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LARGE DIFFUSE DWARFS IN THE DYNAMICALLY COLD TRIPLE GALAXY SYSTEMS

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We report on the discovery of three large diffuse dwarf (LDD) galaxies located in isolated triple systems. They have effective diameters of $3.6 \div 10.0$ kpc and effective surface brightness of $26.2 \div 27.3$ ^{m}/sq. arcsec. We note that the LDD galaxies tend to occur in small groups with a very low dispersion of radial velocities. The total (orbital) mass of the triplets approximately equals to their integral stellar mass within velocity measurement errors. The presence of LDD galaxies in cold multiple systems seems mysterious.

Keywords: *galaxies - dwarf galaxies - low surface brightness galaxies*

1. *Introduction*. Over a wide range of luminosities, the average surface brightness (SB) of galaxies, and their integral absolute magnitude, M, follow a relation $SB = (1/3)M + \text{const}$, which corresponds to an approximate constancy of the average volumetric stellar density for major and dwarf galaxies [1]. However, with the advent of deep sky surveys, a specific population of low surface brightness galaxies has been discovered, whose luminosity is typical of dwarf systems and whose sizes are comparable to those of normal galaxies. These objects are called "ultradiffuse galaxies" (UDG). As defined by van Dokkum et al. [2], these include galaxies with a central surface brightness in the g-band $SB_g(0) > 24$ ^{m}/sq. arcsec and a linear effective diameter $A_{50} > 3.0$ kpc, within which half of the galaxy's luminosity is contained.

Many UDG galaxies have been discovered in the nearby clusters: Virgo [3], Fornax [4] and Coma [5], and a small number have been also found in nearby groups around NGC 253, Cen A, NGC 5485 [6-8]. A catalog of 7070 UDG candidates selected over 20000 sq. degr. of sky was recently published by Zaritsky et al. [9]. According to [10], about 40% of UDG objects are found in clusters, about 20% are located in groups, and the remaining 40% occur in scattered filaments, avoiding common field regions. No isolated UDG galaxies have yet been discovered. This arrangement of diffuse galaxies relative to the elements of the cosmic web indicates that the structure of UDG galaxies is determined not so much by features of their internal evolution as by the influence of external environment. The disperse stellar structure of UDG galaxies is obviously a sensitive

indicator of the tidal influence of their neighbors.

Studying the closest examples of UDG galaxies helps to advance our understanding of their specifics. In the Local Volume with a radius of 10 Mpc, 15 objects were noted [11] that meet the criterion of an ultradiffuse galaxy. All of these UDG objects are located in the known nearby groups. Among them, some (Sag dSph, KK 208, Scl-MM-Dw2, And XIX) have an elongated structure with an apparent axial ratio $b/a < 0.5$, which is caused by gravitational disturbance from a massive neighbor. Others (Garland, NGC 3521sat, d0226+3325) have an irregular shape and a young stellar population, indicating that these dwarfs likely formed from tidal tails and bridges on the outskirts of major galaxies. We consider it appropriate to strengthen the criterion for a large diffuse dwarf (LDD) galaxy, selecting into this category objects of even lower surface brightness, having a round smooth shape and lack of young stellar population. As a criterion for a galaxy to belong to a LDD object, we use the following conditions:

i. The effective diameter of a galaxy in the *g*-band is $A_{50,g} > 3.0$ kpc;

ii. Effective surface brightness in the *g*-band $SB_{50,g} > 26.0^{m}$/sq. arcsec;

iii. Apparent axial ratio $b/a > 0.5$;

iv. Morphological type dSph with a smooth shape and an old population ($g - r > 0.50$).

Of the thousand galaxies in the Local Volume, only five known galaxies satisfy these conditions: CenMM-dw1, IKN, KK 77, Cen-MM-dw3 and NGC 4631dw1 with distances in the range (3.6 - 7.4) Mpc, effective diameters $A_{50} = (3.1 - 5.6)$ kpc, effective surface brightness $SB_{50} = (26.2 - 28.1)^{m}$/sq. arcsec and absolute magnitudes $M_B = (-11^{m}.6 - -12^{m}.6)$. The names of the galaxies are indicated as they are presented in the Updated Nearby Galaxy Catalog [1], a regularly updated version of which is available on-line[1]. It is likely that the Local Volume contains other LDD galaxies that have not yet been discovered due to the incompleteness of deep sky surveys.

