INFALL OF NEARBY GALAXIES INTO THE VIRGO CLUSTER AS TRACED WITH HUBBLE SPACE TELESCOPE

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ABSTRACT

We measured the tip of the red giant branch distances to nine galaxies in the direction to the Virgo cluster using the Advanced Camera for Surveys on the Hubble Space Telescope. These distances put seven galaxies (GR 34, UGC 7512, NGC 4517, IC 3583, NGC 4600, VCC 2037, and KDG 215) in front of Virgo and two galaxies (IC 3023 and KDG 177) likely inside the cluster. Distances and radial velocities of the galaxies situated between us and the Virgo core clearly exhibit the infall phenomenon toward the cluster. In the case of spherically symmetric radial infall, we estimate the radius of the “zero-velocity” surface to be \( (7.2 \pm 0.7) \) Mpc, which yields a total mass of the Virgo cluster of \( (8.0 \pm 2.3) \times 10^{12} \) \( M_\odot \), in good agreement with its virial mass estimates. We conclude that the Virgo outskirts do not contain significant amounts of dark matter beyond their virial radius.

Key words: galaxies: clusters: individual (Virgo) – galaxies: distances and redshifts – galaxies: kinematics and dynamics

Online-only material: color figures

1. INTRODUCTION

In the standard \( \Lambda \)CDM cosmological model, groups and clusters are built from the merging of already-formed galaxies embedded in massive dark haloes (White & Rees, 1978). Besides the dynamically evolved core, characterized by a virial radius \( R_v \), any cluster has a more extended region where galaxies are falling toward the cluster center. In the simplest case of spherical symmetry, the region of infall has a “surface of zero-velocity” at a radius \( R_0 \) that separates the cluster from the global Hubble expansion. The ratio \( R_0/R_v \) lies in the range of 3.5–4.0 and is slightly dependent on the adopted cosmological parameter \( \Omega_\Lambda \) (Tully 2010; Karachentsev 2012).

As it has been noted by different authors (Vennik 1984; Tully 1987; Crook et al. 2007; Makarov & Karachentsev 2011; Karachentsev 2012), the total virial masses of nearby groups and clusters leads to a mean local density of matter of \( \Omega_m \simeq 0.08 \), that is, 1/3 of the mean global density \( \Omega_m = 0.24 \pm 0.03 \) (Spergel et al. 2007). One possible explanation of the disparity between the local and global density estimates may be that the outskirts of groups and clusters contain significant amounts of dark matter beyond their virial radii, beyond what is anticipated from the integrated light of galaxies within the infall domain.

If so, to get agreement between local and global values of \( \Omega_m \), the total mass of the Virgo cluster (and other clusters) must be three times their virial masses. A measure of this missing mass can be made by mapping the pattern of infall into the cluster (or group). Uniquely in the case of the Virgo cluster, it is possible to resolve the location of galaxies in three dimensions and separate peculiar galaxies of infall from cosmic expansion as well as from virial motions. The possibility of a massive dark superhalo around Virgo can be easily tested using accurate distances at the near surface of the Virgo infall boundary with tip of the red giant branch (TRGB) measurements.

As shown by Lynden-Bell (1981) and Sandage (1986), in the case of a spherical over-density with cosmological parameter \( \Lambda = 0 \), the radius \( R_0 \) depends only on the total mass of a group (cluster) \( M_T \) and the age of the universe \( t_0 \):

\[
M_T = \left( \frac{\pi^2}{8G} \right) R_0^3 t_0^{-2},
\]

where \( G \) is the gravitational constant. Measuring \( R_0 \) via distances and radial velocities of galaxies outside the virial radius of the system \( R_v \), one can determine the total mass of the system independent of its virial mass estimate.

