcal{MZ}0$	Number of stars
$-3.2 < \mathcal{MZ}0 < 0$	164
$0 < \mathcal{MZ}0 < 1$	112
$1 < \mathcal{MZ}0 < 2$	106
$2 < \mathcal{MZ}0 < 3$	62
$3 < \mathcal{MZ}0 < 4$	28
$4 < \mathcal{MZ}0 < 5$	20
$5 < \mathcal{MZ}0 < 8.03$	13
Total	504

Among the stars under consideration, $\mathcal{MZ}0 > 2$ for 123 objects (24.4%); $\mathcal{MZ}0 > 3$ for 61 stars (12%); $\mathcal{MZ}0 > 4$ for 33 stars; and $\mathcal{MZ}0 > 5$ for 13 stars. Many of these stars should actually be variable. For example, the relation of B_T, V_T, Hp on the serial number of observation for NSV 24420 = HIP 89981 is shown in Fig. 10, and a similar relation for NSV 24923 = HIP 97757, in Fig. 11.

Both diagrams show repeated simultaneous deviations of brightness from the mean values.

Among the 504 NSV stars, 467 are listed in the AAVSO VSX database; 47 NSV stars do not enter the AAVSO list. The latter stars have the following NSV numbers:

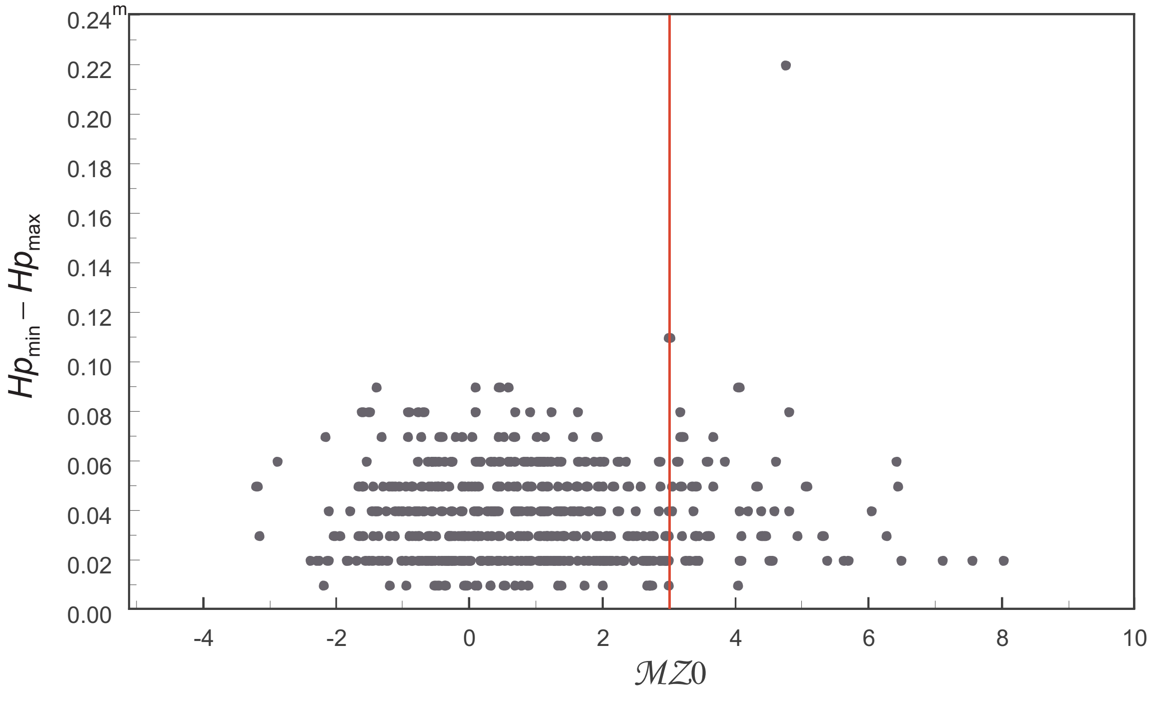

Figure 9. Positions of the NSV and NSVS stars on the $\mathcal{MZ}$ vs $(Hp_{min} - Hp_{max})$ diagram

