"Scraggy" dark halos around bulge-less spiral galaxies

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Accepted XXX. Received XXX; in original form XXX

ABSTRACT

We use a sample of 220 face-on bulge-less galaxies situated in the low density environment to estimate their total mass via orbital motions of supposed rare satellites. Our inspection reveals 43 dwarf companions having the mean projected separation of 130 kpc and the mean-square velocity difference of 96 km/s. For them, we obtain the mean orbital-mass-to-K-band luminosity ratio of 20 ± 3. Seven bulge-less spirals in the Local Volume are also characterized by the low mean ratio, $M_{orb}/L_K = 22 ± 5$. We conclude that bulge-less Sc-Scd-Sd galaxies have poor dark halos, about two times lower than that of bulgy spiral galaxies of the same stellar mass.

Key words: galaxies: bulges – galaxies: spiral – galaxies

1 INTRODUCTION.

Among the galaxies with stellar masses of more than, $10^{10} M_\odot$ the flat disc-like objects without the evidence of the central bulge constitute about 10%. Almost all of them are classified as late-type spirals: Sc, Scd, and Sd according to de Vaucouleurs et al. (1976). Some of them demonstrate small pseudo-bulges formed during the process of the secular disc evolution. Unlike classical bulges, the pseudo-bulges show a nearly exponent stellar density profile and the evidence of current star formation (Kormendy & Kennicutt 2004). The observed abundance of the spiral discs without spheroidal stellar component imposes a challenge to models of the hierarchical clustering of galaxies via their consecutive merging (Kormendy et al. 2010).

Bulge-less galaxies are the most distinguishable when they are seen strictly edge-on. A Reference Flat Galaxy Catalog = RFGC (Karachentsev et al. 1999) lists 4236 "flat" galaxies covering the all sky. Karachentseva et al. (2016) have selected from the RFGC catalog 817 ultra-flat galaxies (UFG) with an apparent axial ratio $a/b > 10$. The environment of the UFGs is characterized by low spatial density, a deficit of massive satellites and almost total absence of dwarf spheroidal satellites with old stellar population.

Inner structure of the UFGs is practically unseen due to the disc inclination. To determine the bulge-less galaxy structural features, Karachentsev & Karachentseva (2019) collected 220 galaxies of the Sc, Scd, and Sd types, seen almost face-on. According to statistical analysis, about half of the galaxy sample have bar-like substructures, in most part of the discs the unresolved (star-like) nuclei are seen, and a considerable part (27–50)% of the face-on galaxies have peripheral distortion of their spiral pattern.

There is an idea that secular stability of very thin stellar discs requires the presence a very massive dark halo around them (Banerjee & Jog 2013). The shape of this halos is supposed to be nearly spherically symmetric. Unfortunately, the rotation curves obtained for the UFGs, extend not so far from the center (Uson & Matthews 2003, Makarov et al. 2001), which makes it impossible to evaluate the true dimension and mass of the dark halo. Determining the total dark halo mass by radial velocities and projected separations of the satellites is more promising method. However, the difficulties arise even with such approach. The search for satellites with measured radial velocities around the UFGs shows that ~60% of ultra-flat galaxies have not any detected physical satellites inside the virial radius $R_{vir} \sim 250$ kpc, about 30% of the UFGs enter together with a rather bright neighbors in scattered associations (filaments, walls), and only ~10% of ultra-flat galaxies are the dominant objects in physical multiple systems (Karachentsev et al. 2016). In the following we present the results of searches for satellites around 220 late type spiral galaxies seen face-on as well as the estimates of the total mass of the bulge-less galaxies.

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Table 1. Face-on bulge-less galaxies with orbital mass estimates.

