Serendipitous discovery of a faint dwarf galaxy near a Local Volume dwarf *

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Accepted XXX. Received XXX; in original form XXX

ABSTRACT
A faint dwarf irregular galaxy has been discovered in the HST/ACS field of LV J1157+5638. The galaxy is resolved into individual stars, including the brightest magnitude of the red giant branch. The dwarf is very likely a physical satellite of LV J1157+5638. The distance modulus of LV J1157+5638 using the tip of the red giant branch (TRGB) distance indicator is 29.82 ± 0.09 mag (D = 9.22 ± 0.38 Mpc). The TRGB distance modulus of LV J1157+5638sat is 29.76 ± 0.11 mag (D = 8.95 ± 0.42 Mpc). The distances to the two galaxies are consistent within the uncertainties. The projected separation between them is only 3.9 kpc. LV J1157+5638 has a total absolute V-magnitude of −13.26 ± 0.10 and linear Holmberg diameter of 1.36 kpc, whereas its faint satellite LV J1157+5638sat has $M_V = −9.38 ± 0.13$ mag and Holmberg diameter of 0.37 kpc. Such a faint dwarf was discovered for the first time beyond the nearest 4 Mpc from us. The presence of main sequence stars in both galaxies unambiguously indicates the classification of the objects as dwarf irregulars (dIrRs) with recent or ongoing star formation events in both galaxies.

Key words: galaxies: dwarf – galaxies: distances and redshifts – galaxies: stellar content – galaxies: individual: LV J1157+5638

1 INTRODUCTION
In recent years, the search for previously unknown dwarf galaxies has attracted considerable attention. This interest is associated with a number of unsolved, but well-known problems with modern cosmological ΛCDM theory. The problem of ‘lost satellites’ is one of them. The luminosity function of the galaxies in the Local Volume contains about an order of magnitude fewer dwarfs than predicted by the ΛCDM theory (Klypin et al. 1999, 2015). Consequently, the search for missing satellites is especially important, and this search has been quite successful in recent years. Particularly rich families of faint satellites were discovered around the two giant galaxies of the Local Group: Andromeda and the Milky Way (Laevens et al. 2015; Homma et al. 2016; Bechtol et al. 2015; Koposov et al. 2015). The discovery of very faint nearby dwarf galaxies makes it possible to clarify the structure and dynamics of our Local Group, which in turn is necessary for constructing a model of the formation and evolution of the Local Group.

For more distant galaxy groups we naturally lose more faint satellites. Nevertheless, recent observations on ground-based telescopes, and follow-up observations with the Hubble Space Telescope, substantially reduce these gaps. Such a survey was performed for the M 81 group (Chiboucas et al. 2009), where 12 new dwarf galaxies were found. Recently, searches for faint galaxies in the Centaurus A group were successfully carried out (Crnojević et al. 2016; Müller et al. 2017a), and these surveys led to the discovery of more than 60 new dwarf galaxy candidates. Even in more distant groups like, for example, the M 101 group at the distance of 7.2 Mpc (Lee & Jang 2012), observational surveys bring the discovery of new dwarf satellites (Javanmardi et al. 2016; Müller et al. 2017b; Danieli et al. 2017). Park et al. (2017) also recently reported the discovery of 22 dwarf members of the group around NGC 2784 (at the distance about 9.8 Mpc).

However, not only groups around giant galaxies should be taken into account. Karachentsev & Makarov (2008) in the framework of a binary galaxy study in the Local Supercluster drew attention to the existence of a large number of systems consisting exclusively of dwarf galaxies. A similar claim was made by Tully et al. (2006). Makarov & Uklein

* Based on observations made with the NASA/ESA Hubble Space Telescope, program GO-13442, with data archive at the Space Telescope Science Institute. STScI is operated by the Association of Universities for Research in Astronomy, Inc. under NASA contract NAS 5-26555.
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L. N. Makarova et al.

Figure 1. HST/ACS combined distortion-corrected mosaic image of the LV J1157+5638 field in the $F606W$ filter (left panel). The image size is $1.2 \times 1.8$ arcmin. Enlarged combined $F606W + F814W$ images of LV J1157+5638 and the new dwarf satellite are shown at the right panel.

