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# Estimation of the Hubble constant from the scatter of the fundamental plane distances of groups and clusters of galaxies ($71.1 \pm 2.8$ km s$^{-1}$ Mpc$^{-1}$)

F. Kopylova and A. Kopylov

Special Astrophysical Observatory of the Russian Academy of Sciences, Nizhny Arkhyz, 369167 Russia

**Abstract.** To determine the peculiar velocities of galaxy clusters relative to the Hubble Flow, we need to measure the distances of galaxy systems using some method that is sensitive to their distances. The fundamental plane (FP) of early-type galaxies is one such method and is widely used for such problems. Using the FP, we determined the angular distances of 140 groups and galaxy clusters in the local Universe ($z < 0.15$) and constructed a Hubble diagram between distances and radial velocities in the CMB reference frame in the framework of the flat $\Lambda$CDM model ($\Omega_{\rm m}$=0.3, $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$). We obtained the average deviation of the relative distances $\gamma$ from the Hubble dependence for this model $< \Delta\gamma >= -0.0066 \pm 0.0023$ ($N = 140$). The minimum deviation we found corresponds to the value of the Hubble constant 71.1 km s$^{-1}$ Mpc$^{-1}$. We found that the logarithmic standard scatter of the relative distances of groups and clusters of galaxies on the Hubble diagram (subtracting peculiar velocities) is $\pm 0.0173$ ($N = 140$), which corresponds to the deviation of the Hubble constant $71.1 \pm 2.8$ km s$^{-1}$ Mpc$^{-1}$. For a sample of galaxy clusters ($N = 63$) with X-ray luminosity in the range $(0.15\text{–}4)\times10^{44}$ erg/s, we obtained $71.1 \pm 2.1$ km s$^{-1}$ Mpc$^{-1}$.

**Keywords:** galaxies: clusters, elliptical and lenticular, fundamental parameters, distances and redshifts; cosmology: large-scale structure of universe

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## 1 Introduction

The gravitational attraction of the elements of a large-scale structure is the main cause of the peculiar velocity of galaxies, clusters of galaxies. The peculiar velocity of galaxies at small $z$ can be estimated as $V_p \approx cz_{\text{obs}} - cz_{\text{H}} \approx cz_{\text{obs}} - H_o D$, where $D$ is the comoving distance of the galaxy, $H_o$ is the Hubble constant. To determine the peculiar velocities of galaxy clusters relative to the Hubble Flow, it is necessary to measure the relative distances of galaxy systems using some distance sensitive method. The fundamental plane of early-type galaxies (Dressler et al. 1987; Djorgovski & Davis 1987) is widely used to study the properties of galaxies and to determine the relative distances and peculiar velocities of galaxy clusters (for example, Hudson et al. 1999; Batiste & Batuski 2013).

Previously, using the FP for a large sample of galaxy systems ($z < 0.1$), we determined the relative distances and peculiar velocities of galaxy clusters in the Leo, Hercules, Bootes, Coropa Borealis, and Ursa Major superclusters based on SDSS (DR4, 8 data) (Kopylova & Kopylov 2007, 2014, 2017). In addition to superclusters of galaxies, our sample included groups and clusters of galaxies (the most distant galaxy systems in our sample) located in the region of the large void in the distribution of rich Abell clusters (Giant Void, $\alpha \approx 13^h, \delta \approx 40°, < z > \approx 0.107$, the maximum diameter is equal to 214 Mpc) (Kopylov & Kopylova 2002).

It is known that in the expanding Universe the surface brightness changes as $SB \propto (1+z)^{-4}$ ($z$ is the redshift of the galaxy, SB is the surface brightness of the the galaxy): a cosmological dimming of the surface brightness occurs. The factor $(1+z_{\text{H}})^{-2}$ is due to the cosmological expansion of the Universe, the factor $(1+z_{\text{obs}})^{-2}$ is due to relativistic effects. This gives the correction for the cosmological dimming of the surface brightness of galaxies in an expanding Universe, for example Mohr & Wegner (1997) — $C = 5\log(1+z_{\text{obs}}) + 5\log(1+z_{\text{H}})$. In this paper we show that if we take into account only the first part of the correction $5\log(1+z_{\text{obs}})$, caused by the motion of galaxies, then the evolution of the average surface brightness with $z$ is $Q_r = 3.76$ mag/arcsec$^2$.

We will also look at a sample of identical measurements of the relative distances of 140 groups and clusters of galaxies as a whole. The work was carried out by us using data from the SDSS[1] (Sloan Digital Sky Survey Data Realease 7, 8) and NED[2] (NASA Extragalactic Database).