| Galaxy       | $B_t$  | $V_{LG}$ | mod D | $T$ | $log L_K$ | $\Delta V$ | $R_p$ | $log M_{orb}$ | $M_{orb}/L_K$ |
|--------------|-------|----------|-------|-----|-----------|------------|-------|---------------|----------------|
| IC1562       | 13.60 | 3771     | 33.56 | c   | 10.69     | 122        | 60    | 12.02         | 21             |
| NGC0255      | 12.41 | 1694     | 31.70 | c   | 10.45     | 37         | 173   | 11.45         | 10             |
| ESO542-004   | 15.00 | 5657     | 34.50 | d   | 10.29     | -66        | 199   | 12.01         | 52             |
| UGC02043     | 14.96 | 5316     | 34.40 | c   | 10.67     | -18        | 128   | 10.69         | 1              |
| ESO479-022   | 15.39 | 7266     | 35.07 | c   | 10.61     | 45         | 168   | 11.60         | 10             |
| UGC02323     | 15.66 | 8139     | 35.33 | c   | 10.99     | -281       | 41    | 12.58         | 39             |
| UGC02692     | 14.07 | 6337     | 34.77 | c   | 11.09     | -42        | 92    | 11.28         | 2              |
| NGC1376      | 12.85 | 4137     | 33.82 | c   | 11.14     | -115       | 134   | 12.32         | 15             |
| NGC1599      | 14.10 | 3947     | 33.73 | c   | 10.60     | 100        | 155   | 12.26         | 46             |
| UGC03703     | 15.35 | 7260     | 35.14 | c   | 10.72     | -96        | 189   | 12.31         | 39             |
| UGC04380     | 15.05 | 7554     | 35.24 | c   | 10.86     | 134        | 208   | 12.64         | 60             |
| UGC05169     | 15.44 | 7699     | 35.29 | d   | 10.45     | -81        | 41    | 11.50         | 11             |
| NGC2967      | 12.28 | 1679     | 32.16 | c   | 10.80     | 101        | 191   | 12.36         | 36             |
| UGC05474     | 14.89 | 6347     | 34.71 | cd  | 10.54     | 42         | 80    | 11.22         | 5              |
| UGC05483     | 15.13 | 6014     | 34.77 | c   | 10.62     | -21        | 46    | 10.38         | 1              |
| NGC3506      | 13.16 | 6252     | 34.87 | c   | 11.42     | 1         | 135   | 8.20          | 0              |
| PGC014006    | 14.13 | 7543     | 35.26 | c   | 11.25     | 168        | 190   | 12.80         | 35             |
| NGC3596      | 11.79 | 1062     | 31.32 | cd  | 10.42     | -101       | 25    | 11.48         | 12             |
| NGC3938      | 10.87 | 841      | 30.87 | c   | 11.03     | -179       | 156   | 12.77         | 55             |
| IC3271       | 14.57 | 7083     | 35.13 | c   | 10.97     | 63         | 103   | 11.68         | 5              |
| NGC4653      | 12.77 | 2471     | 33.08 | c   | 10.85     | 37         | 68    | 11.04         | 2              |
| NGC5434      | 13.94 | 4587     | 34.21 | c   | 10.84     | 115        | 41    | 11.81         | 9              |
| NGC5468      | 12.95 | 2734     | 33.40 | c   | 10.90     | 68         | 55    | 11.48         | 4              |
| PGC050801    | 15.09 | 8562     | 35.51 | c   | 10.70     | 43         | 54    | 11.07         | 2              |
| IC1221       | 14.59 | 5706     | 34.63 | cd  | 10.64     | 75         | 96    | 11.80         | 14             |
| NGC6821      | 13.62 | 1680     | 31.86 | d   | 10.33     | -28        | 127   | 11.07         | 6              |
| NGC7137      | 13.05 | 1977     | 32.16 | c   | 10.57     | 152        | 77    | 12.32         | 56             |
| NGC7495      | 13.76 | 5133     | 34.28 | c   | 11.06     | -39        | 73    | 11.12         | 1              |
| NGC7535      | 14.28 | 4884     | 34.17 | cd  | 10.63     | 8          | 47    | 9.55          | 0              |
| ESO0605-016  | 13.23 | 7999     | 35.28 | c   | 11.55     | -68        | 142   | 11.89         | 2              |

(1) galaxy name; (2) apparent $B$-magnitude from HyperLEDA (Makarov et al. 2014); (3) radial velocity with respect to the Local Group center; (4,5) distance modulus and morphological type from HyperLEDA; (6) logarithm of K-band luminosity expressed in the solar units; (7) radial velocity difference of satellite relative to the central galaxy; (8) a satellite projected separation; (9) logarithm of orbital mass; (10) orbital mass-to-luminosity ratio.

