Early-Type (E, S0) Galaxies in the Catalog of Isolated Galaxies (KIG)

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We use the data of modern digital sky surveys (PanSTARRS-1, SDSS) combined with HI-line and far ultraviolet (GALEX) surveys to reclassify 165 early-type galaxies from the Catalog of Isolated Galaxies (KIG). As a result, the number of E- and S0-type galaxies reduced to 91. Our search for companions of early-type KIG galaxies revealed 90 companions around 45 host galaxies with line-of-sight velocity differences $|dV| < 500$ km s$^{-1}$ and linear projected separations $R_p < 750$ kpc. We found no appreciable differences in either integrated luminosity or color of galaxies associated with the presence or absence of close neighbors. We found a characteristic orbital mass-to-luminosity ratio for 26 systems “KIG galaxy–companion” to be $M_\odot/L_K = (74 \pm 26)M_\odot/L_\odot$, which is consistent with the $M_{\text{orb}}/L_K$ estimates for early-type isolated galaxies in the 2MIG catalog (63$M_\odot/L_\odot$), and also with the $M_{\text{orb}}/L_K$ estimates for E- and S0-type galaxies in the Local Volume: 38$\pm$22 (NGC 3115), 82$\pm$26 (NGC 5128), 65$\pm$20 (NGC 4594). The high halo-to-stellar mass ratio for E- and S0-type galaxies compared to the average (20$\pm$3)$M_\odot/L_\odot$ ratio for bulgeless spiral galaxies is indicative of a significant difference between the dynamic evolution of early- and later-type galaxies.

Keywords: galaxies: elliptical and lenticular—galaxies: haloes

1. INTRODUCTION

According to generally accepted concepts, early-type (elliptical and lenticular) galaxies reside mostly in clusters of galaxies, whereas spiral galaxies are located in the general field and at the periphery of clusters. This is the well-known “morphology–density” effect (Dressler et al. 1980, Oemler 1974), which triggered various hypotheses about the origin and subsequent evolution of early-type galaxies. It is believed that in clusters of galaxies, where mass density is sufficiently high, early-type galaxies formed as a result of various processes, such as sweeping-out of gas (ram pressure) dynamical friction, tidal effects (tidas), merging, etc. (Lacerna et al. 2016). Identification and analysis of the properties of isolated early-type galaxies as objects residing in regions with low mass density supposed to be free of the influence of close neighboring galaxies of approximately the same luminosity (size) is of special interest.

Many authors have been identifying isolated galaxies both down to their certain limiting magnitude (or angular size) or within a volume of fixed distance, based on the data from available surveys and catalogs. We published the first Catalog of Isolated Galaxies (hereafter referred to as KIG, Karachentseva 1973). Isolated objects among almost 30,000 galaxies of the Zwicky catalog (Zwicky et al. 1968) with apparent magnitudes $m \leq 15.7$ and declinations $\delta > -2^\circ 30'$ were identified by uniformly applying the isolation criterion to all galaxies of the POSS-I photographic sky survey. The criterion takes into account foreground and background objects, namely: isolated galaxies were considered to be those with such angular diameter $a_i$ that their “neighbors” with diameters $1/4a_i < a_j < 4a_i$ were located at projected separations $R_{ij} \geq 20a_j$. Of 1050 KIG galaxies about 16% are early-type systems (E, S0), whereas the remaining ones are spiral and irregular galaxies and galaxies of unclear type.

Given the typical size of about 20 kpc, according the selection criteria a KIG galaxy should have no “significant” neighbors (i.e., those that influence its dynamic isolation) within the volume of $2 \times 10^8$ kpc$^3$ (Karachentseva 1980). Adams et al. (1980) showed that KIG galaxies should not have been influenced by neighboring galaxies over the past several billion years, and hence they must have been isolated through-
out almost their entire lifetime. Verley et al. (2007b,a) applied statistical criteria (based on local density and tidal force) to assess the degree of isolation and showed that the evolution of KIG galaxies was driven by internal processes (Adams et al. 1980, Verley et al. 2007b,a).