[1] http://www.sdss.org
[2] http://nedwww.ipac.caltech.edu

## 2 The fundamental plane distances of groups and clusters of galaxies

Our sample contains 140 groups and clusters with the number of early-type galaxies grater than 3 within our chosen radius $R_{200}$. The measurement of the dynamical parameters of galaxy clusters is described in detail, for example, in Kopylova & Kopylov (2017). The selection of early-type galaxies within the radius $R_{200}$ was done in the same way for all clusters of galaxies. We applied the following criteria to the parameters of the galaxies (as in Kopylova & Kopylov 2017). Using the above criteria, we selected 2654 early-type galaxies in galaxy systems and constructed a common fundamental plane for them in the comoving coordinate system using the least squares method. The FP equation is: $\log R_e(\mathrm{kpc}) = (0.991 \pm 0.124)\log\sigma + (0.318 \pm 0.020) < \mu_e > +\gamma$, where $R_e$ is the effective radius of the galaxy in kiloparsecs, $< \mu_e >$ is the mean effective surface brightness within this radius, $\sigma$ is the central dispersion of the radial velocities of the stars, and $\gamma$ is the zero-point of the FP, which varies with distance when $\log R_e$ is measured in arcseconds. The zero-point of our sample was obtained for the accepted standard model $\Lambda$CDM and is equal to $\gamma = -8.066 \pm 0.003$. The standard deviation of the FP zero-point is 0.071, which corresponds to a $\sim 16\%$ error in determining the distance of one galaxy. The formal error in determining the cluster distance depends on the number of galaxies used and varies from 2% to 12%.

Galaxy cluster angular distances $\gamma$ ($\log R_e$ in arcsec) are converted to redshifts $z_{\mathrm{FP}}$ using the Peebles approximation (Peebles 1993): $D = (cz/H_o\,(1-0.225z)/(1+z)$. Part of the surface brightness dimming of the galaxies ($5\,\log\,(1+z_{\mathrm{H}})$) is taken into account in the zero-point of the FP. Figure 1 shows the Hubble diagram (upper panel) between the relative distances — $\gamma$ zero-points and redshifts (CMB). Clusters around the Giant Void (the most distant galaxy systems in our sample) are shown as empty blue circles. It can be noted that in Fig. 1 the Hubble relation correctly describes the FP distances of groups and clusters of galaxies, starting from the Coma cluster ($z = 0.024$) to the Giant Void ($z < 0.15$). The lower panel shows the residuals of the Hubble law.

The given Hubble diagram makes it possible to determine the corresponding redshift of the $z_{\mathrm{FP}}$ cluster from the observed individual distance in arcseconds, $\log R_e$. The peculiar velocities in the comoving coordinate system are equal to the difference between the spectroscopic and photometric redshifts, that is, $V_{\mathrm{pec}} = c\,(z_{\mathrm{CMB}} - z_{\mathrm{FP}})/(1 + z_{\mathrm{FP}})$, where $c$ is the speed of light, and $z_{\mathrm{CMB}}$ is the redshift of the cluster relative to the CMB, $z_{\mathrm{FP}}$ is the redshift of the cluster corre-

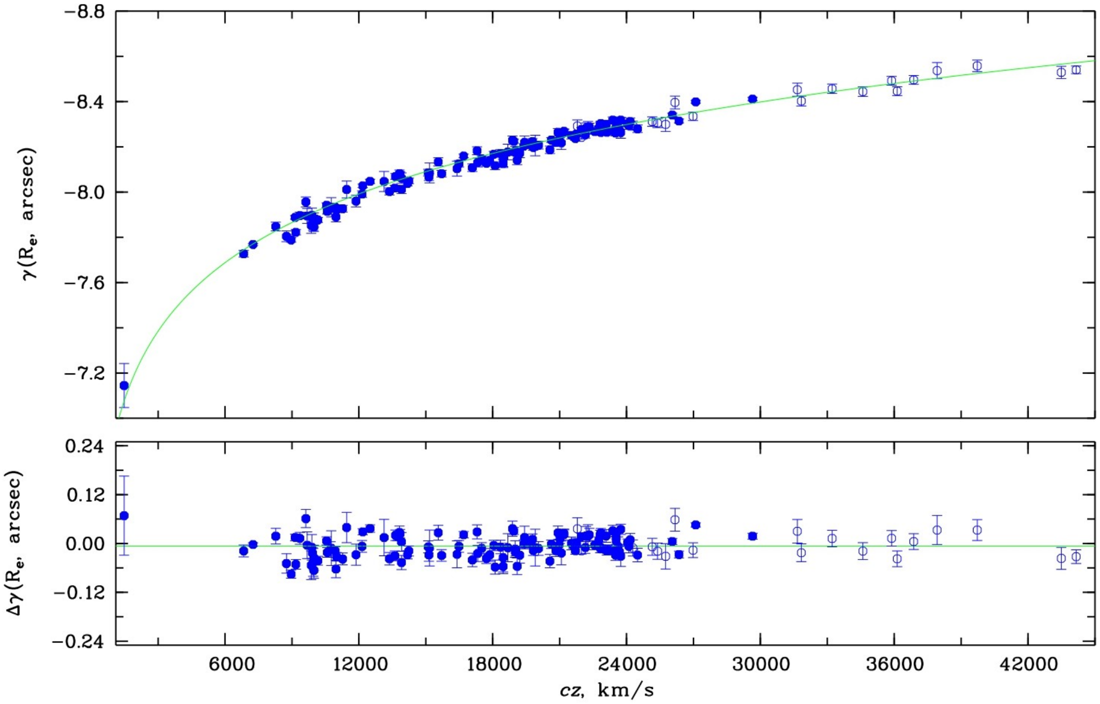


**Fig. 1.** FP distances of 140 groups and clusters of galaxies, zero-points of the fundamental plane $\gamma$, as a function of radial velocity (CMB) (Hubble diagram). Empty circles show the systems of galaxies ($N = 19$) around the Giant Void. The thick line shows the expected Hubble dependence in the $\Lambda$CDM cosmological model with $\Omega_m = 0.30$. The lower curve shows the deviations from the Hubble dependence.