2. *A LDD galaxy in the NGC 3056 triplet.* While searching for new nearby dwarf galaxies in DESI Legacy Imaging Surveys, DR10 [12], we discovered a low surface brightness object at coordinates RA = 09:54:43.9 DEC = -28:30:54 (J2000). Its image is shown on the left panel of Fig.1. To the north of it at a distance of 13', there is a galaxy of type S0a with a radial velocity $V_{LG} = 674$ km s^{-1} relative to the centroid of the Local Group. This galaxy with its two satellites: ESO 435-016 and ESO 435-020 forms a triple system, presented in the list of nearby isolated triplets of galaxies [13]. The parameters of this system are shown in Table 1. Its columns contain: galaxy name; its coordinates; morphological type; apparent *B*-magnitude; radial velocity in km s^{-1}; projection separation

[1] *http://www.sao.ru/lv/lvgdb*

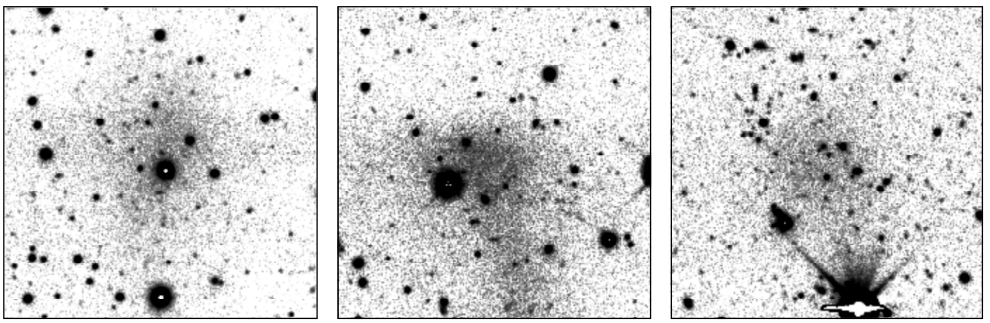

Fig. Images of three large diffuse dwarf galaxies from the DESI Legacy Imaging Surveys: LDD 0954-28, LDD 0911-14 and LDD 0852-02 from the left ro right. Each image size is $2' \times 2'$. North is to the top, East is to the left.

from the main galaxy, R_p, in kpc; estimate of the orbital (projected) mass $M_p = (16/\pi G)\Delta V^2 R_p$ in units of $10^{10} M_\odot$, where ΔV is the difference in radial velocities of the satellite and the host galaxy, and G is the gravitational constant [14]. The irregular galaxy ESO 435-020 has a peculiar structure with signs of recent merging. A feature of the triplet is the small dispersion of the radial velocities of galaxies, comparable to the errors in velocity measurements. The reason for this may be the projection effect, when the velocity vectors of both satellites are almost perpendicular to the line of sight. The observed low velocity dispersion may also be a consequence of the low total mass of the galaxy triplet.

The last row of the table corresponds to the LDD galaxy we noted with a very low surface brightness. We assume that this object is a physical member of the triplet. The analysis undertaken by Karachentseva et al. [15], showed that isolated dSph galaxies are extremely rare. In the volume of the Local Supercluster with a radius of approximately 40 Mpc, only a dozen such putative cases have been noted. Radial velocity measurements in dSph galaxies are very difficult due to the absence of a noticeable amount of neutral hydrogen in them and due to the low optical surface brightness. In those rare cases when such measurements were

Table 1

PROPERTIES OF NGC 3056 TRIPLET OF GALAXIES

Name	RA(2000.0) deg	DEC(2000.0) deg	Type	B mag	V_{LG} km s^{-1}	R_p kpc	M_p 10^{10}
NGC 3056	148.637	-28.298	S0a	12.6	674±5	0	-
ESO 435-016	149.691	-28.622	Im	13.5	678±4	209	0.4
ESO 435-020	149.838	-28.133	Irr-p	14.4	673±2	227	0.03
LDD 0954-28	148.683	-28.515	Sph	17.8	-	47	-

possible, the radial velocities of spheroidal dwarfs turned out to be close to the velocities of neighboring normal galaxies [16], making the assumption of their isolation unlikely.

