BLUESHIFTED GALAXIES IN THE VIRGO CLUSTER

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We examine a sample of 65 galaxies in the Virgo cluster with negative radial velocities relative to the Local Group. Some features of this sample are pointed out. All of these objects are positioned compactly within a virial zone of radius 6° in the cluster, but their centroid is displaced relative to the dynamic center of the cluster, M 87, by 1.°1 to the northwest. The dwarf galaxies in this sample are clumped on a scale of ∼10' (50 kpc). The observed asymmetry in the distribution of the blueshifted galaxies may be caused by infall of a group of galaxies around M 86 onto the main body of the cluster. We offer another attempt to explain this phenomenon, assuming a mutual tangential velocity of ∼300 km s^{-1} between the Local Group and the Virgo cluster owing to their being repelled from the local cosmological void.

Keywords: galaxies: blueshifted: Virgo

1 Introduction

Of the approximately one million galaxies with measured radial velocities, about a hundred of them have negative radial velocities relative to the center of the Local Group. If we exclude the 31 galaxies which form part of the Local Group (LG), the rest are distributed over the sky in an extremely nonuniform fashion: two dwarf spheroidal galaxies (KK 77 and IKN) with velocities of –96 and −1 (±60) km s^{-1}, respectively, are satellites of the neighboring M 81 spiral, while the remaining 65 galaxies are concentrated in the central region of the nearest cluster in Virgo around the giant elliptical galaxy Virgo A = NGC 4486. It is possible that several other blueshifted galaxies exist in the group nearest us around the giant galaxies Maffei 1, Maffei 2, and IC 342, but it is very difficult to measure radial velocities in this region of the sky because of the strong ($\sim 5^m - 6^m$) absorption and emission by hydrogen in the Galaxy. It is evident that the observed distribution over the sky of galaxies with negative radial velocities reflects both the depth and the proximity to us of neighboring potential wells; that is, it contains important information on the local segment of the evolving large-scale structure.

2 List of blueshifted galaxies in Virgo

According to the Virgo Cluster Catalog [1] the population of the cluster numbers more than 2000 members, most of which are dwarf irregular (dIr), elliptical (dE), and spheroidal (dSph) systems. Their overall number has increased with time as a result of different surveys of galaxy redshifts in the northern sky, as well as because of special programs aimed at studying the kinematics of the Virgo cluster [2–9]. As Binggeli et al. [7], as well as others, have shown the Virgo cluster consists of several subclusters which differ in their average velocities, dispersions in their velocities, and dominant types in their populations; this suggests that the dynamic relaxation of the cluster is incomplete. The bulk of the population of Virgo is concentrated around the brightest galaxy NGC 4486 (M 87). The X-ray intensity peak of the hot intergalactic gas in Virgo also lies in M 87, which suggests that this radio galaxy is the dynamic center of the cluster. According to Binggeli et al. [7], the average heliocentric velocity of the main Virgo cluster is $+1050 \pm 35$ km s^{-1} with a standard deviation of $\sigma = 650$ km s^{-1}. Here the average and standard deviation depend significantly on the choice of boundaries for the cluster and the morphological type of the galaxies.

At the time [7] was published, the total number of galaxies with negative radial velocities relative to the centroid of the Local Group ($V_{LG} < 0$) was 42. For some of the galaxies (VCC 584, VCC 1035) the negative velocities have not been confirmed by subsequent, more accurate measurements. A great advance in the study of the kinematics was provided by a "blind" survey of the cluster in the HI line at the Arecibo radio telescope [10–12], as well as by the appearance of new radial velocity data from the Sloan Digital Sky Survey SDSS [13]. Here it should be noted that the SDSS survey yielded improved values for the radial velocities of the members of Virgo, but it also produced a number of false "galaxies" with velocities $V_h \simeq 0$. Fig. 1 shows the distribution of the radial velocities of ∼800 galaxies in the central region of Virgo. A sharp peak can be seen near $V_h \simeq 0$ owing mainly to binary stars which are, nevertheless, listed in the HyperLeda