Numerous measurements of distances to nearby galaxies obtained recently with the Hubble Space Telescope (HST) allowed us to investigate the Hubble flow around the Local Group (LG; Karachentsev et al. 2009) and some other nearest groups: M 81 (Karachentsev & Kashibadze 2006) and Cen A. The average total-to-virial mass ratio for the proximate groups, derived from \( R_0 \) via Equation (1) and from \( R_v \), turns out to be \( (M_T/M_v) = 0.60 \pm 0.15 \) (Karachentsev 2005). However, as it was not by Peirani & Pacheco (2006, 2008) and Karachentsev et al. (2007), in a flat universe dominated by dark energy, the resulting \( M_T(R_0) \) mass is higher than that derived from the canonical Lemaître-Tolman Equation (1). In the “concordant” cosmological model with \( \Lambda \) term and \( \Omega_m \) as a matter component, Equation (1) takes the form

\[
M_T = \left( \frac{\pi^2}{8G} \right) R_0^3 h_0^2 / f^2(\Omega_m),
\]

where

\[
f(\Omega_m) = (1 - \Omega_m)^{-1} - (\Omega_m/2)(1 - \Omega_m)^{-3/2} \times \arccos \left( \frac{2}{\Omega_m} - 1 \right).
\]
Assuming $\Omega_m = 0.24$ and $H_0 = 72$ km s$^{-1}$ Mpc$^{-1}$, one can rewrite Equation (2) as

$$\left(\frac{M_T}{M_\odot}\right) = 2.12 \times 10^{12} \left(\frac{R_0}{\text{Mpc}}\right)^3.$$ (4)

It yields a mass that is 1.5 as large as derived from the classic Equation (1). This correction leads to a good agreement on average between the $R_0$ mass estimates and virial masses for the galaxy groups discussed above.

The most suitable object to explore the infall phenomena on a cluster scale is the nearest massive cluster of galaxies in Virgo. The kinematics and dynamics of Virgo cluster infall were studied by Hoffman et al. (1980), Tonry & Davis (1981), Hoffman & Salpeter (1982), Tully & Shaya (1984), Teerikorpi et al. (1992), and Ekholm et al. (1999, 2000). In a model developed by Tonry et al. (2000, 2001) based on distance measurements of 300 E and S0 galaxies via their surface brightness fluctuations, the Virgo cluster with its center distance 17 Mpc and virial mass $M_v = 7 \times 10^{14} M_\odot$ generates an infall velocity of the LG toward Virgo of about 140 km s$^{-1}$. With this value of the virial mass, the expected radius of the infall zone is $R_0 = 7.0$ Mpc or $\Theta_0 = 23^\circ$ in angular measure. Recently, Karachentsev & Nasonova (2010) considered the existing data on radial velocities and distances of 454 galaxies situated within $\Theta = 30^\circ$ around the Virgo and came to the conclusion that the value of the radius $R_0$ lies in the range 5.0–7.5 Mpc. In the standard $\Lambda$CDM model with the parameters $\Omega_m = 0.24$ and $H_0 = 72$ km s$^{-1}$ Mpc$^{-1}$ (Spergel et al. 2007), these quantities of $R_0$ correspond to a total cluster mass $M_T = 2.7-8.9 \times 10^{14} M_\odot$.

The mass estimate derived from external galaxy motions does not contradict the virial mass obtained from internal motions. However, the present accuracy is insufficient to judge whether or not the periphery of the Virgo cluster contains a significant amount of dark matter outside its virial radius $R_v = 1.8$ Mpc (Hoffman et al. 1980).

### 2. EXPECTED PATTERN OF THE INFALL

Figure 1 represents the picture of Virgo-centric infall based on current observables collected by Karachentsev & Nasonova (2010). It shows a relation between radial velocities in the LG rest frame and distances of galaxies within a cone of radius $\Theta_v = 6^\circ$, covering the virialized core. Galaxy samples with distances derived by different methods are marked by different symbols. The unperturbed Hubble flow with a slope of $H_0 = 72$ km s$^{-1}$ Mpc$^{-1}$ is given by an inclined dashed line. The solid and dotted lines correspond to the mean Hubble flow in a model of a point-like cluster mass with $2.7 \times 10^{14}$ and $8.9 \times 10^{14} M_\odot$.