(2012) have compiled a sample of similar groups formed exclusively of dwarf galaxies with $M_K > -19$ in the $K$ filter. The majority of the list consists of galaxy pairs, and the most populated system contains six members. Dwarf galaxy groups account for about 5% of all groups in the Local Supercluster (Makarov & Uklein 2012). Taking into account the selection effects, the total number of multiple dwarf systems should be at least 5–6 times greater. The authors show that groups of dwarf galaxies are located in low density regions and evolve without the influence of massive neighbours.

Despite difficulties in finding faint satellites of dwarf galaxies, a number of discoveries have recently been made (Chengalur & Pustilnik 2013; Crnojević et al. 2014; Carlin et al. 2016; Smercina et al. 2017). Although targeted hunts give us a substantial increase in the number of dwarf galaxies of the Local Volume, new objects can also be found in the analysis of serendipitously observed areas of sky. In this paper, we report the discovery of an extremely small galaxy located near the LV J1157+5638 dwarf galaxy. The object was detected by us during the data analysis of images from HST/ACS program SNAP–13442.

2 OBSERVATIONS AND DATA REDUCTION

LV J1157+5638 was observed on October 18, 2013 with HST/ACS in the course of the SNAP project 13442 (PI: R.B.Tully), that was undertaken to acquire accurate photometric distances of a sample of Local Volume galaxies. With accurate distances, we generate three-dimensional maps of the distribution of galaxies and decouple the expansion and peculiar components of line-of-sight velocities. Dithered images were obtained in the $F606W$ and $F814W$ filters with the exposures summing to 1100 s in each band. Initial reductions used the default HST pipeline. The $F606W$ image of the LV J1157+5638 field is shown in Fig. 1. This compact galaxy is very well resolved into individual stars. It is easily distinguished in the upper part of the ACS image. This region can be seen in detail on the enlarged image at the upper right panel. The off-centre knot of blue brighter stars is well resolved into individual stars, indicating ongoing star

MNRAS 000, 1–8 (XXX)
formation in LV J1157+5638. A newly discovered galaxy is situated about 1.5 arcmin to the south of LV J1157+5638 in the lower right corner of the image. It is shown at the lower right panel, and also visibly resolved into individual stars.

We use the ACS module of the DOLPHOT software package\footnote{http://americano.dolphinsim.com/dolphot/} by A. Dolphin for photometry of resolved stars. The HST data quality files were used to mask bad pixels. DOLPHOT parameters were set and the photometry was performed as recommended in the DOLPHOT User’s Guide for ACS/WFC data. Only stars of good photometric quality were used in the analysis, following the recommendations given in the manual. We have selected the stars with signal-to-noise \((S/N)\) of at least five in both filters and \(|\text{sharp}| \leq 0.3\). The resulting colour-magnitude diagrams (CMD) of the LV J1157+5638 and its satellite are presented in Fig. 2. We call this satellite LV J1157+5638 sat in this paper.

We use artificial star tests incorporated within DOLPHOT to estimate the photometric errors, blending and incompleteness in the crowded fields of nearby resolved galaxies. A significant number of artificial stars were generated in the appropriate magnitude and colour range so that the distribution of the recovered magnitudes is adequately sampled. According to the artificial star experiments, the 50% completeness level is appearing at \(F814W \approx 27.2\) mag and at \(F606W \approx 28.4\) mag.

LV J1157+5638 sat was observed on June 10, 2017 at the 6-meter BTA telescope (SAO RAS) with the multi-mode focal reducer of the BTA SCORPIO in the long slit mode with a grism VPHG1800R (Afanasiev & Moiseev 2005), providing reciprocal dispersion 0.52 \(\AA/\text{pix}\) and spectral range 6100–7100 \(\AA\). The spectral resolution is 2.5 \(\AA\). The total exposure time was 1800 seconds. Unfortunately, Ha-emission was not seen, thus, we could not measure the redshift.

3 THE COLOUR-MAGNITUDE DIAGRAMS

Two colour-magnitude diagrams are presented in the Fig. 2. In the left panel we show stellar populations measured at the ACS/WFC field within the body of LV J1157+5638, and at the right panel are the stars within the tiny satellite LV J1157+5638 sat. Even the CMD of the ‘main’ dwarf looks sparsely populated. We can see upper main sequence at \((F606W - F814W) \leq 0.4\, \text{mag}\), red supergiant plus upper AGB (asymptotic giant branch) stars at \(F814W \leq 25.7\) mag, and the rest are more abundant RGB (red giant branch). Only about 80 stars were resolved in the tiny satellite LV J1157+5638 sat.