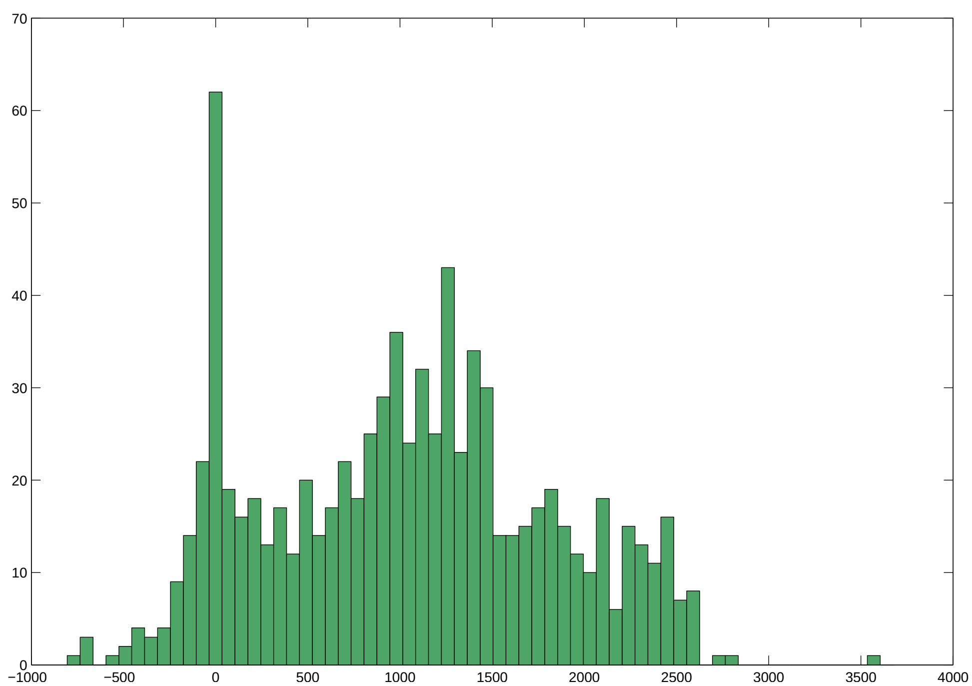

Fig. 1. The distribution of the measured radial velocities of the 825 galaxies in the vicinity of the Virgo cluster. The peak near zero velocity is caused by "star spam" from the SDSS survey.

data base as galaxies. It is evident that more than one hundred of these observations can significantly distort the statistics of blueshifted galaxies in Virgo.

Table 1. List of Virgo cluster galaxies with negative radial velocities.