The distance of the Virgo cluster itself is now well established by observations of Cepheid variables in four galaxies. The Cepheid distances anchor precision relative distances for 84 galaxies with HST surface brightness fluctuations (SBF) measurements (Mei et al. 2007; Blakeslee et al. 2009) and four galaxies with Type Ia supernovae (SN) measurements (Jha et al. 2007). These galaxies reside in the cluster core at $R_{13} = (16.5 \pm 2)$ Mpc and therefore are useless as tracers of the Virgo-centric infall.
At large distances on the diagram, behind the Virgo cluster, while most distance measures are based on the optical or infrared Tully–Fisher (TF) relation with typical errors of ~20%, there is one very well constrained group. The Virgo W’ group around NGC 4365 (de Vaucouleurs 1961) with ($V_{LG}$) $\simeq$ 1000 km s$^{-1}$ contains one galaxy with both a Cepheid and SNIa measurement and five other galaxies with $HST$ SBF measurements. These observations locate Virgo W’ at 23 Mpc, 6.5 Mpc behind Virgo. The group velocity and distance indicate that this group lies very near the edge of the Virgo infall zone at $R_0$ on the far side of the cluster.

The most feasible way to trace the Z-like wave of Virgo-centric infall in detail is to make distance measurements to galaxies on the front side of the cluster via the TRGB method. This method (Lee et al. 1993) is applicable to galaxies of all morphological types and provides the needed distance accuracy of ~5%–7% (Rizzi et al. 2007). The greatest precision will be achieved with lines of sight tight to the cluster where projection factors with radial motions will be minimal. Unfortunately, in the virial cone $\Theta_\ast = 6^\circ$, there is no foreground galaxy with a literature TRGB distance. In the wider area with $\Theta < 15^\circ$, there are only two galaxies (NGC 4826 and GR-8) with existing TRGB distances between the LG and Virgo.

### 3. SELECTION OF TARGETS

The scarcity of TRGB data on the near side of the Virgo-centric infall wave can be understood. In the past, targets for TRGB distance measurements with $HST$ were usually galaxies from the Kranz-Korteweg & Tammann (1979) sample with radial velocities $V_{LG} < 500$ km s$^{-1}$. In the Virgo core direction, a galaxy with a velocity $\sim 500$ km s$^{-1}$ may be a representative of the Local Volume ($R_{LG} < 10$ Mpc) or a Virgo cluster member or even be situated behind the cluster at $R_{LG} \sim 20$ Mpc and infalling toward us. The selection of candidates that might be true nearby galaxies hidden among the huge number of Virgo cluster members is a complicated task. That is why Kranz-Korteweg & Tammann (1979) even excluded the Virgo cluster core ($\Theta < 6^\circ$) from their consideration.

The expected number of missed nearby galaxies in the region R.A. $= [12.0^h - 13.0^h]$ and Decl. $= [0^\circ - 25^\circ]$ can be estimated as follows. The Catalog of Neighboring Galaxies (Karachentsev et al. 2004) contains 450 objects with $R_{LG} < 10$ Mpc distributed over the entire sky. In a new version of the catalog by Karachentsev et al. 2013 (UNGC), updated with fresh data from recent optical and H$\alpha$ surveys (Sloan Digital Sky Survey (SDSS), HIPASS, ALFALFA, etc.), there are about 800 candidates in almost the same volume to a radius of 11 Mpc. Assuming that the UNGC sample is $\sim 100\%$ complete to $M_B = -12$ mag and taking into account the inhomogeneous distribution of galaxies due to the concentration toward the Supergalactic equator as well as the presence of the Zone of Avoidance along the Milky Way, one can estimate the expected number of nearby ($R_{LG} < 11$) galaxies within the identified $15^\circ \times 25^\circ$ square as $\sim 400$.

We undertook a special search for likely foreground galaxies, inspecting SDSS images of more than 2000 objects in the specified area. Among these, we found 37 galaxies with H$\alpha$ line widths that yield TF distances less than $\sim 11$ Mpc. Their radial velocities lie in the range $V_{LG} = (400-1400)$ km s$^{-1}$ and the majority of these turn out to be blue dwarf galaxies showing no apparent concentration toward the Virgo center. As objects for our pilot program to measure distances with the Advanced Camera for Surveys (ACS) on board $HST$ via the TRGB method, we selected eight galaxies that have smaller TF distance estimates. In the target list, we also included the S0-type galaxy NGC 4600 with a distance estimate via surface brightness fluctuations by Tonry et al. (2001). (The case of the nearby S0a galaxy NGC 4826 with D(sbf) = 7.48 Mpc (Tonry et al. 2001) and D(trgb) = 4.37 Mpc (Jacobs et al. 2009) tells us that these methods sometimes give significantly different distance estimates.) At present, all nine of our targets have been imaged with $HST$ within GO 12878.

