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Dipole bulk velocity based on new data sample of galaxies from the catalogue 2MFGC

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We use the 2MFGC catalogue for investigation of large-scale flows on the basis of the Tully-Fisher relation (TFR). The catalogue contains 18020 galaxies selected from the extended sources of the infrared sky survey 2MASS XSC. The majority of galaxies in the catalogue are spiral galaxies of late morphological types whose discs are visible almost from the edge. For more than a decade of the catalogue usage, the number of galaxies in HyperLEDA database with the measured radial velocities and rotational velocities (that are necessary to construct the TFR) has been increased by about 17 %. In this paper, an updated working sample of 2MFGC galaxies is presented and earlier results are revised taking into account new data. We have confined ourselves to comparison of only the "old" and "new" parameters of the dipole component of the velocity field. The dipole bulk motion of galaxies of this sample with respect to cosmic microwave radiation is characterised by a velocity of $V = 264 \pm 36$ km/s in the direction $l = 308° \pm 8°$, $b = -16° \pm 6°$.

Key words: galaxies, Tully-Fisher relation, bulk velocity of galaxies

INTRODUCTION

Karachentsev justified the use of late morphological types spiral galaxies for investigation of large-scale flows [2] on the basis of the Tully-Fisher relation (TFR). Aiming this, three catalogues of flat galaxies were created: FGC(E) (Flat Galaxy Catalogue and its southern Extension) [3], RFGC (Revised FGC) [4] and 2MFGC (The 2MASS-selected Flat Galaxy Catalogue) [11]. In the present paper we use the 2MFGC catalogue containing 18020 galaxies selected among the extended sources of the infrared sky survey 2MASS XSC [1] with respect to the infrared axes ratio $b/a < 0.3$ approximately corresponding to the optical axes $a/b > 6$. The majority of galaxies in the catalogue are spiral galaxies of late morphological types whose discs are visible almost from the edge.

In 2006 a sample of $N = 3074$ 2MFGC galaxies with known rotation velocities and radial velocities which were necessary for constructing the TFR was created [5]. Individual distances and peculiar velocities of 2724 galaxies of the sample were determined based on multiparameter infrared TFR [5] and published [6]. The dipole bulk motion of galaxies of this sample with respect to cosmic microwave radiation is characterised by a velocity of $V = 199 \pm 37$ km/s in the direction $l = 304° \pm 11°$, $b = -8° \pm 8°$ (in Galactic coordinates).

The sample of 2724 2MFGC galaxies at the time of its creation was one of the most representative and homogeneous samples intended for analysis of non-Hubble galaxy movements at a scale of ~ 100 Mpc. However, over the recent 10 years the number of 2MFGC galaxies with the necessary data has increased significantly. So, in December of 2016 there were ~ 3750 such galaxies in the HyperLEDA database[1]. The aim of this work is to revise earlier results taking into account the new data and using the main TF relation parameters (rotation and radial velocities) from the HyperLEDA database exclusively. In addition to a significantly increased sample this guarantees a unified approach to mutual recalculation of the widths of the 21 cm radioline (at different levels of peak values) and the maximal rotational velocity V_{rot} associated with them.

The second circumstance that must be taken into account revising earlier results is presence of a list of "false" objects among 2MFGC galaxies [12]. The disk-like galaxies catalogue 2MFGC consisting of 18020 objects of the whole sky was automatically selected from 1.64 million extended objects of the 2MASS XSC catalogue [1]. It turned out, that "false" objects included into XSC further moved to the 2MFGC catalogue. They appear due to the false

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association of two or more galaxies and stars during the photometric procedure (when stars project onto the galaxy image). Besides, galaxy with an oblong red bar or bulge, which spiral structure appears only in the visible range, could simulate flat edge-on galaxy. To reduce the impact of such errors several thousand images of galaxies were reconsidered in frames (J, H, K_s) of 2MASS and DSS1 (First Digitized Sky Survey) during the compilation of the 2MFGC. However, with time the need of a complete review of images of 2MFGC objects became clear. The results of the revision were published in [12]. It turned out that 1512 objects of total 18020 were "false". We excluded these object from the consideration in the present paper.