Designation (1)	RA (J2000.0) Dec (2)	V_h (3)	$\pm$	V_{LG} (4)	Type (5)	B_T (6)	Notes (7)
IC3036	12 12 15.08 +12 29 17.7	−2	38	−126	Sm	14.66	
IC3044	12 12 48.49 +13 58 34.6	−182	4	−298	SBc	14.23	
VCC087	12 13 41.27 +15 27 13.0	−159	2	−267	Sm	15.20	
NGC4192	12 13 48.29 +14 54 01.6	−135	7	−246	Sb	10.85	
NGC4212	12 15 39.38 +13 54 05.7	−84	4	−199	Sc	11.78	
VCC181	12 16 14.63 +13 35 11.6	−150	32	−267	Im	17.42	
VCC200	12 16 33.71 +13 01 53.1	22	24	−98	E	14.80	
A224385	12 16 49.76 +13 30 14.4	−87	4	−204	BCD	18.42	
IC3094	12 16 56.03 +13 37 31.6	−159	6	−275	Sab	14.43	
VCC237	12 17 29.40 +14 53 10.0	−323	5	−423	Sdm	16.79	
IC3105	12 17 33.72 +12 23 17.6	−162	3	−284	Sm	14.75	
VCC322	12 19 05.05 +13 58 52.1	−209	10	−323	IAB	15.36	Foreground?
VCC334	12 19 14.27 +13 52 56.1	−236	4	−350	BCD	16.14	
VCC501	12 21 47.99 +12 49 36.1	−105	33	−224	E	17.29	Noisy SDSS Sp
IC3224	12 22 36.12 +12 09 27.0	10	5	−100	BCD	16.6	
VCC628	12 23 15.47 +07 41 22.2	−398	10	−540	Ir	18.43	
VCC636	12 23 21.23 +15 52 06.2	−9	28	−113	S0	16.48	
IC3258	12 23 44.45 +12 28 39.4	−473	6	−593	IB	13.66	Merger?
IC3303	12 25 15.20 +12 42 52.3	−309	25	−427	E	14.75	
VCC788	12 25 16.82 +11 36 19.5	121	29	−3	E	16.79	
VCC802	12 25 29.06 +13 29 53.6	−204	3	−318	Ir	17.61	
IC3311	12 25 33.06 +12 15 37.8	−166	10	−287	Scd	14.70	
VCC810	12 25 33.56 +13 13 38.1	−354	30	−470	E	16.63	Noisy SDSS Sp
VCC815	12 25 37.20 +13 08 37.7	−750	27	−866	E	16.33	
VCC846	12 25 50.56 +13 11 51.8	−729	30	−845	E	16.20	
NGC4396	12 25 58.94 +15 40 16.6	−112	5	−215	Scd	13.09	
VCC877	12 26 09.56 +13 40 23.3	−99	56	−212	E	17.68	
NGC4406	12 26 11.69 +12 56 46.0	−258	23	−374	E	9.83	
VCC892	12 26 20.04 +12 30 36.6	−666	68	−784	E:	18.45	
NGC4413	12 26 32.21 +12 36 38.6	103	5	−16	Sab	12.87	
VCC928	12 26 39.80 +12 30 48.2	−276	23	−395	E	16.23	
IC3355	12 26 51.29 +13 10 27.8	−10	6	−126	IB	15.41	Foreground?
VCC953	12 26 54.74 +13 33 58.3	−450	30	−563	E	15.91	
NGC4419	12 26 56.44 +15 02 50.9	−277	8	−383	SBa	11.99	
VCC997	12 27 22.18 +12 04 07.5	−240	118	−360	E	18.25	Noisy SDSS Sp
KDG132	12 27 31.64 +09 36 08.6	32	33	−100:	Ir	16.43	SDSS Sp for a knot
NGC4438	12 27 45.58 +13 00 31.8	73	8	−43	Sa	10.93	
SDSS	12 28 25.86 +11 14 25.1	124	50	−0	E	18.25	
VCC1129	12 28 44.98 +12 48 35.7	12	138	−105	E	17.75	
VCC1163	12 29 06.43 +14 00 18.5	−453	26	−564	E	16.56	
VCC1175	12 29 18.20 +10 08 09.2	11	3	−118	BCD	15.37	
VCC1198	12 29 32.06 +13 30 37.8	−357	37	−470	E	17.82	
IC3416	12 29 34.98 +10 47 35.8	−72	41	−198	Ir	15.04	

(1)	(2)	(3)		(4)	(5)	(6)	(7)
VCC1239	12 29 51.18 +13 52 04.6	−561	28	−672	E	15.68	
VCC1264	12 30 10.91 +12 11 44.1	−420	59	−539	E	16.90	
IC3435	12 30 39.85 +15 07 47.3	−45	22	−150	S0	15.53	
VCC1314	12 30 49.03 +13 13 26.1	77	40	−37	E	17.34	
IC3445	12 31 19.42 +12 44 16.9	−354	23	−470	E	16.49	
IC3471	12 32 22.85 +16 01 08.3	−135	2	−235	Sdm	15.47	
IC3476	12 32 41.82 +14 03 04.0	−170	7	−280	Sdm	13.36	
IC3492	12 33 19.80 +12 51 12.8	−489	25	−604	E	14.73	
IC3548	12 35 56.62 +10 56 10.9	86	28	−37	E	16.08	
VCC1682	12 36 36.72 +14 13 32.8	41	36	−66	E	17.86	
NGC4569	12 36 49.86 +13 09 48.1	−233	4	−345	Sa	10.11	
UGC7795	12 37 45.34 +07 06 14.0	62	3	−78	Ir	14.72	Foreground?
VCC1750	12 38 15.54 +06 59 39.1	−117	10	−258	BCD	16.76	
VCC1761	12 38 27.74 +14 04 38.2	−162	27	−269	E	16.95	
KDG172	12 39 13.86 +15 37 49.4	57	10	−42	Ir	17.61	
VCC1812	12 39 55.55 +11 51 28.5	−234	41	−351	E	17.31	
VCC1860	12 40 57.29 +15 16 31.1	−24	40	−124	E	18.12	Noisy SDSS Sp
IC3658	12 41 20.65 +14 42 02.4	34	20	−69	E	14.94	
UGC7857	12 41 54.24 +13 46 22.8	101	31	−7	E	14.72	
VCC1909	12 42 07.45 +11 49 42.0	101	38	−16	E	16.16	
IC0810	12 42 09.11 +12 35 48.8	−75	23	−188	S0	14.25	
VCC2028	12 45 37.48 +13 19 42.8	56	28	−52	E	16.72	