Galaxies situated on the nearby boundary of the “zero-velocity sphere” will have radial velocities close to the mean cluster value, $\langle V_{Virgo} \rangle = 1000$ km s$^{-1}$ and, given the expected value $R_0 \simeq 7$ Mpc, distances $R_{LG} \simeq 10$ Mpc. The F814W and F606W images of these galaxies obtained with ACS on board $HST$ in a two orbit per object mode can determine their TRGB distances with an accuracy of ~7% or ~0.7 Mpc. Given a total mass of the cluster within the radius $R_0$ expressed by Equation (4), then the measurement of $R_0 \simeq 7$ Mpc with an accuracy of ~0.7 Mpc can yield a mass of the Virgo cluster with an error of ~30%.

### 4. OBSERVATIONS AND DATA PROCESSING

We have observed nine galaxies with ACS during the $HST$ Cycle 20 (proposal 12878). Between 2012 November 15 and 2013 March 30, we obtained 2080 s F606W and 1640 s F814W images of each galaxy using ACS/Wide Field Camera with exposures split to eliminate cosmic ray contamination. The images were obtained from the STScI archive, having been processed according to the standard ACS pipeline. Stellar photometry was obtained using the ACS module of DOLPHOT (http://americano.dolphinsim.com/dolphot), the successor to HSTPHOT (Dolphin 2000), using the recommended recipe and parameters. In brief, this involves the following steps. First, pixels that are flagged as bad or saturated in the data quality images were marked in the data images. Second, pixel area maps were applied to restore the correct count rates. Finally, the photometry was run. In order to be reported, a star had to be recovered with a signal-to-noise ratio (S/N) of at least five in both filters, be relatively clean of bad pixels (such that the DOLPHOT flags are zero) in both filters, and pass our goodness-of-fit criteria ($\chi \leq 2.5$ and $|{	ext{sharp}}| \leq 0.3$). These restrictions reject non-stellar and blended objects. At the high Galactic latitude of the Virgo cluster, foreground stars from the Milky Way are insignificant contaminants. For some of the most distant galaxies, we extended to stars with $S/N > 2$ in order to evaluate the TRGB. This extension introduces a lot of noise that is monitored by plotting a color–magnitude diagram (CMD) of empty regions beside the galaxy body.

The TRGB is determined by a maximum likelihood analysis monitored by recovery of artificial stars (Makarov et al. 2006). Artificial stars with a wide range of known magnitudes and colors are imposed at intervals over the surface of the target and recovered (or not) with the standard analysis procedures to determine both photometric errors and completeness in the crowded-field environments. The maximum likelihood procedure considers the luminosity function of stars with colors consistent with the red giant branch after compensating for completeness and assesses power-law fits to the distributions above and below a break identified with the TRGB. The slope of the power law faintward of the TRGB break is expected to be approximately 0.3 on a magnitude scale after correction for completeness. If the RGB is sufficiently observed to well below the tip, then the slope can be a free parameter within a
restricted range. However, in the current cases with distances
approaching the effective observational limits, the slope of the
luminosity function fit below the TRGB is set to the expected
value of 0.3. Galactic extinction, minor at the polar location of
the Virgo cluster, is taken from Schlafly & Finkbeiner (2011).

The greatest potential for serious error with a TRGB mea-
surement comes about with confusion of the asymptotic giant
branch (AGB) for the RGB. Stars on the AGB that are burning
both helium and hydrogen in shells closely parallel and overlap
the RGB on a CMD but rise as much as a magnitude brighter.
Their peak brightness, dependent on age and metallicity, can be
misinterpreted as the TRGB. AGB stars have intermediate ages
of 1–10 Gyr although they are only in sufficient quantity to be
confusing at the lower end of that age range (Jacobs et al. 2011).
A general strategy that we employ is clipping of the area of the
HST image to avoid regions of young and intermediate-age stars
(and regions beyond the target dominated by background and
foreground contaminants) in order to maximize the contrast of
the old population contributing to the RGB.