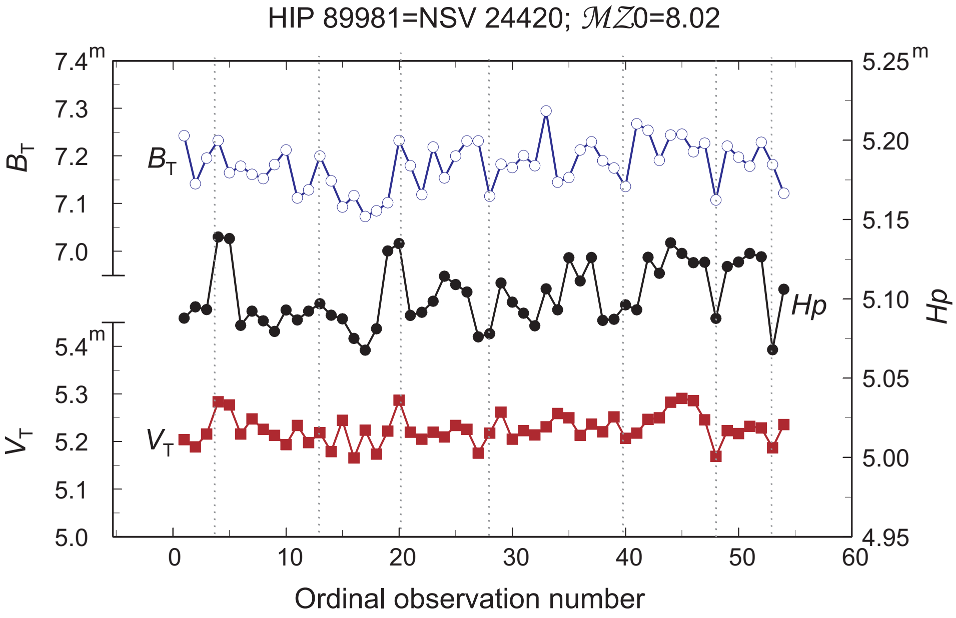

Figure 10. Simultaneously measured B_T, V_T, Hp magnitudes for NSV 24420 = HIP 89981 versus the ordinal number of the observation. $\mathcal{MZ}0 = 8.02$. The vertical dashed lines mark the most prominent correlated parts of the light curves. This star is variable with a high probability.