Adams et al. (1980) reclassified 165 presumed E- and S0-type KIG galaxies, confirming 120 of them as early type galaxies (ETGs). Stocke et al. (2004) performed a detailed analysis of the KIG-sample and found 65 isolated elliptical and 37 isolated S0-type galaxies, i.e., according to their data, the KIG contains about 9.7% ETGs. Stocke et al. (2004) performed a detailed analysis of the KIG-sample and found 65 isolated elliptical and 37 isolated S0-type galaxies, i.e., according to their data, the KIG contains about 9.7% ETGs.

Sulentic et al. (2006) used the POSS-II photographic sky survey for their new visual classification of KIG galaxies and found the fraction of early-type galaxies in KIG to be of about 14%. Hernandez-Toledo et al. (2008) classified 579 KIG galaxies using SDSS DR6 data and the CAS system (Conselice 2003). They found the fraction of E+S0 galaxies to be significantly smaller—8.5% (3.5–5%)—than that obtained by Sulentic et al. (2006). Buta et al. (2019) reported a new classification of 719 KIG galaxies and found early-type systems to make up 14% (5.3% and 8.7% for E and S0 galaxies, respectively) of the sample.

The AMIGA project\(^1\) team made a very important contribution to the study of the properties of KIG galaxies (see also Sulentic (2010)).

New sky surveys were released since the publication of the KIG catalog—SDSS (York et al. 2020), 2MASS (Skrutskie et al. 2006), and 2MXSC (Jarrett et al. 2000). They were used in compiling new catalogs and lists of isolated galaxies: UNAM-KIAS (Hernandez-Toledo et al. 2010) based on SDSS DR6; 2MIG (Karachentseva et al. 2010) based on the 2MASS infrared all-sky survey; the LOG catalog (Karachentsev et al. 2011) of isolated galaxies in the Local Supercluster volume; (Argudo-Fernandez et al. 2015) list based on SDSS DR10 (Ahn et al. 2014), and others. Some properties of isolated galaxies were described, in particular, in Hernandez-Lorenzo et al. (2012, 2013), Lacerna et al. (2018, 2016).

While compiling catalogs and lists of isolated galaxies, the above authors used various modifications of the KIG isolation criterion. They adopted different values for the allowed magnitude difference \(dm\) between the isolated galaxy and its possible neighbors, allowed radial velocity difference \(dV\), and their projected separation \(R_p\). These characteristics vary over rather wide ranges (\(dm = 1–3\) mag, \(dV = 300–1000\) \(\text{km} \text{s}^{-1}\), \(R_p = 250–1000\) kpc), see, e.g., Argudo-Fernandez et al. (2015), Hernandez-Toledo et al. (2010), Reda et al. (2004). The most stringent criterion for galaxies believed to be isolated is described in Marcum et al. (2004): \(|dV| = 350\) \(\text{km} \text{s}^{-1}\), \(R_p = 2500\) kpc, and the absence of nearby companion brighter than \(M_V = -16.5\). This criterion revealed only nine KIG galaxies; the authors performed \(BVR\) photometry of these galaxies, determined their types, and tried to find companions even without the knowledge of radial velocities. The small number of galaxies considered makes it impossible for us to make any comparisons.

Identification of isolated galaxies in new catalogs goes along with their morphological classification. Note that morphological classification of galaxies even now remains to a great extent subjective. This classification, which began with the works of Hubble, de Vaucouleurs and Sandage, is continued in Buta et al. (2019) (see references therein) and Graham (2019), where Graham provides an extensive review of studies dedicated the classification of galaxies. We return to this issue in Section 2.

According to the classical definition of elliptical galaxies, they can be described as smooth, regular-shaped galaxies without dust or gas and without structural details in the center and "body" of the galaxy. They have red colors and, usually, absorption-line spectrum. As for lenticular galaxies, Hubble back then believed them to be intermediate between elliptical and spiral galaxies.