The calibration of the absolute value of the TRGB includ-
ing a small color term has been described by Rizzi et al.
(2007). The RGB is redder for older or more metal rich popu-
lations but galaxies inevitably have old and metal poor com-
ponents, resulting in reasonable stability of tip magnitudes in the
F814W band. Images, CMDs, photometry tables, TRGB mea-
surements, and distance determinations are made available at
http://edd.ifa.hawaii.edu by selecting the catalog CMDs/TRGB
(Jacobs et al. 2009).

5. TRGB DISTANCES TO NINE TARGET GALAXIES

Images of our target galaxies taken from SDSS are shown in
Figure 2. Each field has a size of 6 × 6 arcmin. North is up and
east is to the left. The HST ACS footprints are superimposed
on the SDSS frames. In Figure 3, a mosaic of enlarged ACS
(F606W + F814W) images of the nine galaxies is shown. Their
size is 1 arcmin each; north is up and east is to the left. CMDs
of F814W versus (F606W-F814W) are presented in Figure 4.

A summary of some basic parameters for the observed
galaxies as well as the resulting distance moduli for them are
given in Table 1. Some additional comments about the galaxy
properties are briefly discussed below.
Figure 3. Mosaic of enlarged ACS (F606W + F814W) images of the nine galaxies. Field sizes are 1 arcmin on a side and north is up and east is to the left.

GR34 = VCC530, UGC7512, and VCC2037. These are irregular-type dwarf galaxies with narrow H I lines. New TRGB distances to them agree with the TF distances, confirming all the galaxies to be situated in front of the Virgo cluster.

NGC 4517. This Sd galaxy seen edge-on has the major angular diameter about 12′, extending far beyond the ACS frame. Its CMD is constructed from an outskirt field along the minor axis to sample the halo and avoid crowded dusty regions of star formation. The TF distance to NGC 4517 is consistent with the TRGB distance.

IC 3583. This Magellanic-type dwarf has an asymmetric diffuse halo extended to the west. The field contributing to the CMD that is shown in Figure 4 is clipped to minimize young and intermediate-age populations and optimize the contribution of the old population. See Figure 5 for the CMD for the full ACS field and an outline of the excised region containing many young stars. Together with a bright spiral galaxy NGC 4569, IC3583 forms the optical pair Arp 76 with a radial velocity difference of 1245 km s$^{-1}$. The northwest part of NGC 4569 is seen in the southeast corner of the ACS frame. Our estimate of distance to NGC 4569 via its TRGB yields $D > 17$ Mpc.

NGC 4600. This is a gas-poor dwarf lenticular galaxy with Hα emission in the core (Karachentsev & Kaisin 2010). We recognize a moderate agreement in the distance estimates for NGC 4600 via surface brightness fluctuations (Tonry et al. 2001) and from TRGB. It is a bit unexpected to find this isolated dS0 galaxy in front of the Virgo cluster rather than in the virial core.

KDG 215 (LEDA 44055). This galaxy is gas-rich, low surface brightness dwarf with a narrow H I line, a high hydrogen mass-to-stellar mass ratio $M_{\text{H}I}/M_*=3.1$, and a narrow RGB characteristic of a low-metallicity system. KDG215 lies more than a magnitude closer than any of the other targets, at 4.8 Mpc.

IC 3023 and KDG 177 (VCC1816). Both the galaxies of Im type are H I-rich and active star formation objects typical of field
galaxies. In spite of their narrow H\textsc{i} lines (44 and 30 km s\textsuperscript{−1}), they both appear to belong to the Virgo cluster. The TRGB are not seen as would have been the case if these galaxies were in the Virgo foreground. In each case, the TRGB is probably being seen around $I \sim 27$, as expected for a cluster member. These tentative measurements are at the limit of the current HST photometry and we do not attempt a distance determination.

Apart from these objects, there are five other galaxies in front of the Virgo cluster that have accurate distance measurements. Information about them is collected in Table 2. We use the data on distances and radial velocities of these 7 + 5 galaxies from Tables 1 and 2 to trace the near-side Virgo-centric infall. Two probable Virgo core galaxies with uncertain distances (IC 3023 and KDG 177) are excluded from consideration. In addition, the analysis will include the galaxy NGC 4365 in the Virgo W’ cloud as a representative with an accurate distance of the back-side infall to the Virgo cluster. Its parameters are given in the last line of Table 2.