MULTI-PARAMETER TFR AND A SEQUENCE OF CALCULATIONS

Multiparameter TFR is used to take into account possible physical causes of the spread of conventional (two-parameter) TFR by introducing additional regressors. Summarising the results of previous papers (see, e. g., [5]) we adopt the following seven-parameter TFR:

$$M_{\rm K} = C_1 + C_2 \cdot \log W_c + C_3 \cdot Jhl + C_4 \cdot Jcdex + C_5 \cdot (J^c - K^c_s) + C_6 \cdot \log r_{25} + C_7 \cdot t \equiv \equiv \sum_j C_j x^j. \quad (1)$$

Here $W_c = 2V_{rot}/(1+V_{\rm h}/c)$ is the radioline 21 cm "width" corrected for the cosmological expansion, in fact determined by the doubled maximum rotation velocity from HyperLEDA; $V_{\rm h}$ is the heliocentric radial velocity of the galaxy; c is the speed of light. The first two terms on the right-hand side of Eq. 1 are the main regressors of the TFR. The remaining five terms are designed to track the correlation of the absolute magnitude $M_{\rm K}$ with the effective surface brightness Jhl , the concentration index $Jcdex$ (the ratio of the radii within which the 3/4 and 1/4 light of the galaxy are concentrated), the colour $J^c - K^c_s$, the decimal logarithm of the axes ratio $\log r_{25}$ and the numeric code t of the morphological type. Here J^c and K^c_s are the apparent J and K_s magnitudes corrected for the absorption in the Galaxy: $J^c = J - 0.207 \cdot A_{\rm g}$, $K^c_s = K_s - 0.084 \cdot A_{\rm g}$, in accordance with [13], $A_{\rm g}$ is absorption in the Galaxy in the B-band. We have not taken into account internal absorption, since its values are presented in HyperLEDA for a much smaller number of objects, what substantially reduces the sample. The values $\log r_{25}$, $A_{\rm g}$, t were taken from HyperLEDA; J, K_s, Jhl, $Jcdex$ were taken from the 2MFGC (XSC) catalogue. Differences from regression in [5] consist in the presence of an additional regressor with a numerical code of morphological type and calculation of the absolute M_K value, rather than the M_J value, on the left side of Eq. 1.

At the first stage of the calculations we calibrate the model (Eq. 1), that means the calculation of the coefficients C_j, $j = 1, \ldots, 7$ by the method of least squares with unit weights. To do this, for each galaxy the absolute K_s-magnitude (on the left side of Eq. 1) was estimated by the formula:

$$M_{\rm K} = K^c_s - 5 \log d - 25 \quad (2)$$

where d is the luminosity distance in Mpc estimated from the radial velocity in the 3K (cosmic microwave background radiation) system,

$$d = V_{3K}/H_0.$$

The Hubble constant was assumed to be 72 km/s/Mpc. The velocity V_{3K} was calculated from $V_{\rm h}$ according to [7].

In the second stage, we find the distances from Eq. 2 with the absolute magnitude calculated from the calibrated TFR (Eq. 1),

$$d = {\rm dex}[0.2 \cdot (K^c_s - \sum_j C_j x^j - 25)],$$

and find the individual peculiar velocities of the galaxies

$$V_{\rm pec} = V_{3K} - H_0 d$$

Finally, in the third stage, the obtained array of peculiar velocities was used to calculate the orthogonal components $\vec{V} = (V_1, V_2, V_3)$ of the dipole bulk velocity

$$V_{{\rm pec},i} = \vec{V} \cdot \vec{e}_i + V_{p,i}$$

by minimising the sum of the squares of the "noise" component of the peculiar velocity (i is the serial number of the galaxy in the sample). Here $\vec{e}_i = (\cos l_i \cos b_i, \sin l_i \cos b_i, \sin b_i)$ is the unit vector of the direction to the i-th galaxy in the frame associated with the Galactic coordinates l, b. On the orthogonal components we calculate the modulus and direction of the bulk motion of 2MFGC galaxies. We calculated the errors in this way. First we found the diagonal components B_{VV}, B_{ll}, B_{bb} of the covariance matrix $\hat{B}$ in the basis $\{\vec{e}_V, \vec{e}_l, \vec{e}_b\}$ and then determined the errors as $\Delta V = (B_{VV})^{1/2}$, $\Delta l = \arctan\{(B_{ll})^{1/2}/V\}$, $\Delta b = \arctan\{(B_{bb})^{1/2}/V\}$.