3. *Other examples of LDD in triplets of galaxies*. The catalog of isolated galaxy triplets in the Local Supercluster [17] contains data on 168 triple systems with radial velocities $V_{LG} < 3500$ km s^{-1}. The sample of these triplets is characterized by the following median parameters: member radial velocity dispersion of 40 km s^{-1}, projected harmonic radius of 155 kpc, projection (orbital) mass of $5 \cdot 10^{11} M_{\odot}$, and orbital mass-to-stellar mass ratio $M_p/M_* = 25$.

We assumed that a low velocity dispersion in a multiple galaxy system may be a favorable factor for the presence of very diffuse objects in it. Among 168 nearby triplets, there are 17 systems with the small ratio $M_p/M_* < 2$, located in the Legacy Imaging Surveys area. Looking at these cases, we found two more triple systems with major members NGC 2781 and UGC 4640, containing candidate LDD objects. Their images are shown in the middle and right panels of Fig.1. Data on these triplets are presented in Tables 2, 3, the parameters of which are similar to those in Table 1. Radial velocities of galaxies and their errors are taken from Lyon Extragalactic Database = LEDA [18]. The distances to NGC 2781 (30.6 Mpc) and UGC 4640 (49.0 Mpc) were estimated from their radial velocities taking into account local cosmic flows in the Numerical Action Method model [19]. The

Table 2

PROPERTIES OF NGC 2781 TRIPLET OF GALAXIES

Name	RA(2000.0) deg	DEC(2000.0) deg	Type	B mag	V_{LG} km s^{-1}	R_p kpc	M_p 10^{10}
NGC 2781	137.864	-14.817	S0a	12.5	1766±22	0	-
DDO 57	137.832	-15.051	Im	14.8	1784±2	94	3.6
MCG-02-24-03	138.028	-15.432	Sm	15.2	1794±6	101	9.3
LDD 0911-14	137.856	-14.703	Sph	18.2	-	46	-

Table 3

PROPERTIES OF UGC 4640 TRIPLET OF GALAXIES

Name	RA(2000.0) deg	DEC(2000.0) deg	Type	B mag	V_{LG} km s^{-1}	R_p kpc	M_p 10^{10}
UGC 4640	132.933	-02.134	Sc	13.8	3091±3	0	-
Arp 257a	132.909	-02.367	Sm	14.4	3103±4	200	3.4
Arp 257b	132.908	-02.354	Im	16.8	3106±6	189	5.0
LDD 0852-02	133.148	-02.177	Sph	19.2	-	184	-

distance to NGC 3056 (12.2 Mpc) was determined from surface brightness fluctuations [20].

As a control sample, we searched for LDD galaxies in the virial zones of 17 triplets with an $M_p/M_* > 100$ and didnot find a single LDD object. Since triplets of galaxies with $M_p/M_* < 2$ constitute only 10 percent of their total number (17/168), the probability of three triplets with LDD members falling into this category is 0.001.

4. *Surface photometry of LDD galaxies*. We performed surface photometry of three new very low surface brightness galaxies, absent in [9] catalog, to estimate their structural parameters. For this purpose, data from DESI Legacy Imaging Surveys, DR10 in the *g* and *r* bands were used. The photometry of the galaxies was carried out by measuring photometric curves of growth using standard ellipse-fitting and aperture photometry techniques in photutils[2]. This was preceded by background subtraction. Also, foreground and bright background objects were masked and then the corresponding pixels were replaced by the mean flux in the aperture rings contained in the mask. We fit the resulting curve of growth, $f(r)$, using the following modified exponential law:

$$f(r) = f(r_0) + f^{\exp}(r), \quad r > r_0, \tag{1}$$

where $f^{\exp}(r)$ - the flux corresponding to the standard exponential law and $f(r_0)$ - the additional flux from the inner part ($r < r_0$) of the galaxy. This leads to:

$$f(r) = f_{tot}\left(1 - \frac{f_{tot}^{exp}}{f_{tot}}\left(1 + \frac{r}{h}e^{-r/h}\right)\right), \tag{2}$$

where f_{tot}, f_{tot}^{exp} and h - fitting parameters of the model: total flux, total flux (without adding $f(r_0)$) from the standard exponential law and the exponential scale from the standard exponential law.