2 SATELLITES AROUND FACE-ON BULGE-LESS GALAXIES.

To reveal the physical satellites, we have used the option "To Search for Nearby Objects" proposed in the NASA Extragalactic Database (=NED, http://ned.ipac.caltech.edu/). Around each bright enough galaxy from the list by Karachentsev & Karachentseva (2019) with absolute magnitude $M_B < -19.0$ we have searched for companions with radial velocity difference $|\Delta V| < 300$ km/s ranging in the projected separation $R_p = 250$ kpc. In the next stage, we left only those conditionally isolated cases where other neighbors brighter than the central object were absent within $R_p = 750$ kpc around the face-on galaxy under study. In the process, we excluded a lot of neighboring objects that turned out to be stars or parts of a normal

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galaxy. Altogether, we detected 43 satellites around 30 face-on galaxies. The remaining galaxies from our list do not have satellites in the specified limits of $|\Delta V|$ and $R_p$, or they have as neighbors other bright galaxies violating the isolation condition.

In Table 1 data on the face-on bulge-less galaxies and their satellites are given. Before presenting the data we have to do some explanations. The total $B$-magnitude is corrected for Galactic extinction; the inner extinction for face-on galaxies we prove to be zero. The $K$-band magnitude is calculated via the corrected $B$-magnitude and morphological type (Melnyk et al. 2017). Calculating the satellite projected separation $R_p$, we use the galaxy distance $D = V_{LG}/H_0$ with the Hubble parameter $H_0 = 73$ km/s/Mpc. For nearby galaxies situated in the Local Volume we attracted their individual distance moduli from http://www.sao.ru/lv/lvgdb. The orbital (Keplerian) mass of a galaxy, $M_{\text{orb}} = (16/\pi G) \times \Delta V^2 \times R_p$, is estimated assuming a random orientation of satellite orbits with the mean orbital eccentricity of $\langle e^2 \rangle = 1/2$ (Karachentsev & Kudrya 2014), where $G$ is the gravitation constant. Notes to columns of Table 1 are given below the Table. The distribution of 43 satellites around their host face-on bulge-less galaxies on the modulus of radial velocity difference and the projected separation is presented in Fig.1. Here the mean-square of radial velocity difference is $\langle \Delta V^2 \rangle^{1/2} = 96$ km/s, and the mean projected separation is equal to $\langle R_p \rangle = 130$ kpc.

As it is seen from Table 1, the majority of face-on galaxies with detected satellites belong to the Sc morphological type. The median of their luminosity, 10.71 dex, is comparable with the Milky Way luminosity. (This high value is caused by the fact that in searching for satellites we donated the face-on low luminosity galaxies with their shallow potential well.) The orbital mass values show a pronounced scatter that depends on prevailing character of satellites motions. At fixed value of the orbital eccentricity, the ensemble mean of $M_{\text{orb}}$ is the unbiased estimate of the mass of central galaxy. In the case of an arbitrary eccentricity $e$, the orbital Keplerian mass estimate is expressed as

$$M_{\text{orb}} = (32/3\pi)(1 - 2e^2/3)^{-1} \times G^{-1} \times \langle \Delta V^2 \times R_p \rangle.$$ 

This value grows in three times from severely round motions, $e = 0$, to the pure radial ones, $e = 1$. We assumed the mean value of $\langle e^2 \rangle = 1/2$, corresponding the expected average obtained in the N-body simulations (Barber et al. 2014).

The mean value of the orbital-mass-to-K-band luminosity ratio for face-on bulge-less galaxies is $\langle M_{\text{orb}}/L_K \rangle = 20 \pm 3$ (see last column of Table 1). This ratio diminishes to $17 \pm 3$ having regard to statistical correction for errors of the radial velocity measurements.