sponding to the distance determined from the FP. Peculiar velocities of systems of galaxies are determined in Kopylova & Kopylov (2024).

The sample of groups and clusters of galaxies with more than 7 members has a peculiar velocity relative to the CMB frame $V_{\rm pec} = +170 \pm 90$ km/s. For a sample of clusters in the interval $L_{\rm X} = (0.151–4) \times 10^{44}$ erg/s we have obtained $V_{\rm pec} = -80 \pm 100$ km/s. ($N = 63$). The standard deviations of the radial peculiar velocities with quadratic allowance for the errors are $< V_{\rm pec}^2 >^{1/2} = 714 \pm 7$ km/s and $< V_{\rm pec}^2 >^{1/2} = 600 \pm 7$ km/s. The outflow rates of clusters of galaxies from the void are about $\sim 250 \pm 410$ km/s. The average peculiar velocity of 5 superclusters of galaxies is $+240 \pm 250$ km/s.

## 3 Hubble diagram and deviations from it

There is a contradiction in the definition of the constant $H_o$, one of the fundamental cosmological parameters. The constant $H_o$ estimated on the local distance ladder (Cepheid-supernova distance ladder) does not agree with the value extrapolated from the CMB data, assuming the standard cosmological model, $74.0 \pm 1.4$ km s$^{-1}$ Mpc$^{-1}$ (Riess et al. 2019) and $67.4 \pm 0.5$ km s$^{-1}$ Mpc$^{-1}$ (Planck Collaboration 2020) respectively.

In Fig. 1 the thick green line shows the Hubble relation between the radial velocity in the CMB reference frame and the angular FP distance of groups and clusters of galaxies. The line corresponds to the flat $\Lambda$CDM model $\Omega_\Lambda = 0.7$, $\Omega_\mathrm{m} = 0.3$ and to the Hubble constant $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$. The bottom figure shows the deviations from the Hubble law. We have obtained the average deviation from the Hubble law of the sample ($N = 140$) $< \Delta\gamma > = -0.0066 \pm 0.0023$. The corresponding logarithmic standard scatter is 0.0275. For a sample in the interval $L_\mathrm{X} = (0.151 - -4) \times 10^{44}$ erg/s, we obtained the average deviation from the Hubble law
$< \Delta\gamma > = 0.0017 \pm 0.0028$ ($N = 63$) with a standard scatter 0.0224, corresponding to a deviation of 5.11% ($\pm 3.6$ km s$^{-1}$ Mpc$^{-1}$). If we subtract the peculiar velocities of groups and clusters of galaxies in the Fig 1, then the distance measurement errors actually determine the scatter in the Hubble diagram. In this case, the logarithmic standard scatter is 0.0173 for the whole sample ($N = 140$) and is equal to the Hubble constant deviation of $\pm 2.8$ km s$^{-1}$ Mpc$^{-1}$). For a sample in the interval $L_\mathrm{X} = (0.151\text{–}4) \times 10^{44}$ erg/s, we found that the logarithmic standard scatter is 0.0130 for ($N = 63$) and corresponds to the Hubble constant deviation of $\pm 2.1$ km s$^{-1}$ Mpc$^{-1}$. The minimum standard scatter corresponds to the value of the Hubble constant 71.1 km s$^{-1}$ Mpc$^{-1}$.

## 4 Conclusions

In the course of this work we found that the peculiar velocities of most galaxy systems are small, but show a dependence on their X-ray luminosity. We have found that the average peculiar velocity of five galaxy superclusters of galaxies is $+240 \pm 250$ km/s, and the outflow rate of groups and clusters of galaxies from the Giant Void, measured from 19 galaxy systems, is $\sim 250 \pm 410$ km/s. We have measured the average deviation from the Hubble relation between distance and radial velocity (within the flat $\Lambda$CDM model) of groups and clusters of galaxies (without peculiar velocities). The logarithmic standard scatter is $\pm 0.0173$, which corresponds to the deviation of the Hubble constant $H_0 = 71.1 \pm 2.8$ km s$^{-1}$ Mpc$^{-1}$. For a sample with

$L_{\mathrm{X}} = (0.151–4) \times 10^{44}$ erg/s we obtained a deviation with a standard scatter corresponding to the deviation of the Hubble constant $H_0 = 71.1 \pm 2.1$ km s$^{-1}$ Mpc$^{-1}$.

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