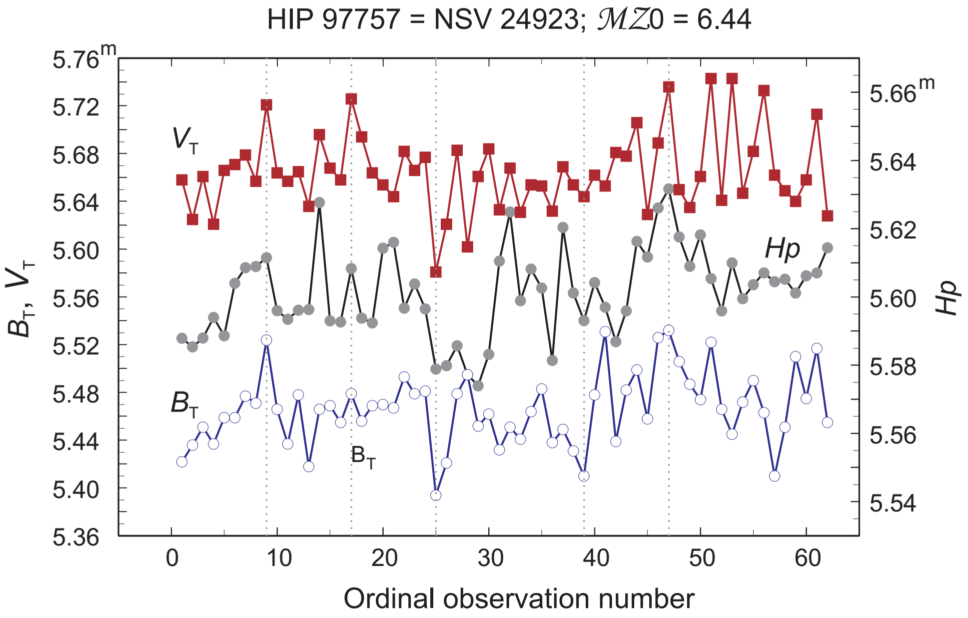

Figure 11. Simultaneously measured B_T, V_T, Hp magnitudes for NSV 24923 = HIP 97757 versus the ordinal number of the observation. $\mathcal{MZ}0 = 6.022$. The vertical dashed lines mark the most prominent correlated parts of the light curves. For clarity, the curves were shifted along the ordinate, by $0^{\rm m}\!.4$ downwards for the B_T band and by $0^{\rm m}\!.4$ upwards for V_T. This star is variable with a high probability.

02990, 05426, 09915, 13336, 15165, 15478, 15594, **15755**, 15816, **16228**, **16351,** 16353, 16390, 16738, 16744, 17418, 17882, 18090, 19580, 19751, 19940, **20099**, 20109, 20215, 20429, 20619, 20902, 20927, 23672, 23850, 24040, **24405**, 24406, **24626**, 24669, 24848, **24872**, **24881**, 24891, **24943**, 25003, **25772**, 25781, 25891, **25922**, 25999, 26115.

The numbers in boldface are stars with $\mathcal{MZ}0 > 2$.

Let us now consider briefly the stars from the AAVSO list. Among the 8636 stars in our sample, 792 stars enter the AAVSO Variable Star Index (VSX). 632 of them have GCVS names or NSV numbers (173 and 459 stars, respectively). 160 AAVSO stars are present neither in the GCVS nor in the NSV catalog, while 140 of them, according to the AAVSO data, are periodic variables with known periods.

Of the 181 stars listed in the GCVS, 8 stars are not contained in the VSX. We present these stars, with their MZ0 values, in Table 1.

Table 1

star	MV Dra	V0668 Lyr	V0831 Her	EZ UMa
$\mathcal{MZ}0$	-0.695	-0.512	0.894	1.304
$(Hp_{min} - Hp_{max})$	$0^m.06$	$0^m.05$	$0^m.03$	$0^m.04$
star	FX UMa	V0917 Ori	V0449 Aur	DP Cet
$\mathcal{MZ}0$	4.704	0.244	5.673	10.596
$(Hp_{min} - Hp_{max})$	$0^m.04$	$0^m.08$	$0^m.10$	$0^m.11$

The table shows that the $\mathcal{MZ}$-technique confirms the variability only for FX UMa, V0449 Aur, and DP Cet, but it should be remembered that using Hipparcos data for stars with amplitudes that low permits to detect only about 20% of all variables by means of the $\mathcal{MZ}$ technique.

4 An Analysis of the Variability Flags in the Hipparcos Catalog

First, we quote the description of the variability characteristics (flags in the field H52), as it is given in the documentation of the Hipparcos catalog.

"C" : "constant" stars or, more strictly, stars not detected as variable. These include stars used as photometric standards. The category also included cases noted as variable in the Hipparcos Input Catalogue. Caution must be exercised in assuming that entries flagged "C" are non-variable: they may be variable at levels below the Hipparcos detectability threshold, or they may have shown variability in the past (e.g. Be stars, or long-period eclipsing binaries);

"D": a "duplicity-induced variability" flag was assigned according to the difference between the "dc" and "ac" magnitudes and according to the angular separation and magnitude difference of a double or multiple system. If "D" is set the entry is not necessary a physical variable, and not necessary seen as variable in Hp ("dc scale");