3 SATELLITES OF THE FACE-ON BULGE-LESS GALAXIES IN THE LOCAL VOLUME.

The Local Volume limited by the radius of 11 Mpc, is unique in having an abundance of galaxies which distances are measured at the Hubble Space Telescope with accuracy of about 5%. The summary sample on the galaxy distances is presented in the
Updated Nearby Galaxy Catalog = UNGC (Karachentsev et al. 2013) as well as in the regularly replenished data base http://www.sao.ru/lv/lvdb (Kaisina et al. 2012). In the Local Volume faint dwarf galaxies are seen which are lost in more distant and less researched regions of the universe. The knowledge of the high accuracy measured distances permits to separate the physical satellites of bright galaxies against foreground and background objects with more confidence. In the Local Volume there are seven face-on bulge-less galaxies from the list of Karachentsev & Karachentseva (2019): IC 342 (3.28 Mpc), NGC 5068 (5.15 Mpc), M 101 (6.95 Mpc), NGC 6946 (7.73 Mpc), NGC 3344 (9.82 Mpc), NGC 628 (10.19 Mpc), and NGC 3184 (11.12 Mpc). Here in parentheses the distances from observer are given. Of them, two low luminosity galaxies, NGC 3344 and NGC 5068 have no satellites with measured radial velocities. The remaining five galaxies have from 5 to 9 physical satellites, the data on which are presented in Table 2. Its columns contain: (1) galaxy name, (2) the total apparent B-magnitude, (3) the projected separation in kpc, (4) the difference between the radial velocities of the satellite and the host galaxy, in km/s.

The distribution of 38 satellites on their modulus velocity difference and projected separation is presented in Fig.2. As one can see, the satellite velocity differences do not exceed 150 km/s, justifying the above selection limit of $|\Delta V| < 300$ km/s in the search for galaxies situated in more distant volume. About half of satellites are located outside of a characteristic virial radius \( \sim 250 \) kpc. Nethertheless, they all are inside the “zero velocity sphere” \((R_0 \sim 1 \) Mpc), which separates the collapsing group members against the global cosmic expansion. Obviously, beyond the Local Volume, many distant satellites with \( R_\rho > R_{\text{vir}} \) are lost among the general field galaxies. Table 3 contains the basic parameters of the nearby groups. As seen from the data, even the brightest satellites appear to be fainter of the central galaxy at 3–5 magnitudes. Thus, the application of the model of test particles moving around central massive body is quite correct in evaluating the total mass of the central galaxy.

In the Local Volume there are two another groups, NGC 253 and NGC 5236, where the dominated member is a spiral bulge-less galaxy but oriented arbitrary. We give their data in the bottom of Table 3. The K-band luminosities and orbital mass estimates for these nearby groups are rather similar to ones from Table 1 obtained for more distant systems. Particularly, the mean total mass-to-luminosity ratio for the Local Volume bulge-less galaxies, \(<M_{\text{orb}}/L_K> = 22 \pm 5\), is practically the same as the value \((20 \pm 3)\) derived for the remote Sc-Sd galaxies.

It should be noted that according to the data by Karachentsev & Kudrya (2014), the Local Volume contains five groups: M 31, M 81, NGC 4258, NGC 4736, and NGC 3627, where the bulgy Sab–Sbc galaxies dominate, and also three groups: NGC 5128, NGC 4594, NGC 3115, where the objects are grouping around the E, S0, Sa galaxies. These groups are characterized of the mean values of total mass-to-luminosity ratio \( <M_{\text{orb}}/L_K> = 41 \pm 9\) and \( <M_{\text{orb}}/L_K> = 88 \pm 30\), respectively. In spite of poor statistics, these results can indicate that the dark mass-to-luminous mass ratio grows when the fraction of galaxy spheroidal stellar sub-system increases.
Table 2. Companions of face-on bulge-less galaxies in the Local Volume.

| Galaxy     | \( B_t \) | \( R_p \) | \( \Delta V \) |
|------------|-----------|-----------|--------------|
| IC 342     | 9.1       | 0         | 0            |
| KK35       | 15.7      | 15        | -97          |
| UGCA 86    | 13.5      | 89        | 36           |
| NGC 1569   | 12.1      | 312       | -67          |
| NGC 1569   | 11.8      | 312       | -126         |
| Cam A      | 14.8      | 326       | -77          |
| Cam B      | 16.1      | 365       | 46           |
| Cas 1      | 15.3      | 526       | 4            |
| M 101      | 8.3       | 0         | 0            |
| NGC 5477   | 14.2      | 44        | 73           |
| PGC2448110 | 17.3      | 92        | 14           |
| NGC 5474   | 11.5      | 96        | 46           |
| UGC 8882   | 15.8      | 110       | 104          |
| GBT1355+54 | -         | 152       | -33          |
| Holm IV    | 13.8      | 163       | -106         |
| NGC 5585   | 11.2      | 429       | 79           |
| Cam A      | 14.8      | 326       | -77          |
| Cam B      | 16.1      | 365       | 46           |
| Cas 1      | 15.3      | 526       | 4            |
| M 101      | 8.3       | 0         | 0            |
| NGC 6946   | 9.6       | 0         | 0            |
| NGC 628    | 9.8       | 0         | 0            |
| NGC 3184   | 10.3      | 0         | 0            |
| UGC 1171   | 15.7      | 132       | 81           |
| UGC 1176   | 14.4      | 150       | -27          |
| SDSS0138+14| 18.0      | 153       | 86           |
| KDG 10     | 16.3      | 296       | 132          |
| AGC 112454 | 17.5      | 297       | 14           |
| UGC 1056   | 14.8      | 374       | -62          |
| JKB 142    | 18.4      | 404       | 65           |
| UGC 1104   | 14.5      | 481       | 29           |
| SDSS0142+13| 17.4      | 501       | 15           |
| NGC 3184   | 10.3      | 0         | 0            |
| KUG1013+414| 15.4      | 90        | -85          |
| SDSS1028+42| 17.5      | 445       | -34          |
| NGC 3104   | 13.6      | 543       | 8            |
| SDSS1025+43| 17.3      | 561       | 58           |
| KUG1004+392| 15.6      | 629       | 9            |