6. ESTIMATING THE TOTAL MASS OF THE VIRGO CLUSTER

As noted above, the analysis of available observational data on radial velocities and distances for several hundred galaxies in the vicinity of the Virgo cluster leads to the conclusion that the radius of the zero-velocity surface of the cluster lies in the range $R_0 = (5.0–7.5)$ Mpc (Karachentsev & Nasonova 2010). According to Equation (4), this scatter in $R_0$ leads to a wide scatter in the total mass estimates of the cluster, $M_T = (2.7–8.9) \times 10^{14} M_\odot$, exceeding a factor of three.
Figure 5. Example of spatial clipping to reduce contamination from young populations on the TRGB measurement. The left panel shows the full-field CMD for IC 3583. The right panel gives the positions of stars in the ACS field with stars with F606W-F814W > 0.6 in red and stars with F606W-F814W < 0.6 in blue. Blue stars are concentrated toward the center. Only stars outside the exclusion box are included in the CMD for this galaxy shown in Figure 4.

(A color version of this figure is available in the online journal.)

Table 1

| Name      | R.A. (J2000) Decl. | VLG | D     | Θ     | BT   | T   | mFUV  | m21     | W2D  | ITRGB         | D_{HST} |
|-----------|-------------------|-----|-------|-------|------|-----|-------|---------|------|----------------|---------|
| IC 3023   | 121001.7+142201   | 710 | 7.7   | 5.4   | 15.35| 10  | 16.78 | 16.33   | 44   | ~27            | ~17     |
| GR34      | 122207.6+154757   | 1205| 8.9   | 4.0   | 15.95| 10  | 19.04 | 18.24   | 25   | 25.94±0.15     | 9.29±0.93|
| U7512     | 122541.3+020932   | 1354| 10.6  | 10.3  | 15.20| 10  | 17.40 | 15.31   | 65   | 26.37±0.09     | 11.8±1.2 |
| N4517     | 123245.5+000654   | 978 | 9.7   | 12.3  | 11.09| 7   | 15.86 | 12.39   | 307  | 25.67±0.12     | 8.34±0.83|
| IC 3583   | 123643.5+131534   | 1024| 7.6   | 1.7   | 13.31| 9   | 15.43 | 15.66   | 105  | 26.04±0.06     | 9.52±0.95|
| KDG 177   | 123958.5+134653   | 913 | 8.2   | 2.6   | 16.36| 10  | 18.47 | 16.17   | 30   | 25.37±0.09     | 8.90±0.89|
| N4600     | 124023.0+030704   | 713 | 7.4   | 9.6   | 13.70| 0   | 20.38 | 18.50   | 29   | 26.01±0.08     | 9.63±0.96|
| VCC2037   | 124615.3+101212   | 1038| 7.4   | 3.3   | 15.80| 10  | 17.90 | 15.79   | 25   | 24.33±0.07     | 4.83±0.34|

Note. (1) Galaxy name, (2) equatorial coordinates, (3) radial velocity in km s⁻¹ in the LG rest frame from NASA Extragalactic Database (http://ned.ipac.caltech.edu/), (4) linear distance (in Mpc) as given in UNGC, estimated via the TF relation (tf) or from surface brightness fluctuations (sb), (5) angular separation Θ (in degrees) from the Virgo cluster center that has been identified with NGC 4486, (6) apparent integrated B magnitude as given in UNGC, (7) morphological type in de Vaucouleurs scale, (8) far-ultraviolet integrated magnitude from the Galaxy Evolution Explorer space telescope (Gil de Paz et al. 2007), (9) H-t line magnitude m_{21} = 17.4–2.5 log F_{HI}, where F_{HI} is an H I flux in Jy km s⁻¹ from Haynes et al. (2011) or the Lyon Extragalactic Database (LEDa; http://leda.univ-lyon1.fr/), (10) H t line width (in km s⁻¹) at the 50% level of the maximum, (11) TRGB magnitude and its 68% uncertainty from the maximum likelihood analysis, and (12) the linear distance (in Mpc) and conservative global characterization of 10% uncertainty for a one-orbit ACS observation of a galaxy near 10 Mpc.