We have made a detailed analysis of the available observational data and, by excluding the "star spam", compiled a list of 65 galaxies in Virgo with $V_{LG} < 0$. These are listed in Table 1. The columns of the table list the following data on the galaxies: (1) galaxy number in standard catalogs, (2) equatorial coordinates at the epoch J2000.0, (3) average heliocentric radial velocity and the error in it, (4) radial velocity relative to the centroid of the Local Group with the apex parameters from [14] used in the NED, (5) morphological type, (6) B-band apparent total magnitude, and (7) brief comments. Of the 65 galaxies in this list, the radial velocities of 27 have been determined with high accuracy using the HI line.

The distribution of the blueshifted galaxies with respect to their radial velocities V_{LG} and apparent magnitudes m_B is shown in Fig. 2. The galaxies of early types (E, S0, dE, dSph) are indicated by red circles, and those with a young population (S, dIr, BCD) are indicated by blue ones. For a distance to the Virgo cluster of 17.0 Mpc [15] and an absolute magnitude for the dwarf galaxies fainter than -16.5^m, their relative number in the sample is 80 %. Of the 13 galaxies with normal and high luminosities, only one, NGC 4406, is elliptical.

Fig. 3 shows the distribution of the galaxies with negative velocities over the sky in equatorial coordinates. The virial region of the cluster, with a radius of $\Theta_{VIR} = 6.^\circ 0$, is indicated by a large circle. The galaxies of earlier and later types are indicated in the same way as in the previous figure. The position of the galaxy M 87 as the physical center of the cluster is indicated by a cross. The inclined straight line corresponds to the