Nevertheless, clear signs of the upper main sequence at \((F606W - F814W) \leq 0.4\) are presented, and the RGB is well represented. Among brighter stars \((F814I \leq 25\) mag\) we can distinguish a few red supergiants, but the main sequence only rises to roughly match the level of the TRGB at \(F814W\). It is obvious that we still have populations in this dwarf which are not fully resolved in the body of the galaxy with these exposures, and deeper images are needed. At the same time, the presence of main sequence stars in both galaxies unambiguously indicate, that we can classify the objects as dwarf irregulars (dIrrs). Therefore, we can expect recent or ongoing star formation events in the galaxies. According to the GALEX and Hα data (see Table 1, where the general parameters and results are indicated), LV J1157+5638 has sufficient ongoing star formation, whereas its satellite is too faint to evince ongoing star formation activity with the data available.

4 DISTANCE MEASUREMENT AND STAR FORMATION

We have determined a photometric TRGB distance of both LV J1157+5638 dwarf galaxy and its expected satellite with our \textsc{trgbtool} program which uses a maximum-likelihood algorithm to obtain the magnitude of TRGB from the stellar luminosity function (Makarov et al. 2006). The measured TRGB magnitude of LV J1157+5638 is \(F814W_{\text{TRGB}} = 25.74 \pm 0.07\) mag in the ACS instrumental system. A photometric distance of LV J1157+5638 dwarf galaxy was also estimated with the same data in the Extragalactic Distance Database (EDD)\footnote{http://edd.ifa.hawaii.edu/}. The TRGB magnitude given there is \(F814W_{\text{TRGB}} = 25.66 \pm 0.13\) mag. The both estimations are consistent within 1σ uncertainty. Using the calibration for the TRGB distance indicator by Rizzi et al. (2007) and the Galactic extinction \(E(B-V) = 0.017\) from Schlafly & Finkbeiner (2011), we derived the true distance modulus for LV J1157+5638: \(29.82 \pm 0.09\) mag \((D = 9.22 \pm 0.38\) Mpc). The CMD of the LV J1157+5638 sat is poorly populated, and the galaxy is distant which makes uncertainties of the distance estimation large. Nevertheless, the \textsc{trgbtool} program is working quite well even in this case. The measured TRGB magnitude of LV J1157+5638 sat is \(F814W_{\text{TRGB}} = 25.68 \pm 0.09\) mag. We obtained the distance modulus for this dwarf \(29.76 \pm 0.11\) mag \((D = 8.95 \pm 0.42\) Mpc). The distances to the both galaxies are consistent within the uncertainties. Therefore, we can claim, that the considered dwarfs are very likely a physical pair with the projected separation 3.9 kpc between them.

Since the red giant branch is clearly visible in both our galaxies, we can estimate the average metallicity of these stars. According to Lee et al. (1993):

\[
[\text{Fe}/\text{H}] = -12.64 + 12.6(V-I)_{0.35} - 3.3(V-I)_{0.35}^2,
\]

where \((V-I)_{0.35}\) is the colour of RGB stars at the level of 0.5 mag fainter than TRGB value. We calculated \([\text{Fe}/\text{H}] = -2.30 \pm 0.07\) dex and \([\text{Fe}/\text{H}] = -2.08 \pm 0.10\) dex for the main galaxy and its satellite, respectively.

The isochrones of these metallicities were superimposed on the CMDs of the studied dwarfs (see Fig. 2), so that we can approximately estimate the age of the resolved stars. In the LV J1157+5638 galaxy, we can assume the presence of a small number of stars \(\sim 10\) Myr old, which indicates an evident ongoing star formation, as can be seen also from Hα data (see section 3). At the same time, the upper main sequence of the dwarf is not densely populated, so we cannot expect a recent intense burst of star formation. Relatively young stars of the age of 50–100 Myr are also present in the galaxy. In addition, we can assume from the theoretical isochrones, that the age of the resolved red giants can be from 1 to 10–13 Gyr, i.e. the galaxy most likely includes...
the oldest RGB stars. As can be seen from the figure, we cannot exclude somewhat higher metallicity of the RGB stars, $[\text{Fe/H}] = -1.74$. However, photometric errors play a significant role in this part of the CMD, that is difficult to make certain conclusions.