In this paper we adhere to the above cutoff values of parameters, especially, given that available observational data allow one to quite definitively classify elliptical and lenticular KIG galaxies. We considered only early-type galaxies tagged in the KIG as being of E or S0 (or E–S0)

\(^1\) http://www.iaa.es/AMIGA.html
type. The authors of recent studies subdivide lenticular galaxies into two classes: (1) pure-bulge galaxies and (2) galaxies with disk properties: bluer color, emission lines in the spectrum, etc. (see Fraser-McKelvie et al. (2018), Tous et al. (2020) and references therein). A description of the properties of lenticular galaxies can also be found in the extensive introduction to paper Deeley et al. (2020). Its authors propose, based on the data of the SAMI survey (Green et al. 2018), two possible scenarios for the formation of S0-type galaxies: either fading of spirals or formation as a result of galaxy mergers. The results of the photometry of 42 galaxies are reported in Sil’chenko et al. (2020); the above authors point out a probably different dynamic history of S0-type galaxies in different environments.

Here, we use modern sky surveys to perform a new classification of early-type galaxies (ETG) from the KIG catalog for two reasons: (1) earlier classifications reported in 1973 and 2006 have become outdated and (2) the other catalogs of isolated galaxies mentioned above are based on different sky-survey data—2MASX and SDSS. We introduce a new classification and subdivide KIG galaxies into ETGs without companions and ETGs with insignificant (small) companions—we use the latter to compute orbital masses of the “ETG galaxy–companion” systems.

The paper has the following layout.

Section 2—identification and morphological classification of early-type galaxies in the KIG based on PanSTARRS-1 survey data.

Section 3—results of the search for companions/neighbors and description of their main properties.

Section 4—comparison of the properties of early-type KIG galaxies with and without their satellites/neighbors.

Section 5—determination of the orbital masses of some KIG galaxies based on the data about their nearest neighbors.

Section 6 presents the concluding remarks.

2. MORPHOLOGICAL CLASSIFICATION OF EARLY-TYPE KIG GALAXIES

In our work we proceeded from the assumption that all 165 galaxies classified as E or S0 in the KIG are isolated and imposed no constraints with respect to their radial velocities, apparent magnitudes, or sky positions. After excluding 74 galaxies that turned out to be spiral, we use the measured properties provided by various databases for the remaining ETG galaxies. We use HyperLEDA (Makarov et al. 2014) as our source of integrated magnitudes $b_t$, Galactic and internal extinction $A_G$ and $A_i$, ($A_i=0$ for E and S0-type galaxies), 21-cm-line magnitudes $m_{21}$, and absolute $B_t$-band magnitudes $m_{abs}$. We adopt from NED the radial velocities $V_{LG}$ (km s$^{-1}$) in the frame of the centroid of the Local group, compute the radial velocity differences, and the linear “KIG galaxy–companion” separations. We compute the distances and absolute properties of the galaxies from their $V_{LG}$ adopting the Hubble constant of $H_0 = 73$ km s$^{-1}$ Mpc$^{-1}$. We determine the $g$–$r$ and $g$–$i$ colors from SDSS survey data in the close-to-AB magnitude system.

We adopt the far-ultraviolet magnitudes $m_{FUV}$ from the GALEX survey (Martin et al. 2005). To estimate the stellar masses of E- and S0-type galaxies from their $K$-band luminosities, in Section 6 we use the directly measured $K_s$-band magnitudes adopted from the NED database. We determine the $K$-band magnitudes for companions of various morphological types from their $B$-band magnitudes and morphological type $T$ via relation

$$\langle B - K \rangle_{corr} = 4.60 - 0.25 \times T,$$

because the $K$-band magnitudes of late-type galaxies are highly underestimated in the 2MASS survey. We compute the integrated star-formation rate $SFR$ for all galaxies by formula (6) from Melnyk et al. (2017) with extinction corrections applied (formulas (2) and (5) in the same paper).