The same as in [5], we exclude galaxies that deviate more than $3\sigma_{TF}$ from the TFR, as well as the galaxies whose individual peculiar velocities in the 3K system exceeded 3000 km/s, supposing that such deviations are due to observation errors, and not physical causes. "Cleaning" of the data was carried out until the process of exclusions converged.

Table 1: Coefficients of TFR.

j	—	1 (1)	2 ($\log W_c$)	3 (Jhl)	4 ($Jcdex$)	5 ($J^c - K^c$)	6 ($\log r_{25}$)	7 (t)	σ_{TF}, N
1	C_j	−20.57	−4.096	0.508	−0.0664	−1.750	0.327	0.0266	0.712
	ΔC_j	0.52	0.085	0.022	0.0127	0.086	0.079	0.0089	$N = 3619$
	F_j	1591	2315	534	27.3	410	17.0	8.8	
2	C_j	−12.28	−6.059	0.278	0.0053	−1.190	0.393	0.0214	0.449
	ΔC_j	0.40	0.072	0.016	0.0086	0.061	0.054	0.0060	$N = 3173$
	F_j	945	7079	309	0.039	376	53.2	12.7	
3	C_j	−12.25	−6.054	0.276	—	−1.182	0.396	0.0211	0.449
	ΔC_j	0.40	0.072	0.016	—	0.060	0.054	0.0060	$N = 3173$
	F_j	955	7158	314	—	388	54.7	12.7	
4	C_j	−12.98	−5.873	0.292	0.0038	−1.249	0.405	0.0256	0.458
	ΔC_j	0.40	0.070	0.016	0.0086	0.062	0.052	0.0059	$N = 3262$
	F_j	1070	6956	341	0.037	410	60.5	18.3	
5	C_j	−12.75	−6.534	9.320	—	—	—	—	0.477
	ΔC_j	0.41	0.071	0.015	—	—	—	—	$N = 3173$
	F_j	978	8566	472	—	—	—	—	
6	C_j	−4.41	−7.488	—	—	—	—	—	0.511
	ΔC_j	0.15	0.059	—	—	—	—	—	$N = 3173$
	F_j	897	15982	—	—	—	—	—	

NEW SAMPLE AND CALIBRATION OF TFR

Our previous sample of 2MFGC galaxies was compiled from many original sources, as well as the NED and HyperLEDA databases (see [5]). It consisted of 3074 objects. However, not all of them were suitable for research on the basis of TFR and its multiparameter generalisations. After applying the cleaning criteria mentioned above we obtained a sample of 2724 galaxies. For this sample individual distances and peculiar velocities were calculated according to [5], and the parameters of the multipole structure of the velocity field [8] were estimated on the basis of the relativistic model of the velocity field [9].

The construction of the new sample is described below. For every object included to our sample we demanded a non-zero value of the TFR parameters, such as $V_{\rm rot}$, $V_{\rm h}$, $\log r_{25}$, t, $A_{\rm g}$ in HyperLEDA and Jhl, $Jcdex$, J, K_s in 2MFGC catalogues. This condition gave us a sample of size $N = 3743$. The exclusion of "false" objects reduces the sample to $N = 3619$, consequently, in the sample $N = 3743$ with all the necessary data 124 objects are "false".