"M": "possibly micro-variable", with amplitude below 0.03 mag (stars classified with high confidence as micro-variable are flagged "U");

"P": "periodic variable". This flag may supersede entries for which flag "D" is also appropriate;

"R": "revised colour index". When the flag "R" is set the $V - I$ index was corrected during the variability analysis, The effect of an erroneous $V - I$ index is a spurious linear trend in the Hp magnitude of the epoch photometry, with no physical origin. When identified during the data analysis, this could be taken into account in classifying the type of variability, i.e. whether spurious or not;

"U": "unsolved variable". Entries are classified as "unsolved" if they do not fall into the other variability categories – this class also includes irregular or semi-irregular variables, and possible variables with amplitudes more than 0.03 mag;

"␣": a "blank" indicates that the entry could not be classified as variable or constant with any degree of certainty (e.g. due to presence of one of more outliers in the epoch photometry).

181 GCVS stars of our sample have the following types of variability by Hipparcos:

"␣" (blank)	39
"M" (possibly micro-variable)	13
"P" (periodic variable)	49
"U" (unsolved variable)	58
"C" (constant)	22

22 stars are of type "C". They are V1728 Aql, AY Ari, KZ Cam, AV Cap, HT Cet, EP Cnc, KX Cnc, KU Com, LW Com, LS Com, LU Del, V0377 Gem, V0831 Her, V0401 Hya, HR Lib, V2711 Oph, V1260 Ori, V0400 Peg, BU Psc, PV UMa, FI UMa and EV Vir. All these stars have $\mathcal{MZ}0 < 1.28$, therefore, the $\mathcal{MZ}$ technique, strictly speaking, does not permit to establish variability of these stars based on the results of Hipparcos and Tycho photometry.

Among the 49 stars of "P" type, 33 stars have $\mathcal{MZ}0 > 2$, and 29 of them have $\mathcal{MZ}0 > 3$. Thus, the $\mathcal{MZ}$ technique confirms variability for most "P"-type stars.

Among the 58 stars of "U" type, 34 stars have $\mathcal{MZ}0 > 3$, and their variability is not in doubt. V2093 Cyg has the largest parameter, $\mathcal{MZ}0 = 48.75$.

Among the 13 stars of "M" type, three stars have large probabilities to be variable. These are ε Eri (see Fig 8), π Vir, ψ^2 Aqr. For these stars, $4.46 < \mathcal{MZ}0 < 6.81$. All the others have $\mathcal{MZ}0 < 3$.

39 stars of the "blank" type have $\mathcal{MZ}0$ values ranging from -2.65 to $+3.28$. Only two stars have $\mathcal{MZ}0 > 3$, and 3 stars have $\mathcal{MZ}0 > 2$. It appears that most stars of the "blank" type are not variable.

5 Selection of Stars That Are Most Likely Non-variable

We have decided that, in spite of the particular $\mathcal{MZ}0$-parameter, all stars contained in the GCVS, NSV catalog, in the AAVSO VSX database, or having the "U", "P", "D", and "M" Hipparcos variability types, as well as stars for which we are not able to calculate the $\mathcal{MZ}0$ parameter, should be excluded from the candidate standard stars. A total of 7249 stars was left at this stage.

Our further examination showed that there were numerous cases of stars with only one value: $\mathcal{MZ}0_{Hp,BT}$, or $\mathcal{MZ}0_{Hp,VT}$, or $\mathcal{MZ}0_{BT,VT}$, considerably in excess of 3, while the other parameters were within 2, or maybe even negative. Most often, we encounter $\mathcal{MZ}0_{BT,VT} > 3$, while $\mathcal{MZ}0_{Hp,BT}$ and $\mathcal{MZ}0_{Hp,VT}$ do not suggest simultaneous brightness variations. An example of deviations that are not due to the star's variability but to other causes is shown in Fig. 12. Such cases require additional future analysis.