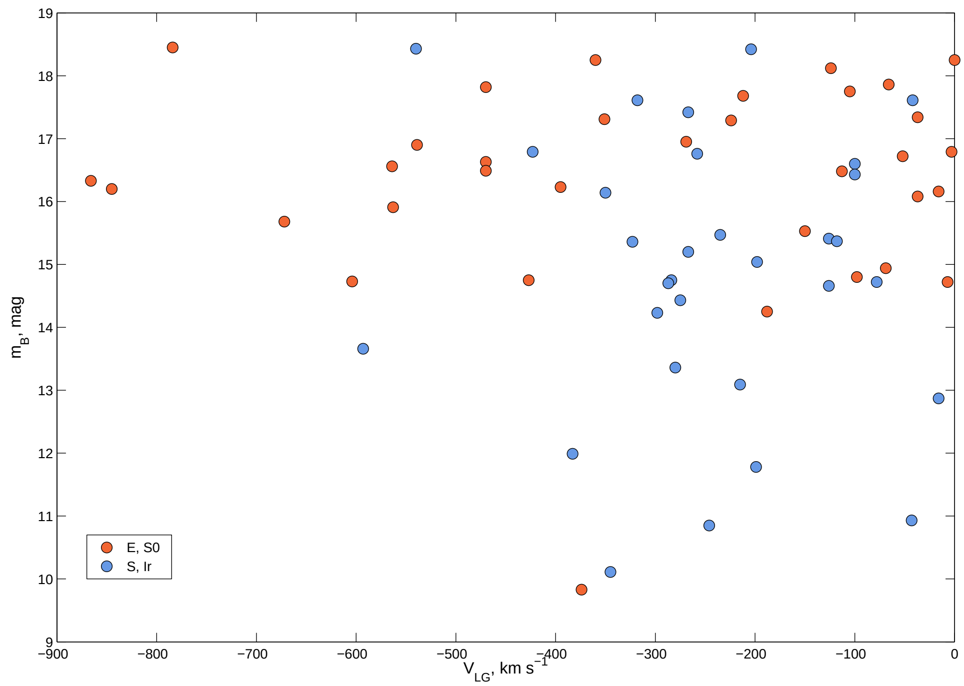

Fig. 2. Apparent magnitudes and radial velocities of galaxies in Virgo that are approaching us. Galaxies of early (E, S0, dSph) and late (S, Ir, BCD) types are indicated, respectively, by red and blue circles.

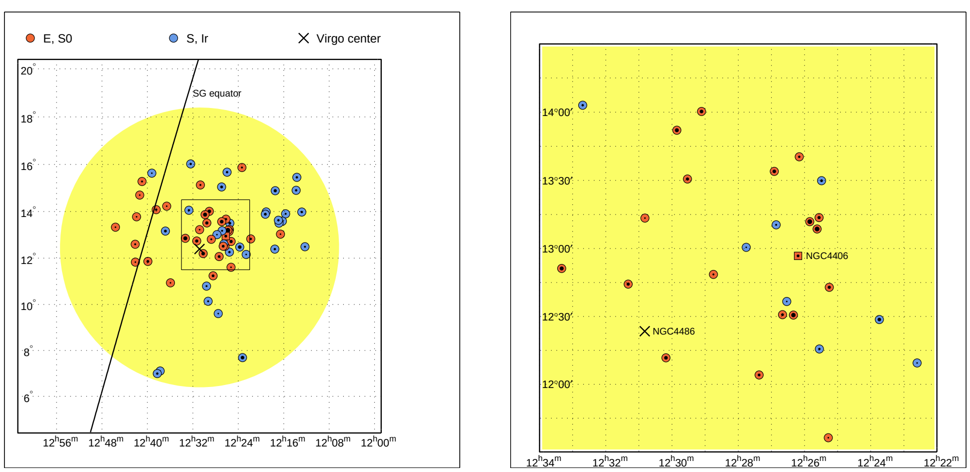

Fig. 3. The distribution in equatorial coordinates of the 65 galaxies with negative radial velocities. The circle, of radius 6°, filled with yellow color marks the virial zone of the cluster around the radio galaxy M 87, which is indicated by an X. The densest region (the square) is magnified in the frame on the right.

supergalactic equator. The thick central zone, itself, is shown enlarged in the right hand frame of the figure.

3 Some features of the distribution of blueshifted galaxies

The distribution over the sky of the 65 galaxies with negative radial velocities is characterized by several features that may be important for understanding the kinematics and evolution of the cluster.

(a) The blueshifted galaxies are distributed over the sky much more compactly than the rest of the population of Virgo. All the galaxies with $V_{LG} < 0$ lie, without exception, inside the virial radius $\Theta_{VIR} = 6\overset{\circ}{.}0$ of the cluster.

(b) The centroid of the present sample does not coincide with the dynamic center of Virgo (M 87), and is shifted significantly to the NW by $1\overset{\circ}{.}10 \pm 0\overset{\circ}{.}35$.

(c) The galaxies of early and late types have significantly different positions relative to the center of the cluster: E and SO galaxies lie predominantly to the east, while objects with a young population (dIr, BCD, S) lie mainly to the west and south.