The results of measuring the integral magnitudes of galaxies *g* and *r*, effective radii $r_{50,g}$ and $r_{50,r}$ are presented in Table 4. It also shows $B = g + 0.542(g - r) + 0.141$ and $V = g - 0.496(g - r) - 0.015$ integral magnitudes of galaxies in *B* and *V* system [21].

As one can see, the integrated color indices $B - V$, taking into account the color excess $E(B - V)$ due to extinction, turns out to be typical for dSph galaxies with old stellar population. The effective linear diameters $A_{50} > 3.0$ kpc of all three diffuse galaxies and their effective surface brightness $SB_{50} > 26.0^{\text{m}}$/sq. arcsec satisfy the conditions formulated above for LDD galaxies. The assumption that these LDD galaxies are physical members of the triplets under consideration looks very plausible, given that such diffuse objects have not yet been discovered in the general

[2] *https://photutils.readthedocs.io/en/stable/*

Table 4

PHOTOMETRIC PARAMETERS OF THE LDD GALAXIES

Name	g mag	r mag	B mag	V mag	$r_{50,g}$ "	$r_{50,r}$ "	$SB_{50,g}$ mag/sq.arcsec	$A_{50,g}$ kpc	$B-V$ mag	$E(B-V)$ mag	M_B mag
LDD0954-28	17.31	16.75	17.75	17.02	30.77	31.96	26.74	3.64	0.73	0.065	-12.95
LDD0911-14	17.76	17.12	18.25	17.43	19.83	19.65	26.24	5.88	0.64	0.046	-14.37
LDD0852-02	18.70	18.08	19.18	18.38	21.10	21.15	27.31	10.02	0.62	0.016	-14.34

field. The absolute magnitudes of these LDD galaxies, indicated in the last column of Table 4, are 1-3 mag brighter than similar objects in the Local Volume.

5. *Brief discussion*. We estimated the stellar mass of galaxy triplets M_* using the ratio $M_*/M_\odot = 0.6(L_K/L_\odot)$ according to Lelli et al. [22]. The values of the total luminosity of triplets in the *K*-band are taken from the catalog [17] with correction for the adjusted distance. Data on Table 5 show that the estimate of the total (projected) mass of triplets turned out to be approximately equal to their stellar mass within the M_p errors due to the velocity measurement errors. From this we can conclude that the "cold" kinematics of the triplets under consideration does not require the presence of a noticeable amount of dark matter in them. It remains unclear how such a feature of triplets can be related to the presence in their volume of very diffuse galaxies with old stellar populations.

In general, various possible scenarios for the formation of LDD galaxies have been discussed in the literature: a high angular momentum of the LDD [22], a stellar feedback from the host galaxy [23], and "failed Milky Way" mechanism [24].

Note that the average projection separation of LDD galaxies, 92 kpc, is about half the average distance of late-type satellites, 170 kpc. The same effect of segregation of dSph and dIrr galaxies is also well known in other groups and clusters of galaxies.

The diffuse satellite LDD 0911-14 exhibits a strong shape distortion in the form of a tidal tail directed towards the massive host galaxy NGC 2781. Our photometry of this satellite was limited to the main body of the object. Taking into account the tidal tail almost doubles the integral luminosity and effective

Table 5

TRIPLE SYSTEMS OF GALAXIES WITH LDD

Name	D Mpc	$\log(M_*)$ 10^{10}	$\log(M_p)$ 10^{10}
NGC 3056	12.2	0.87	0.22±0.20
NGC 2781	30.6	5.11	6.45±2.85
UGC 4640	49.0	2.51	4.20±0.80

diameter of this galaxy.