First block of Table 1 contains coefficients C_j of dependence (Eq. 1), their errors ΔC_j and the significance in terms of Fisher statistics F_j for the sample of $N = 3619$. As it can be seen, for this sample we obtained a rather large scatter of points on the TF diagram, $\sigma_{TF} = 0.^m712$. After successively performing eight iterations of the exception we obtained a sample of 3173 galaxies that is characterised by a spread $\sigma_{TF} = 0.^m449$ and formally corresponds to an accuracy of $\sim 19\,\%$ of the distance determination. In Figure 1 TF diagrams in the plane ($\log W_c, M_{\rm K}$) before sample cleaning ($N = 3619$) and after ($N = 3173$), respectively, are shown. The coefficients, their errors and the significance for the cleaned sample $N = 3173$ are given in the second block of Table 1. Hence, discarding of 446 galaxies (12 % of the sample) leads to reducing of scatter of the TFR by 1.6 times. The regressor with concentration index appeared to be insignificant for the cleaned sample ($F_4 = 0.039$, comparing to the Fisher quantile $F_{1,\infty}(99\%) = 6.63$). For the sample $N = 3173$ we calculated parameters of the 6-parameter regression in the form of Eq. 1, but without the concentration index; the results are given in the third block of Table 1. The coefficients of block 2 and block 3 differ negligibly among themselves.

It is interesting how many "false" objects would be removed from the sample during the cleaning process if they were left it in the sample $N = 3743$. It turned out that 12 objects of the 124 "false" objects are discarded by the 3σ criterion, 23 objects — by the criterion of 3000 km/s and 4 — by both criteria.

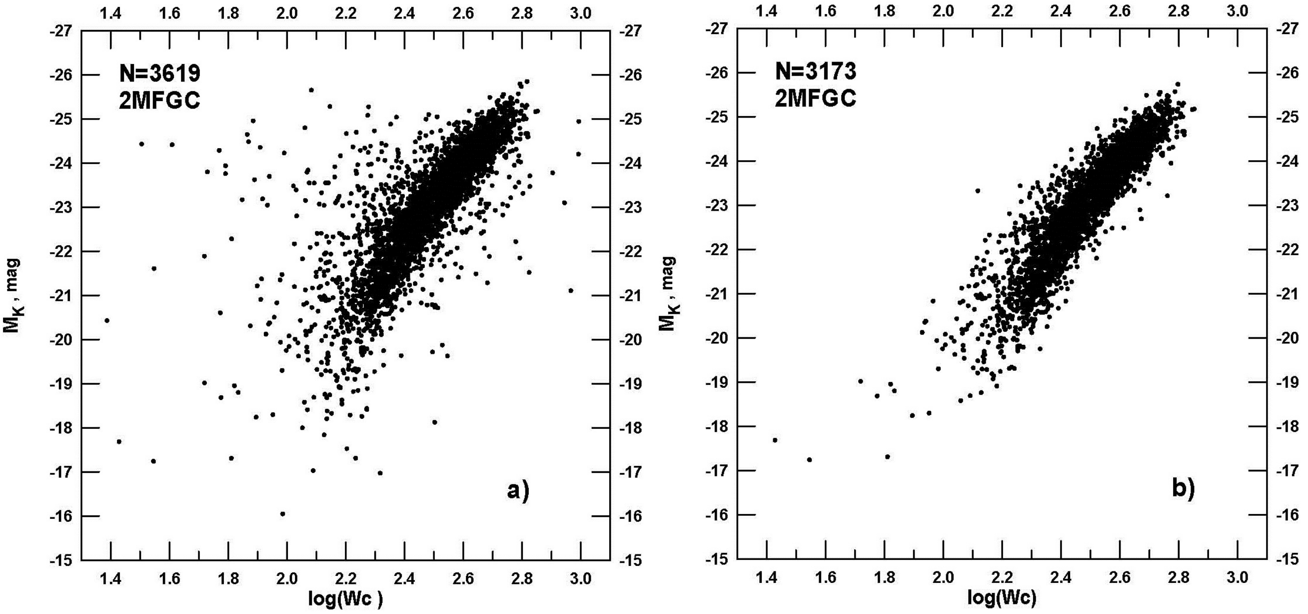

Fig. 1: TF diagrams in the plane $(\log W_c, M_{\rm K})$: before (left) and after (right) cleaning of the sample.

In total, 39 "false" objects of 124, or 31.5 %, are discarded. The remaining 85 "false" ones have data compatible with the TFR. The coefficients of the TFR for the sample $N = 3262$ obtained by cleaning the sample $N = 3743$ are presented in the 4th block of Table 1. Comparison with the data of block 2 shows that the "false" objects do not play an important role in the calibration of the TFR.