(d) The dwarf galaxies with $V_{LG} < 0$ manifest a small scale clumping effect. Thus, the galaxies VCC 181, AGC 224385, and IC 3094 form a triplet in projected onto the sky, while VCC 322 and VCC 334 form a pair with a small difference in radial velocities. Other examples of multiple systems are VCC 810/815/846, VCC 892/928, and UGC 7795/VCC 1750. The characteristic scale of the clumping for these objects is $\sim$ 10' or 50 kpc, while the median difference in their velocities is about 70 km s^{-1}. These groups contain galaxies with young, as well as old, populations. If it is real, the dynamic isolation of these pairs and triplets within the cluster is highly unexpected.

4 Discussion

Binggeli et al. [7] and Jerjen et al. [16] proposed an explanation for the observed shift of the centroid of the galaxies with negative velocities relative to the dynamic center of Virgo in terms of a separate grouping of galaxies associated with the giant elliptical galaxy NGC 4406 (M 86). In the sky this galaxy lies near the centroid of the blueshifted galaies (see the right hand frame of Fig. 3), and its radial velocity, -374 km s^{-1}, is close to the average velocity of our sample of galaxies (see Fig. 2). According to these authors, M 86, together with the cloud of satellites surrounding it, is incident onto (merging with) the center of Virgo (M 87) from the further edge of the cluster at a relative velocity of $\sim$ 1400 km s^{-1}, which is a bit more than twice the mean square virial velocity of the members of Virgo. Moving at this velocity, M 86 and its companions will intersect the virial radius of the cluster (1.8 Mpc) after 1.3 billion years and will continue moving towards our Galaxy.

The distances to M 86 and six other galaxies with negative radial velocities, VCC 200, VCC 810, VCC 815, VCC 846, VCC 928, and NGC 4419 have been measured [15–17] from the surface brightness fluctuations (SBF). The distance of M 86, itself, 17.5±0.4 Mpc, and the average distance of the other six galaxies, 17.3±1.1 Mpc are the same, to within the limits of error, as the average for the cluster as a whole (17.0 Mpc).

The hypothesis according to which the grouping of galaxies around M 86 is incident on the main body of the cluster centered at M 87 seems quite plausible, as it is consistent with the general paradigm of cluster formation through the merger of small clumps (groups). However, the reason for the observed spatial segregation in terms of morphological types among the galaxies of Virgo with negative radial velocities is still unclear. The scenario in which the cloud around M 86 transits through the virial zone of Virgo does not provide an explanation for the observed bunching of dwarf galaxies in the cloud of M 86 on a scale of ∼50 kpc, since low mass multiple systems of this sort could easily be destroyed by tidal forces in the central zone of the cluster. Numerical simulation of the passage of an association of dwarf groups through the central region of the Virgo cluster might help resolve this puzzle.

In addition to the above features, there is yet another distinct tendency that can be seen in the subsystem of blueshifted galaxies in Virgo. If we restrict the sample to ever more negative values of V_{LG}, then the position in the sky of the centroid of the remaining galaxies shifts systematically to the NW, while the spread in the positions of the galaxies relative to the sliding centroid becomes smaller. The upper frame of Fig. 4 illustrates the drift in the sky of the centroid of the galaxies, which range in terms of V_{LG} from zero to the maximum negative value (–866 km s^{-1}). The positions of the sliding centroid are indicated by dots which are joined by straight lines. The numbers next to them correspond to the number of galaxies in the averages and the numbers in parentheses, to the average radial velocities obtained by averaging the radial velocities of the 15, 20, 25, ..., 65 members of the sample. The lower frame of Fig. 4 shows the analogous drift of the centroid, but with the reverse ordering, from –866 km s^{-1} to zero. The behavior of the sliding centroid in the plots of Fig. 4 is obviously difficult to match with a simple picture where all the blueshifted galaxies form a group around NGC 4406 which is incident, as a whole, on the Virgo cluster with its center alongside NGC 4486.