Our classification is based on PanSTARRS-1 (PS-1) sky survey (Chambers et al. 2016). We

\url{http://classic.sdss.org/dr7/algorithms/fluxcal.html#sdss2ab}
Table 1. Early-type KIG galaxies without companions. (1)—galaxy name, (2)—compactness according to the catalog of Zwicky et al.: compact—c, very compact—vc, extremely compact—ec, (3)—the type according to HyperLEDA, (4)—the type estimated based on PanSTARRS-1

| KIG | Zwicky Type (LEDA) | Type (PS-1) | KIG | Zwicky Type (LEDA) | Type (PS-1) |
|-----|--------------------|-------------|-----|--------------------|-------------|
|     |                    |             |     |                    |             |
| 14  | S0                 | S0          | 636 | S0                 | S0 pec      |
| 57  | E-S0, S2           | S0          | 670 | vc                 | S0          |
| 99  | S0-a               | S0          | 684 | E                  | E           |
| 101 | E-S0               | E-S0        | 701 | E?                 | S0 pec      |
| 110 | E                  | E           | 763 | E                  | S0          |
| 118 | E-S0               | E-S0        | 770 | vc                 | E           |
| 127 | E-S0               | E           | 792 | c                  | S0          |
| 136 | E                  | E           | 816 | S0                 | S0          |
| 174 | c                  | S?          | 820 | E-S0               | S0          |
| 179 | c                  | E-S0        | 823 | c                  | E           |
| 256 | ec                 | E-S0        | 824 | E                  | S0          |
| 378 | E-S0               | E pec       | 826 | c                  | E           |
| 387 | c                  | E-S0        | 827 | vc                 | E           |
| 412 | c                  | E           | 833 | ec                 | E-S0        |
| 443 | S0-a               | S0          | 836 | vc                 | E           |
| 452 | c                  | E-S0        | 845 | c                  | E           |
| 462 | c                  | E-S0        | 865 | c                  | E-S0        |
| 490 | c                  | S0, ring    | 870 | E-S0               | E pec       |
| 521 | S0                 | S0          | 877 | E-S0               | E pec       |
| 529 | E                  | E-S0        | 894 | c                  | E-S0        |
| 570 | S0-a               | S0 pec      | 896 | c                  | E-S0        |
| 574 | vc                 | E           | 920 | E-S0               | S0          |
| 582 | c                  | E-S0 pec    | 981 | c                  | E           |

estimate the galaxy types mostly based on the shape of the object, but also take into account the presence of 21-cm HI lines, bright optical emission lines, and emissions in the far ultraviolet (FUV) according to GALEX data (Martin et al. 2005).

We present the results of classification in Table 1 (KIG galaxies without satellites) and Table 2 (galaxies with satellites/neighbors). We consider satellites to be galaxies that are more than 1 mag fainter than the “host” KIG galaxy. The apparent magnitudes of neighbors are approximately comparable to those of KIG galaxies. Where necessary, we consider satellites and neighbors separately. Note that only one galaxy – KIG 664 (S0 according to our estimate) – has
no measured radial velocity and we therefore could not include it into either Table 1 or Table 2.

Typical elliptical galaxies that we classified by their shape have absorption-line spectra and exhibit no emissions either in the optical bands or in FUV. The properties of S0 galaxies were described, in particular, in the Introduction to paper Deeley et al. (2020).

Ashley et al. (2019) describe the selection criterion as well as optical and HI properties of the galaxies that they believed to be extremely isolated, IEG sample, \( N = 25 \). These galaxies have absolute \( B \)-magnitudes in the \([-14.2; -20.7]\) range and \( \langle B-V \rangle = 0.58 \). The same criterion was used to select extremely isolated early-type galaxies (IEG) in the SDSS survey (Fuse et al. 2012), see also the classification there). The above authors write about careful selection, which left only 33 galaxies. However, 14 of these are dwarf galaxies being 1–2 magnitude fainter than typical early-type galaxies. We checked E-type galaxies from Table 1 in Fuse et al. (2012) and found them to be characterized by bright emission lines typical for BCD galaxies. According to our definition, they are not classical elliptical galaxies, although they, on the average, have a round shape. The differences between our data and sample Fuse et al. (2012) may be due to a selection effect typical for flux-limited surveys. Therefore because of different depths of the samples (200 and 70 Mpc for our sample and that of Fuse et al. (2012), respectively), the SDSS sample is shifted toward blue galaxies of low luminosity located at small redshifts.