Apparently, there are no stars younger 100 Myr in the tiny satellite (see the right panel of Fig. 2). This agrees with the Hα and GALEX data, and indicates the absence of ongoing star formation. The isochrones of the metallicity estimated from the RGB colour well fit the CMD as a whole. LV J1157+5638 sat also most likely includes the oldest RGB stars up to about 13 Gyr old.

5 INTEGRAL AND SURFACE PHOTOMETRY

Both LV J1157+5638 and LV J1157+5638 sat dwarfs are situated well within the ACS/WFC field, allowing us to perform integral and surface photometry of the galaxies. Total and surface photometry was made on the fully processed distortion-corrected HST/ACS F606W and F814W images. Foreground stars were removed from the frames by fitting a first order surface in a rectangular pixel-area in the nearest neighbourhood of a star. The sky background in the ACS images is insignificant but, to remove possible slight large scale variations, the sky was approximated by a tilted plane, created from a two-dimension polynomial, using the least-squares method. The accuracy of the sky background determination is about 1 – 2 % of the original sky level. To measure total magnitudes in F606W and F814W bands, integrated photometry was performed in increasing circular apertures from the visual geometric centre to faint outskirts of the galaxies. The total magnitude was then estimated as
the measured total magnitudes are $V = 16.61 \pm 0.04$ mag and $I = 16.05 \pm 0.04$ mag for the main galaxy, and $V = 20.43 \pm 0.06$ mag and $I = 19.75 \pm 0.06$ mag for the satellite. The estimated errors include the photometry and sky background uncertainties, as well as the transformation errors from instrumental ACS magnitudes to the standard $V$ and $I$ magnitudes (Sirianni et al. 2005). The respective absolute magnitudes of $LV J1157+5638$ are $M_V = -13.26 \pm 0.10$ and $M_I = -13.80 \pm 0.10$, taking into account Galactic extinction (Schlafly & Finkbeiner 2011), and the distance modulus from the present paper (see above). The absolute magnitudes for $LV J1157+5638$ sat are $M_V = -9.38 \pm 0.13$ and $M_I = -10.04 \pm 0.13$. Azimuthally averaged surface brightness profiles of $LV J1157+5638$ and $LV J1157+5638$ sat were obtained by differentiating the galaxy growth curves with respect to the radius. The resulting profiles in $V$ and $I$ bands are displayed in Fig. 3. They are calculated to the level of about 27.5 mag arcsec$^{-2}$ in $I$ band and about 29.5 mag arcsec$^{-2}$ in $V$ band. The surface brightness of $LV J1157+5638$ sat is very low, resulting the quite noisy profiles.

The calculated profiles of the main galaxy and its satellite were fitted by an exponential intensity law of brightness distribution, which is generally appropriate for both dwarf irregular and spheroidal galaxies:

$$\mu(r) = \mu_0 + 1.086 \times (r/h),$$

where $\mu_0$ is the central surface brightness and $h$ is the exponential scale length. The galaxies follow this distribution law quite well, excluding the hump at 1-3 arcsec of the radius, caused by a noticeable star-forming region in the main galaxy. Unweighted exponential fits to the surface brightness profiles were obtained by linear regression. The derived central surface brightness and the exponential scale lengths are given in Table 1. The uncertainties are formal fitting errors.

6 DISCUSSION AND CONCLUDING REMARKS

We discover a new faint dwarf irregular galaxy, detected in the HST/ACS images. The galaxy is resolved into individual stars, including the RGB, which allowed us to measure the TRGB distance to this galaxy. This dwarf is very likely a physical companion of $LV J1157+5638$. Thus, we were able to detect a satellite of a dwarf galaxy. The structure of the neighbourhood of our objects is demonstrated in the Fig. 4. It is obvious, that $LV J1157+5638$ is situated far away from any giant galaxies and their satellite families.

The closest neighbour, dwarf irregular galaxy KKH 73, is situated at the projected distance of 83 arcmin (220 kpc) from $LV J1157+5638$. The second nearest galaxy, dwarf irregular KDG 78, is located at the projected distance of 352 arcmin (940 kpc) from $LV J1157+5638$ (see Fig. 4). Unfortunately, both neighbours, KKH 73 and KDG 78, do not have photometric distance estimations. Their heliocentric radial velocities $V_r(KKH73) = 596 \pm 6$ km s$^{-1}$ and $V_r(KDG78) = 574.8\pm1.7$ km s$^{-1}$, from the LV database\(^3\) exceed the radial velocity of $V_r(LV J1157+5638) = 416.3 \pm 1.4$ km s$^{-1}$. It is highly unlikely that they form a physically bounded system.