Table 2

| Name      | R.A. (J2000) Decl. | VLG | D     | Θ     | BT   | T   | Reference       |
|-----------|-------------------|-----|-------|-------|------|-----|-----------------|
| N4527     | 123408.4+023913   | 1591| 14.1   | SN    | 9.8  | 11.38| Jha et al. 2007 |
| N4536     | 123427.0+021117   | 1662| 14.3   | cep   | 10.3 | 11.16| Riess et al. 2005|
| N4725     | 125026.6+253003   | 1176| 12.4   | cep   | 13.9 | 10.11| Freedman et al. 2001|
| N4826     | 125644.2+214105   | 365 | 4.37   | 0.44 | TRGB | 11.2 | 9.30 | Jacobs et al. 2009|
| GR-8      | 125840.4+141330   | 139 | 2.13   | 0.21 | TRGB | 9.1  | 14.79| Tully et al. 2006|
| N4365     | 122428.3+071904   | 1112| 23.1   | 2.3  | sbf  | 5.3  | 10.52| Blakeslee et al. 2009|

Note. The column designations are similar to those in Table 1.
New accurate distance measurements to relatively few galaxies residing near the front side of Virgo fix the $R_0$ and $M_T$ quantities in a narrower interval.

Figure 6 reproduces a pattern of the Hubble flow in front and back of the Virgo cluster restricted to the most accurate constraints. Compared with Figure 1, it exhibits a much more distinct characteristic of the infall. Open circles in the Figure 6 show the galaxies from Table 2 with accurate distance estimates. The solid circles correspond to seven galaxies in front of the Virgo cluster with distances measured in this program with HST. The horizontal bars indicate distance errors. The gray vertical column denotes the zone of virial motions.

The horizontal dashed line marks the unperturbed Hubble flow. The inclined dashed line marks the unperturbed Hubble flow in front of the Virgo cluster. The grey vertical column denotes the zone of virial motions.

As seen from Figure 6, the straight line of unperturbed Hubble flow with the parameter $H_0 = 72 \text{ km s}^{-1} \text{ Mpc}^{-1}$ crosses the Virgo center at $V_{LG} = +1188 \text{ km s}^{-1}$, which corresponds to the infall velocity of LG toward Virgo: $\Delta V_{LG} = (975 \pm 29) - 72(16.5 \pm 0.4) = -213 \pm 41 \text{ km s}^{-1}$. This quantity is not significantly higher than the previous estimates: $-139 \text{ km s}^{-1}$ (Tonry et al. 2001) and $-185 \text{ km s}^{-1}$ (Tully et al. 2008).

The presented data also show that the solid wave-like line crosses the line of the mean cluster velocity at a distance of 9.3 Mpc. Therefore, the radius of the zero-velocity surface around the Virgo cluster turns out to be $R_0 = 16.5 - 9.3 = 7.2 \text{ Mpc}$. There are at least three circumstances affecting this estimate: (1) uncertainty of the Virgo center position, which is $\sim 0.4 \text{ Mpc}$, (2) uncertainty of the mean velocity of the cluster $\sim 30 \text{ km s}^{-1}$ corresponding to $\sim 0.3 \text{ Mpc}$ on the distance scale, and (3) the mean-square scatter of galaxies with respect to the Z-like line that consists of $\sim 0.5 \text{ Mpc}$. Considering these factors as being statistically independent, we obtain the sought-for radius

$$R_0 = (7.2 \pm 0.7) \text{ Mpc}.$$

According to Equation (4), this quantity corresponds to the total mass of the Virgo cluster:

$$M_T = (8.0 \pm 2.3) \times 10^{14} M_\odot.$$

Virial mass estimates for Virgo are: 6.2 (de Vaucouleurs, 1960), 7.5 (Tully & Shaya, 1984), and 7.2 (Giraud, 1999), in units of $10^{14} M_\odot$. These values all have been normalized to a Virgo cluster distance of 16.5 Mpc. As one can see, the total cluster mass estimate via $R_0$ is consistent with the average virial mass estimate, $M_v = (7.0 \pm 0.4) \times 10^{14} M_\odot$. Consequently, the zone of infall, at a radius four times the virial radius (assuming $\Omega_2 = 0.24$), does not contain a large amount of mass outside $R_v$.