### Table 2: Early-type KIG galaxies with satellites/neighbors.

| Galaxy          | Zw | T (LEDA) | T (PS-1) |
|-----------------|----|----------|----------|
| (1)             | (2)| (3)      | (4)      |
| KIG 24          | E  | S0       |          |
| neighb.1, CGCG 409-21 | S0-a| S0     |          |
| KIG 25          | S0 | S0       |          |
| sat.1, UGC 287  | Scd| Scd      |          |
| KIG 79          | E-S0 | S0 |          |
| neighb.1, CGCG 461-14 | S0 | S0 |          |
| neighb.2, UGC 1485 | Sc | Sc pec |          |
| neighb.3, CGCG 461-20 | Sc | S pec |          |
| KIG 89          | E  | E        |          |
| sat.1, KKH 8    | Ir | Ir       |          |
| KIG 111         | c  | E        | E        |
| sat.1, AGC 122418 | G | Sm     |          |
| KIG 161         | Sa | S0       |          |
| sat.1, PGC 138829 | G | Scd     |          |
| KIG 184         | SABa | S0 |          |
| neighb.1, CGCG 234-15 | SABb| Sb |          |
| KIG 189         | E  | E        |          |
| sat.1, PGC 2228154 | G | Ir     |          |
Table 2: (Continued)