According to Klypin et al. (2015), the LV galaxy sample is complete up to $M_B \sim -14$ mag. We can estimate the total number of fainter galaxies using the Schechter luminosity function approximation with the parameters \(\phi_s = 1.25 \times 10^{-7} h^3 \text{ Mpc}^{-3}\), \(\alpha = -1.3\), and \(M_* = -20.0 + 5 \times \log(h)\) in $B$ filter, taking into account that \(h = 0.73\). The absolute magnitude of $LV J1157+5638$ sat is approximately $M_B = -8.9$, assuming the average colour of the LV dIrrs to be $(B-V) = 0.48 \pm 0.2$ (Sharina et al. 2013). The resulting expected number of galaxies in the Local Volume ($D < 10$ Mpc) with luminosities from $M_B = -8$ to $M_B = -14$ is 1830. Assuming a random distribution of these galaxies, we can estimate the probability of random projection of one of these galaxies into a circle with a radius of 1.5 arcmin, which is approximately 0.017 per cent. Similarly, a random location of this galaxy inside a sphere with a radius of 0.3 Mpc is 4.9 per cent. Thus, there is a very small probability of accidental detection of two dwarf galaxies in such a small spatial area, i.e. the two studied dwarfs are very likely to be physically connected.

General parameters of the galaxies under study are presented in Table 1. Judging by the total and surface photometry data in the table, $LV J1157+5638$ sat is similar to extreme Local Group dwarfs. At the same time $LV J1157+5638$ sat looks quite faint and rather compact and could be similar to d1005+68, the satellite of a dwarf galaxy in the M81 group discovered by Smirnova et al. (2017).

Fig. 5 represent total absolute $V$-magnitudes of the Local Volume dwarf galaxies versus their linear distances. The data were extracted from the HyperLeda database (Makarov et al. 2014). Here black dots are measurements from original works, and grey dots are the magnitudes originally measured in $B$ and translated to the $V$-magnitudes according to the mean colours of the LV dwarf galaxies of different types from the work of Sharina et al. (2013). $LV J1157+5638$ is shown with red circle and $LV J1157+5638$ sat with red star. It is interesting to note, that the Local Group dwarf galaxy family is relatively well studied, a lot of really faint objects are discovered. A number of known faint dwarf galaxies is rapidly decreases with increasing distance. It is obvious, that $LV J1157+5638$ sat is extremely faint for its distance. It is highly possible, that most of faint satellites are still unknown at the distance of 5–10 Mpc.

According to Makarov & Uklein (2012), their groups of dwarf galaxies form a continuous sequence in the distribution of luminosities and masses with associations of dwarfs discovered by Tully et al. (2006) in an analysis of the three-dimensional distribution of nearby galaxies. The dwarf companion $LV J1157+5638$ sat discovered by us, together with its ‘main’ irregular dwarf probably represents an example of a dwarf group of extremely low luminosity. This extends the sequence of dwarf galaxy groups to the faint and ultra-faint luminosities.

Wheeler et al. (2015) carried out hydrodynamic zoom-in simulations of isolated dark matter halos. The authors demonstrate, that every halo is filled with subhalos, many of which form stars. The simulated dwarf galaxies with $M_* \approx 10^6 M_\odot$ host 1–2 satellites with $M_* = 2–200 \times 10^3 M_\odot$. There is the implication that dwarf galaxies throughout the universe should host tiny satellite galaxies of their own.

\(^3\) http://www.sao.ru/lv/lvdb

MNRAS 000, 1–8 (XX)

A dwarf galaxy discovery near the LV dwarf 5
Figure 4. A panorama of the LV J1157+5638 neighbourhood in the supergalactic coordinates. The figure shows the projection of galaxies in a cube of ±2.5 Mpc size. The left panel is a projection on the supergalactic plane XY, while the right panel is the ZY view of the distribution of galaxies. The colour of a dot represents the morphology of the galaxy according to the colour bar. The size of a galaxy corresponds to its luminosity as shown in the legend panel.