This conclusion agrees with the results of N-body simulations performed by Rines & Diaferio (2006) and Anderhalden & Diemand (2011) for a cluster dark matter profile. These authors determined the $M_T/M_v$ ratio to be 1.19 and 1.25, respectively.

We draw attention to the regularity of the infall pattern seen in front of the Virgo cluster. A scatter of 12 galaxies along the vertical scale with respect to the Z-shape line under parameters $M_T = 8.0 \times 10^{14} M_\odot$ and $(\Theta) = 8.7$ corresponds to $\sigma_r = 155 \text{ km s}^{-1}$. When the difference of the individual $\Theta$ of the galaxies is taken into account, the value of $\sigma_r$ drops to 130 km s$^{-1}$. An essential part of this scatter, $\sim 90 \text{ km s}^{-1}$, is caused by errors of the distance measurements, which are $\sim 7\%-10\%$. After a quadratic subtraction of the component related to distance errors, the remaining (“cosmic”) dispersion of radial velocities turns out to be $\sim 95 \text{ km s}^{-1}$. Therefore, one can say that the infall flow pattern around the Virgo cluster looks to be rather “cold.”

7. CONCLUDING REMARKS

The measurements of distances to nearby galaxies with HST makes the picture of galaxy infall into the Virgo cluster much more distinct. Among nine galaxies selected as Virgo foreground candidates for our pilot HST GO 12878 program, seven reside in the expected near region while two others are probably cluster
members. In our list of targets for HST, there are ~30 more galaxies with TF distances around 10 Mpc. Measurements of their distances with HST ACS can give us a more precise estimate of the total mass of the nearest large cluster via infalling galaxy motions. Multicolor images of galaxies that have been obtained with the 3.5 m CFHT under the program “Next Generation Virgo Cluster Survey” (Ferrarese et al. 2012) will be useful in choosing the best candidates for new HST observations.

In the framework of the simplest spherically symmetric radial infall of galaxies into a point-like central mass, the observed distances and radial velocities of galaxies in front of Virgo yield the value of total mass of the cluster in good agreement with the virial mass: $M_{\text{vir}} = (1.14 \pm 0.35) M_\odot$. It should be stressed here that the quantity $M_{\text{vir}} = (8.0 \pm 2.3) \times 10^{14} M_\odot$ was obtained in the case of standard $\Lambda$CDM model with the parameter $\Omega_\Lambda = 0.76$. In the old cosmological model with $\Omega_\Lambda = 0$, the estimate of total mass of the Virgo cluster via motions of surrounding galaxies would be 35%–40% lower, pushing mass estimates almost out of the confidence interval below virial mass estimates derived via internal motions. This circumstance can be considered as another display of the existence of dark energy on a local scale of ~10 Mpc. It can be noted that Tully & Shaya (1984) had already used a similar argument to suggest that a $\Lambda$ term might be appropriate to explain the total kinematic pattern of the Virgo cluster.

According to our estimate, the Hubble flow around the Virgo cluster looks to be rather cold with a characteristic line-of-sight scatter $\sim 95$ km s$^{-1}$. This preliminary result, if confirmed, may impose constraints on some models of cluster formation. More new accurate distance measurements with HST are required to check this claim.

As was noted by Karachentsev et al. (2003) and Tully et al. (2008, 2013), the nearby galaxies residing inside a radius of ~6 Mpc around the LG form a flat configuration (the “Local Sheet”) with surprisingly low peculiar velocities of the barycenters of groups of ~30 km s$^{-1}$. A hint to the existence of the Local Sheet can be seen in Figure 6 too, where three of the nearest galaxies (GR-8, NGC 4826, and KDG 215), all within $D = 5$ Mpc, follow remarkably well the unperturbed Hubble flow. To our knowledge, the existence of such calm domain structures, like the Local Sheet, still has not sufficiently attracted the attention of cosmologists.

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