A similar situation is observed for the old 2006 sample [5]. As it appeared only 29 "false" objects were among 350 objects that were rejected according to the above criteria. In total, in the 2006 sample there were 119 "false" objects, that is, 76 % of false ones remained in the working sample and formally corresponded to TFR.

For comparison, in blocks 5 and 6 of Table 1 for the sample $N = 3173$ we gave the coefficients of the 3-parameter TFR with surface brightness, which is sometimes called the Fundamental Plane for spiral galaxies, and the coefficients of the usual 2-parameter TFR. As can be seen, the spread of these TFRs increased comparing to our main regression of block 3 in Table 1 by 6 % and 14 %, respectively.

THE DIPOLE COMPONENT OF THE BULK VELOCITY

We constructed the histograms of the distributions for the sample $N = 3173$ basing on the arrays of distances and peculiar velocities. Figure 2 shows a histogram of the distribution of galaxies in the sample $N = 3173$ over distances $H_0 d$ calculated in the present study. As can be seen from the histogram, the sample is approximately complete to $H_0 d = 5000 \div 6000$ km/s. After $H_0 d = 6000$ km/s there is a sharp drop in the number of galaxies. There are average distance $\langle H_0 d \rangle = 5925$ km/s, standard deviation from average, $\sigma_{H_0 d} = 2829$ km/s, asymmetry $\gamma_1 = 0.790 \pm 0.043$, kurtosis $\gamma_2 = 0.797 \pm 0.087$.

Figure 3 shows the distribution of galaxies of the same sample $N = 3173$ on peculiar velocities. There are distribution parameters: mean $\langle V_{\rm pec} \rangle = 65$ km/s, deviation $\sigma_{V_{\rm pec}} = 1055$ km/s, asymmetry $\gamma_1 = (-1.67 \pm 4.34) \cdot 10^{-2}$, kurtosis $\gamma_2 = (-8.72 \pm 8.68) \cdot 10^{-2}$. As can be seen, the distribution of peculiar velocities is close to normal.

Using the array of peculiar velocities we calculated the dipole bulk velocity.

Table 2 shows the sample size, the orthogonal components of the dipole velocity (in km/s) in the frame associated with the Galactic coordinates, the dipole velocity modulus (in km/s) and the Galactic coordinates of the apex (in degrees).

In the first row of Table 2 there are parameters of our basic determination of the dipole bulk velocity for a new sample. This determination was obtained for the sample $N = 3173$ based on the 6-parameter regression of block 3 in Table 1. In the second row for comparison we present the results of [5] for the old sample $N = 2724$. As can be seen, using the new data the bulk velocity modulus appeared to be almost 2σ greater and the apex latitude appeared to be almost 1σ lower for approximately the same apex longitude.

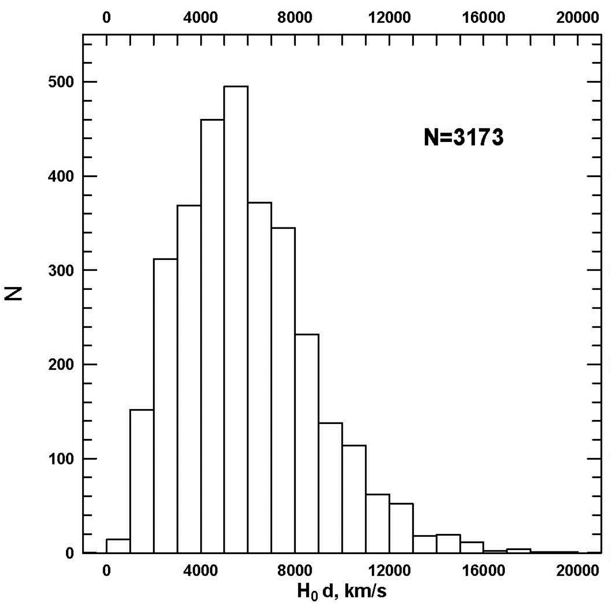

Fig. 2: Distribution of distances H_0d to galaxies of sample $N = 3173$.