Figure 5. A relation between linear distance and total absolute V-magnitude for the Local Volume galaxies. The data are taken from the HyperLeda database. Black dots are represent original measurements, and grey dots are the magnitudes originally measured in B and translated to the V-magnitudes according to the mean colours from Sharina et al. (2013). LV J1157+5638 is shown with red circle and LV J1157+5638 sat with red star.
Table 1. General parameters of LV J1157+5638 and LV J1157+5638 sat.

|                   | LV J1157+5638 | LV J1157+5638 sat |
|-------------------|---------------|-------------------|
| Position (J2000)a | 11°57′53.9″ +56°38′17″ | 11°57′53.9″ +56°36′49″ |
| E(B − V)b, mag   | 0.017          | 0.017             |
| VR, mag          | 16.61 ± 0.04  | 20.43 ± 0.06      |
| TR, mag          | 16.05 ± 0.04  | 19.75 ± 0.06      |
| MTR, mag         | −13.26 ± 0.10 | −9.38 ± 0.13      |
| MTR, mag         | −13.80 ± 0.10 | −10.04 ± 0.13     |
| Central surface brightness in V, mag arcsec−2 | 21.15 ± 0.04 | 23.16 ± 0.06 |
| Central surface brightness in I, mag arcsec−2 | 21.02 ± 0.02 | 22.71 ± 0.06 |
| Exponential scale length in V, arcsec | 3.23 ± 0.02 | 1.39 ± 0.03 |
| Exponential scale length in I, arcsec | 3.96 ± 0.02 | 1.45 ± 0.04 |
| Holmberg diameter in V, a26.5, arcsec / kpc | 30.0 / 1.36 | 8.4 / 0.37 |
| Holmberg diameter in I, a26.5, arcsec / kpc | 39.8 / 1.79 | 10.2 / 0.44 |
| Heliocentric radial velocityd, km s−1 | 416.3 ± 1.4 | – |
| Radial velocity relative to the Local Group, km s−1 | 514 | – |
| Distance modulus, mag | 29.82 ± 0.09 | 29.76 ± 0.11 |
| Distance, Mpc | 9.22 ± 0.38 | 8.95 ± 0.42 |
| Mean metallicity of RGB, [Fe/H], dex f | −2.30 ± 0.07 | −2.08 ± 0.10 |
| F(Hα), erg/cm² sec g | 9.33 × 10⁻¹⁴ | < 0.4 × 10⁻¹⁴ |
| log(SFR)(Hα), M⊙/yr | −2.10 | < −3.50 |
| m(FUV), magh | 18.49 | 22.71 |
| log(SFR)(FUV), M⊙/yr | −2.63 | −4.35 |

The measurements were made from the HST/ACS images.

From Schlafly & Finkbeiner (2011) a

The total magnitudes and central surface brightness are not corrected for Galactic extinction, whereas absolute magnitudes are corrected for the Galactic extinction.

From SDSS DR12 b

From the Catalog & Atlas of the LV galaxies database: http://www.sao.ru/lv/lvdb/ c

The small [Fe/H] uncertainties are mostly reflect the formal errors of the estimate defined by expression given in the Section 4.

Using data from Karachentsev et al. (2015) and our distances d

These GALEX magnitudes were obtained from the Mikulski Archive for Space Telescopes (MAST) (GALEX Public Release GB6/GRT). We estimate the respective SFR with the recipe given in the LV galaxies database for the similar data.

Dooley et al. (2017) also predict 1–6 (2–12) satellites with \( M_r > 10^9 M_\odot \) (\( M_r > 10^8 M_\odot \)) within the virial volume of LMC-sized galaxies, using Caterpillar simulations. The authors emphasize an importance of finding and observing of LMC-sized galaxies, using Caterpillar simulations. The authors emphasize an importance of finding and observing of faint dwarf galaxies for the determination of the galaxy mass function and an importance of searches for faint dwarf groups, which could test ΛCDM theory.

ACKNOWLEDGEMENTS

This research is supported by award GO-13442 from the Space Telescope Science Institute for the analysis of observations with Hubble Space Telescope. This study is supported by the Russian Science Foundation (grant 14–12–00965). We acknowledge the usage of the HyperLeda database (http://leda.univ-lyon1.fr). GALEX data presented in this paper were obtained from the Mikulski Archive for Space Telescopes (MAST). STScI is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555. Support for MAST for non-HST data is provided by the NASA Office of Space Science via grant NNX09AF08G and by other grants and contracts.

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