| Galaxy        | Zw   | T (LEDA) | T (PS-1) |
|---------------|------|----------|----------|
| (1)           | (2)  | (3)      | (4)      |
| sat.2, SDSS J072524.12+422559.1 | S?   | Im       |
| KIG 228       | c    | E        | E        |
| sat.1, WISEA J080731.37+555342.1 | G    | BCD      |
| KIG 233       |      | E-S0     | S0       |
| sat.1, WISEA J081051.83+273404.2 | G    | BCD      |
| neighb.1, AGC 183054 | S?   | Sd       |
| KIG 245       |      | E        | E        |
| sat.1, AGC 181571 |     | Sm       | Ir       |
| sat.2, AGC 188871 |      | G        | Sc       |
| KIG 264       | c    | S0-a     | S0       |
| sat.1, KUG 0832+305 | S?   | Scd      |
| neighb.1, Mrk 390 |     | Sc       | Sb pec   |
| KIG 303       |      | S0       | S0       |
| sat.1, AGC 193009 |      | E        | S0 pec   |
| sat.2, AGC 191082 | SBc  | Scd      |
| sat.3, SDSS J090703.40+034905.7 | SBc  | Scd      |
| KIG 380       |      | E        | E        |
| sat.1, AGC 731423 | S?   | BCD      |
| KIG 396       |      | E-S0     | E        |
| sat.1, SDSS J100413.44+602214.1 | Sd   | Sd       |
| sat.2, KUG 0958+599 | Sd   | BCD      |
| neighb.1, UGC 5408 |      | E-S0     | BCD      |
| neighb.2, CGCG 289-27 | E-S0 | S0       |
| KIG 413       |      | S0-a     | S0       |
| sat.1, PGC 1188869 | S0   | S0       |
| sat.2, AGC 204701 | S?   | Im       |
| sat.3, AGC 204919 | Scd  | Sc       |
| sat.4, AGC 204920 | Sm   | Sm       |
| sat.5, PGC 1181655 |      | E        | BCD      |
| neighb.1, AGC 201427 |      | Sa       | Sa pec   |
| KIG 415       | vc   | E        | S0       |
| sat.1, AGC 203492 | S?   | Sc       |
| KIG 425       | c    | E        | E        |
| sat.1, PGC 2628623 | Sd   | Sm       |
| KIG 426       | vc   | E-S0     | S0       |
| Galaxy | Zw | T (LEDA) | T (PS-1) |
|--------|----|----------|----------|
| (1)    | (2) | (3)      | (4)      |
| sat.1, PC 1034+4938 | emiss.g. | BCD | |
| sat.2, PGC 2336611 | E | S0 | |
| sat.3, PGC 2346694 | Sc | Spec | |
| sat.4, PGC 2335306 | E | E | |
| KIG 437 | E | E-S0 | |
| sat.1, MCG 9-18-17 | E | S0 | |
| sat.2, WISEA J104402.83+523034.7 | S? | Sc? | |
| KIG 480 | Sab | S0 | |
| sat.1, AGC 217484 | Sm | Sdm | |
| neigh.1, UGC 6437 | Sbc | Sc | |
| neigh.2, AGC 12238 | SBbc | Sbc | |
| KIG 513 | ve | E | E | |
| sat.1, AGC 719642 | S? | Sm | |
| neigh.1, AGC 719646 | Sbc | Sbc | |
| KIG 517 | c | S0 | S0 | |
| sat.1, WISEA J120240.67+261248.9 | G | Sd | |
| sat.2, WISEA J120344.73+260345.8 | E | S0 | |
| KIG 557 | c | E | E | |
| sat.1, PGC 1162105 | E | E | |
| sat.2, PGC 1161248 | S0 | S0 | |
| sat.3, PGC 3298012 | S? | Sbc | |
| sat.4, PGC 1157914 | S? | Sc | |
| sat.5, PGC 3297967 | G | Sbc | |
| KIG 578 | c | E | E | |
| sat.1, WISEA J131629.64+200518.5 | S? | BCD | |
| sat.2, WISEA J131728.70+200130.2 | G | S? | |
| KIG 595 | E | E | |
| sat.1, WISEA J133911.75+612916.0 | E? | S0 | |
| sat.2, PGC 2619551 | S? | S0 | |
| KIG 596 | S0-a | S0 pec | |
| sat.1, PGC 2625488 | Sc | BCD | |
| KIG 599 | S0 | S0 pec | |
| sat.1, PGC 2097287 | S? | Sdm | |
| KIG 602 | S? | S0 | |
| sat.1, PGC 1681951 | G | Sc? | |
| Galaxy                  | Zw (LEDA) | T (PS-1) |
|------------------------|-----------|----------|
| (1)                    | (2)       | (3)      | (4)      |
| sat.2, PGC 1678559     | Sbc       | Sc       |
| sat.3, PGC 1678503     | Sb        | S0       |
| sat.4, KUG 1350+232    | Sbc       | Sbc      |
| sat.5, WISEA J135409.10+230454.8 | S? | Im |
| KIG 614                | Sbc       | S0       |
| sat.1, WISEA J141057.79+215317.9 | G | S0 |
| neighb.1, PGC 1657978  | S?        | S0-a     |
| KIG 623                | vc        | E        | E        |
| sat.1, WISEA J141823.99+193432.4 | E | BCD |
| sat.2, WISEA J142021.46+202332.5 | G | Sd |
| KIG 685                | c         | E        | Epec     |
| sat.1, WISEA J152927.49+565558.4 | SBc | Sc |
| KIG 703                | ec        | E        | E-S0     |
| sat.1, WISEA J154723.56+221143.6 | G | BCD |
| KIG 705                | vc        | E-S0     | Epec     |
| sat.1, WISEA J154720.49+370255.6 | S? | Sm |
| KIG 722                |           | E        | E        |
| sat.1, WISEA J160822.82+093957.4 | E? | E-S0 |
| KIG 732                | c         | E        | E        |
| sat.1, Mrk 498         |           | G        | BCD      |
| KIG 768                | vc        | E-S0     | S0 pec   |
| sat.1, WISEA J164441.66+194636.9 | Sbc | Sc |
| neighb.1, CGCG 110-4   | Sc        | Scd      |
| KIG 771                | c         | E        | E        |
| sat.1, PGC 1678008     | S?        | E        |
| sat.2, WISEA J164645.65+225147.1 | E? | S0 |
| sat.3, PGC 1678062     |           | E        | E        |
| sat.4, WISEA J164709.15+225849.6 | S? | Ir |
| sat.5, WISEA J164715.62+224940.9 | G | E |
| sat.6, WISEA J164726.19+225519.5 | S? | E |
| sat.7, PGC 1679574     | S?        | Sc       |
| sat.8, PGC 1676423     |           | E        | E-S0     |
| KIG 898                |           | E-S0     | E        |
| neighb.1, PGC 165874   | G         | S0-a     |
| KIG 903                |           | E        | S0       |
Isolated galaxies marked in the Zwicky et al. (1968) catalog as “compact”, “very compact”, or “extremely compact”, appear in PS-1 images as normal elliptical and lenticular galaxies. The only exceptions are KIG 256, KIG 705, KIG 732, KIG 770, KIG 826, and KIG 833, which appear sufficiently compact even in PS-1. It is clear that on POSS-I images, which were taken about 60 years ago, diffuse envelopes of distant galaxies could not be discerned to say nothing about the structural details of these systems. Our new classification reduced the fraction of early-type galaxies (ETG) in the KIG approximately by half: 91 among 1050 galaxies, i.e., 8.7%, which agrees better with the data from Hernandez-Toledo et al. (2008). The number of E-type galaxies is approximately equal to that of S0-type galaxies, 40 (44%) and 44 (48%), respectively, and the number of E-S0-type galaxies is 7 (8%). The twofold reduction of the fraction of ETG as a result of about half of them being reclassified as spirals is due to better quality of digital CCD images (broader dynamic range) and more rigorous selection. Our results show that isolated ETG galaxies are rather numerous and make up an interesting sample for further study. We compared our data with the morphological classification of Rampazzo et al. (Rampazzo et al. 2020) based on deep photometry. As a result, we excluded KIG 481, KIG 620, KIG 637, KIG 644, KIG 733, and KIG 841 from ETG galaxies because they are classified as bona fide spirals on PS-1 images. The remaining 14 galaxies are early-type objects. The details can be checked in Tables 1 and 4 in Rampazzo et al. (2020), as well as in our Tables 1 and 2.