Another argument can be advanced for explaining the observed features of the galaxies in Virgo with $V_{LG} < 0$. Let the kinematics of the cluster correspond to strictly radial motion in a spherically symmetric cluster with no significant substructures. Evidently, the galaxies with the highest peculiar velocities, both toward and away from the observer, will be concentrated within the narrowest zone of the cluster near its physical center. In this picture, the extreme negative velocities in Virgo should be expected right around M 87, where the velocities of the galaxies are directed almost strictly along the line of sight. But this would be true only if the centroid of the Local Group does not have a tangential velocity relative to the Virgo cluster. If the centers of the Local Group and Virgo move at a mutually tangential velocity V_{tang}, then for two galaxies located at the edges of the virial diameter of Virgo along the direction of the vector V_{tang}, the projection of this component would lead to a difference of $\Delta V = 2 \times \sin \Theta_{VIR} \times V_{tang}$ in the radial

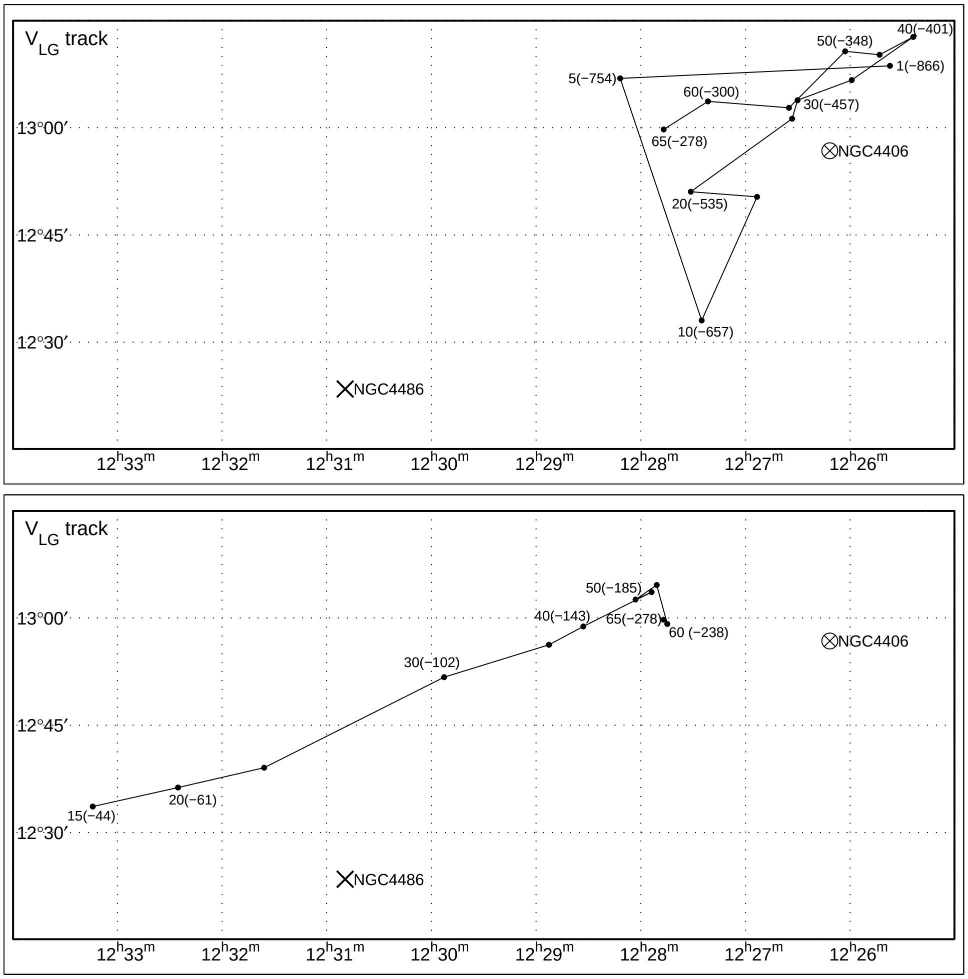

Fig. 4. The position of the centroid of the galaxies, arranged according to the magnitude of their negative radial velocity, as a function of the number of averaged objects with a step size of 5. The numbers in parentheses are the average velocity in km s^{-1}. The upper and lower frames correspond to two different ways of averaging.

velocities. This in turn, would produce a visible shift of the centroid of the galaxies selected for their negative velocities.