It is obvious that galaxy systems with cold kinematics and the presence of very diffuse members can also be found among groups with a larger population. As an example, we note a group of four satellites around the galaxy NGC 660. At a projection distance of 13' east of NGC 660 there is an extremely low surface brightness galaxy (01:43:55.2 + 13:38:42), discovered by Karachentsev & Kaisina [25]. The spiral galaxy NGC 660 itself has a very peculiar shape in the form of two merging galaxies. With its low ratio $M_p/M_* \simeq 3$, this group stands out among other groups in the Makarov & Karachentsev [13] catalog.

Recently, Okamoto et al. [26] discovered an extremely low surface brightness satellite near the nearby spiral galaxy NGC 253 using deep stellar photometry with the Hyper Suprime-Cam on the Subaru telescope. According to the authors, this "ghost" galaxy has an effective diameter of 6.7 ± 0.7 kpc, an effective surface brightness of $SB_{50} \sim 30^{\text{m}}$/sq. arcsec, an apparent axial ratio of $b/a = 0.94$, and old stellar population. This satellite, NGC 253-SNFC-dw1, is located at a projection separation of $R_p = 75$ kpc from the center of NGC 253 and shows weak signs of tidal disruption. In its size and extremely low surface brightness, this dim satellite of NGC 253 is similar to the Milky Way satellite, Antlia 2, with $A_{50} = 5.8 \pm 0.6$ kpc, $SB_{50} = 31.9^{\text{m}}$/sq. arcsec [27] and the satellite of M 31, And XIX, with $A_{50} = 6.2 \pm 2.0$ kpc, $SB_{50} = 31.0^{\text{m}}$/sq. arcsec [28]. Such objects are undetectable by conventional photometry, since their surface brightness is 5-6 mag fainter than that of the UDG galaxies discussed by [3].

It is interesting to note that the galaxy NGC 253, along with NGC 2683 and NGC 2903, has the minimum radial velocity dispersion of satellites ($\sigma_v < 45$ km s^{-1}) among the 25 brightest galaxies in the Local Volume with a luminosity similar to that of the Milky Way. This fits with the trend that the cold kinematics of the satellites (or the deficiency of dark matter in the group) favors the survival in the group of "fragile" satellites with very low stellar density.

We did not consider here the possible reasons for the observed correlation between the presence of LDD galaxies in a group and the deficiency of dark matter in it. Apparently, it is necessary to accumulate richer statistics of such cases, as well as perform dynamic modeling of tidal destruction of diffuse satellites under different assumptions about the shape of the satellites' orbits and the amount of dark matter in the LDD galaxy. According to Penarrubia et al. [29], the tidal influence of the dark halo of the main galaxy in a group reduces the central surface brightness of a satellite and shortens its size. Torrealba et al. [27] noted that *N*-body modeling a strong tidal stripping of a diffuse companion can explain the observed properties of Antlia 2-type galaxies.

More in-depth observations of the mentioned triplets of galaxies both in the optical range and in the neutral hydrogen line could clarify the problem of the

supposed connection between the cold kinematics of the group's satellites and the presence of LDD galaxies in it.

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БОЛЬШИЕ ДИФФУЗНЫЕ КАРЛИКИ В ДИНАМИЧЕСКИ ХОЛОДНЫХ ТРОЙНЫХ СИСТЕМАХ ГАЛАКТИК

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Мы сообщаем об обнаружении трех больших диффузных карликовых (LDD) галактик, расположенных в изолированных тройных системах. Они имеют эффективные диаметры (3.6 - 10.0) кпк и эффективные поверхностные яркости (26.2 - 27.3) зв. вел. с квадратной секунды. Отмечено, что LDD галактики имеют тенденцию встречаться в мелких группах с очень малой дисперсией лучевых скоростей. Суммарная (орбитальная) оценка массы этих триплетов примерно равна их суммарной звездной массе в пределах ошибок измерения лучевых скоростей галактик. Наличие LDD галактик в холодных кратных системах представляется загадочным.

Ключевые слова: *галактики - карликовые галактики - галактики низкой поверхностной яркости*

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