As a result, we have decided to exclude all stars that have $\mathcal{MZ}0 > 2$ as well as those for which at least one of the parameters, $\mathcal{MZ}0_{Hp,BT}$, $\mathcal{MZ}0_{Hp,VT}$, or $\mathcal{MZ}0_{BT,VT}$ exceeds 3, from the list of the 7249 candidate standards. Thus, the list of candidates was reduced to 6484 stars. This list is given in Table 2, available electronically in the html version of this paper. The columns of the Table contain HIP numbers; HD numbers; RA(J2000), DE(J2000); spectral types from the Hipparcos catalog; V magnitudes, $W-B$, $B-V$, and $V-R$ color indices from the Tien Shan catalog; and the $\mathcal{MZ}0$ parameters.

We recommend to use these stars as standards in various astrophotomeric measurements.

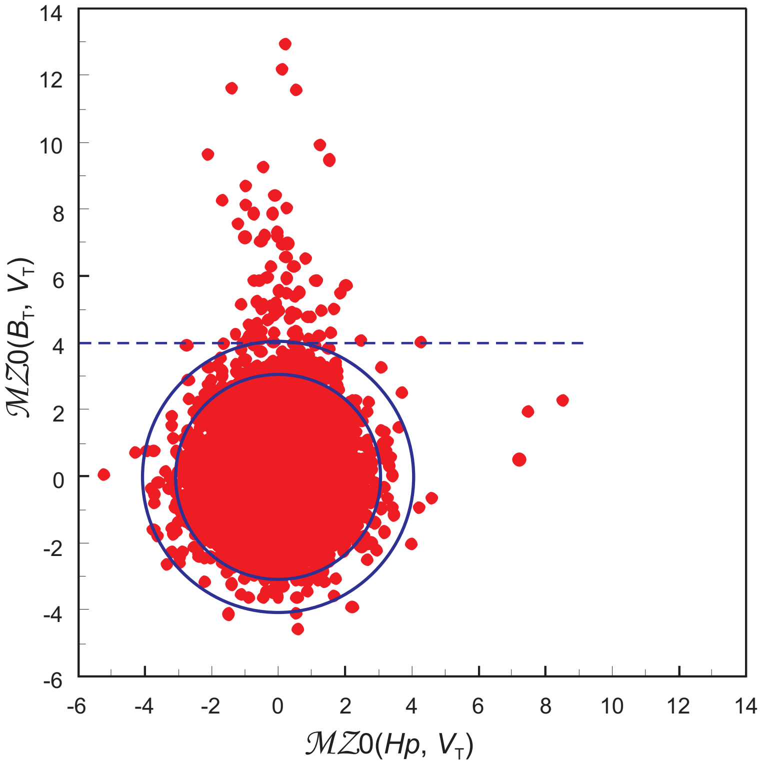

Figure 12. An example of the relation of $\mathcal{MZ}0_{BT,VT}$ on $\mathcal{MZ}0_{Hp,VT}$. The group of data points stretching along the ordinate at $\mathcal{MZ}0_{BT,VT} > 4$ does not reflect variability of the stars but instrumental features of the sky mapper channels.

6 Conclusion

With the exception of the "Hipparcos Epoch Photometry Annex" and "Tycho Epoch Photometry Annex" catalogs, there is no published data on individual simultaneous measurements of stellar magnitudes for extensive lists of stars. Using the data obtained in the Hipparcos experiment is hampered by the presence of large errors in individual measurements in the B_T and V_T channels and by the presence of strong correlations between the channels. The results of individual observations obtained in the process of preparation of catalogs like 2MASS and SDSS are not available. In addition, the results of ground-based observations are always distorted by the presence of correlation between the channels due to temporal variations of atmospheric extinction. It is hoped that the data to be obtained during the execution of the planned space experiments Gaia (Perryman et al. 2005) and Lyra (Zakharov et al. 2013a,b,c), will provide an opportunity to discover and investigate a large number of new variable stars and to get representative samples of different types of variables in different regions of the Galaxy. This will give a chance to obtain new data on the structure and development of the Milky Way.

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