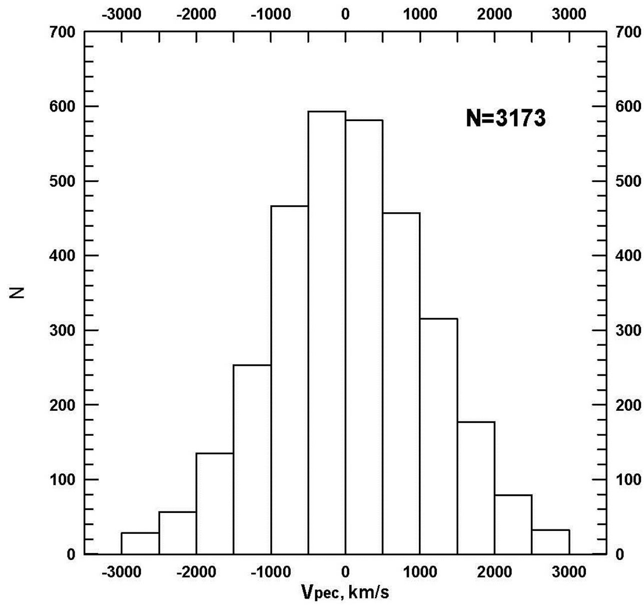

Fig. 3: Distribution of peculiar velocities of galaxies of sample $N = 3173$.

Table 2: Dipole component of bulk velocity in Galactic coordinates.

	Sample	V_1	V_2	V_3	$\|V\|$	l	b
1	$N = 3173$	156 ± 35 (19.4)	-199 ± 36 (30.7)	-74 ± 29 (6.7)	264 ± 36	308 ± 8	-16 ± 6
2	$N = 2724$	110 ± 37 (8.9)	-163 ± 37 (19.2)	-29 ± 30 (0.08)	199 ± 37	304 ± 11	-8 ± 8
3	$N = 2604$	111 ± 36 (9.4)	-196 ± 37 (28.1)	-39 ± 30 (1.6)	229 ± 37	300 ± 9	-10 ± 7

Together with the rejection of "false" objects we carried out (based on the TFR adopted in [5]) a recalculation of the dipole parameters for the old sample $N = 3074$ which in this case was reduced to a sample of $N = 2956$. After cleaning we received the sample $N = 2604$ on the basis of which the dipole parameters had the values given in the third row of Table 2. Comparison with the data of the second line leads to the conclusion that the presence in the working sample of "false" objects (number 118) does not significantly affect the parameters of the dipole: both components of the dipole velocity as well as its modulus and the coordinates of the apex differ within the limits of errors. The maximum difference is close to the 1σ value (but less) for the component V_2.

CONCLUSIONS

In this paper an updated sample of flat galaxies from the 2MFGC catalogue was created. The sample was designed to investigate their collective movements using the Tully-Fisher infrared multiparameter relation. The necessity to update the sample was dictated by at least two reasons: the presence in the HyperLEDA database of new data for construction of the TFR and detection of a sufficiently large number of "false" objects [12] which were discovered more than 10 years after the catalogue was created. According to the sample "goodness" $G = (N/100)^{1/2}/\sigma_{TF}$, introduced in [10] ($N$ is the number of galaxies and σ_{TF} is their dispersion on the TF diagram), the new sample appeared to be somewhat better: the indicator G increased to 12.5 compared to 11.1 for the old sample of 2006 year [5].

Using the data for the new sample several variants of the multiparameter TFR were calibrated and the most accurate dependence was determined. Based on it the individual distances and pecular velocities the parameters of the dipole bulk velocity were calculated. New parameters of the dipole bulk motion based on new sample 3173 of 2MFGC galaxies are: bulk velocity $V = 264 \pm 36$ km/s in the direction $l = 308° \pm 8°$, $b = -16° \pm 6°$. A comparison with the results for the old sample [5] was made: the collective velocity module appeared to be almost 2σ larger and the apex latitude is almost 1σ lower for approximately equal apex longitudes. The accuracy of the determination of the bulk velocity module remained almost unchanged but the accuracy of determination of the coordinates of the apex was improved by 25-30 %. We are going to consider higher multipoles on a new sample in another work.

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