In a study of the local peculiar velocity field of galaxies with measured distances, Tully et al. [18] have determined three main components of the velocity of the Local Group, which together yield its observed motion relative to the cosmic microwave background at a velocity of 630±20 km s^{-1}. One component corresponds to infall of the Local Group on Virgo at a velocity of 185±20 km s^{-1}, the second, to recession from the Local Void at a velocity of 259±25 km s^{-1}, and the third, at 455±15 km s^{-1} is oriented toward the massive Great Attractor (GA) in the HydraCentaurus constellations. These three components are roughly mutually perpendicular. Since the center of the Virgo cluster lies almost on the equator of the Local Supercluster, and the Local Void lies near the supergalactic pole, with V_{tang} = 259 km s^{-1} and $\theta_{VIR} = 6^{\circ}$ we can expect a gradient of the local velocity

$\Delta V \simeq 54$ km s^{-1} oriented in Fig. 2 at a right angle rightward of the equator of the local supercluster. Since the angular size of the infall zone around Virgo is $\Theta_0 = 23°$ [19], the drop in the radial velocities within it cannot exceed $\Delta V \simeq -183$ km s^{-1}. The magnitude of the shift in the centroid of the galaxies with $V_{LG} < 0$ induced by this effect depends on the structural and kinematic features of Virgo. Dividing the sample of 65 galaxies with $V_{LG} < 0$ into two halves by a line on the sky parallel to the supergalactic equator, we obtain an average difference of the radial velocities between the right and left halves of -68 ± 51 km s^{-1}. When the sample is split into two by a line perpendicular to the line joining the galaxies M 86 and M 87, this difference increases to -139 ± 49 km s^{-1}. Thus, we have rough agreement between the expected and observed effect of a tangential velocity in terms of both direction and magnitude. Including the other component of the LG velocity, directed toward the Great Attractor, can improve this agreement once we note that the Virgo cluster (closer to the GA) should be incident on the GA at a higher velocity than the Local Group. This mutual motion produces an additional component of the tangential velocity of the LG relative to Virgo, directed toward the opposite side from the GA (i.e., to the NNW in Fig. 2). Of course, the roles of the various components of the mutual motion of the LG and Virgo require more detailed study.

5 Conclusions

Research on the distribution of the members of the Virgo cluster with extremely high peculiar velocities directed toward or away from us is an important, but still little used tool for understanding the structure and kinematics of this closest cluster. In principle, for choosing between a picture of the merger of individual groups of galaxies with the main body of the cluster or an effect involving mutually tangential motion of the Local Group and Virgo, one could also draw on galaxies with high positive velocities ($\sim 2000 - 2500$ km s^{-1}). However, the distant background of Virgo includes many galaxies with such velocities, so it would be difficult to interpret the observational data.

It should be emphasized that the faintest galaxies in our sample have absolute magnitudes MB brighter than -12.5^m. We might expect that the cluster contains a still larger number of faint galaxies, including some with negative radial velocities. An increase in their statistics is extremely desirable for more detailed analysis of the kinematics of Virgo.

It is also important to note the need to measure the individual distances for objects with $V_{LG} < 0$ in Virgo. Here the most promising method for estimating the distances continues to be the use of surface brightness fluctuations (SBF) of dE and dSph galaxies. The Tully-Fisher method which is applied to dIr and BCD galaxies does not, unfortunately, provide the accuracy needed to distinguish objects at the front and back edges of the cluster. For them, the only bulk method is to determine the distances from the luminosity of the tip of the red giant branch with the aid of the HST and other orbital telescopes.

There is some interest in searching for ultracompact dwarf galaxies with negative radial velocities in Virgo. Judging from the scenarios discussed in the literature [20, 21], dwarf galaxies of this type are formed as a result of their spending a long time in the densest virial zone of a cluster. Thus, observation of even one ultracompact dwarf with $V_{LG} < 0$ would counter the idea that a loose cloud of galaxies surrounding M 86 is incident on (merging with) the main body of the cluster.

Further observational effort must obviously be supplemented by numerical simulations of the kinematics of those members of Virgo with extremely high peculiar velocities.

This work was supported by grants RFBR 07–02–00005 and RFBR-DFG 06–02–04017.

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