4 CONCLUDING REMARKS.

As we noticed above, the thin spiral bulge-less galaxies reside in the low density regions, i.e. have a poor environment. The rare satellites of the Sc–Scd–Sd galaxies are, as a rule, dwarf galaxies containing gas and young stars. Our statistics of satellites around 220 face-on bulge-less galaxies shows that they have the average projected separation of \( \langle R_p \rangle = 130 \) kpc and mean-square velocity difference of 96 km/s. The estimate of the total mass of bulge-less galaxies via orbital motions of their satellites yields the value of \( \langle M_{\text{orb}} \rangle = 12.14 \) dex and \( \langle M_{\text{orb}}/L_K \rangle = 20 \pm 3 \). A similar value, \( \langle M_{\text{orb}}/L_K \rangle = 22 \pm 5 \), is obtained by us for the Local Volume Sc–Sd galaxies, where the separation of physical satellites and field galaxies is more reliable due
Table 3. Suites of companions around the Local Volume bulge-less spirals.

| Galaxy       | D   | n  | Δm\(_{12}\) | \(\langle R_p \rangle\) | \(\sigma_V\) | \(\log L_K\) | \(\log M_{\text{orb}}\) | \(M_{\text{orb}}/L_K\) |
|--------------|-----|----|-------------|-----------------|-----------|-------------|-----------------|----------------|----------------|
| IC 342       | 3.28| 8  | 3.0         | 319             | 76        | 10.60       | 12.28           | 48             |
| M 101        | 6.95| 9  | 3.2         | 204             | 64        | 10.79       | 11.93           | 14             |
| NGC 6946     | 7.73| 8  | 5.8         | 323             | 68        | 10.99       | 12.05           | 11             |
| NGC 628      | 10.19| 9  | 4.6         | 309             | 68        | 10.60       | 12.11           | 32             |
| NGC 3184     | 11.12| 5  | 3.3         | 454             | 49        | 10.52       | 11.87           | 22             |
| Mean         | -   | 8  | 3.8         | 343             | 65        | 10.77       | 12.06           | 22             |

Table 3. Suites of companions around the Local Volume bulge-less spirals.

Comparison, the Sab–Sbc spirals in the Local Volume with much more developed bulges have the ratio \(M_{\text{orb}}/L_K\) = 41 ± 9, and a few in number galaxies of E, S0, Sa types are characterised by the ratio of \(M_{\text{orb}}/L_K\) = 88 ± 30. It seems unlikely that this difference would be caused by different manner of transition from the B-luminosity of a galaxy to its K-luminosity, or the different nature of the orbital motions of the satellites. Obviously, the conclusion about the reduced amount of dark matter per unit of K-band luminosity in the Sc–Sd galaxies needs confirmation on a richer observational material. It is quite possible that the presence of "scraggy" halos in spiral bulge-less galaxies will be explained within the framework of the standard paradigm of the hierarchy galaxy clustering.

**Acknowledgements.**

We thank the referee for his/her valuable comments. The work is supported by the Russian Science Foundation grant 19-12-00145. The paper makes use of the data from NASA Extragalactic Database and from the HyperLEDA.

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