The remaining early-type galaxies in the KIG exhibit morphological peculiarities in approximately 20% of the cases. These peculiarities may be due both to their internal evolution and to recent merging with fainter objects.

Table 3 lists some of the basic properties (means and standard errors of mean) for ETG galaxies in the KIG. The top six rows of the table describe the characteristics of the ETG galaxies proper. The four bottom rows refer to neighbors and satellites of KIG galaxies.

The small size of the sample prevents finding significant differences between E- and S0-type objects (the two top rows in Table 3). An expected tendency is immediately apparent with S0-type galaxies being somewhat bluer than E-type galaxies.

We would like to point out the most peculiar galaxy, KIG 889, which we classify as neither elliptical or lenticular, but which is of interest for a
Table 3. Some basic properties (means and standard errors of mean) for ETG galaxies in the KIG

| Type (PS-1) | N   | $M_{K_s}^{cor}$ | log $M^*$ | $M_{abs}^{LEDA}$ | N   | log(SFR) | log(sSFR) | N   | log $M_{HI}$ | N   | $g - r$ | $g - i$ |
|------------|-----|---------------|--------|-----------------|-----|---------|----------|-----|-------------|-----|--------|--------|
|            |     |               |        |                 |     |         |          |     |             |     |         |        |
| E (all)    | 43  | $-24.15 \pm 0.13$ | 10.99 $\pm 0.05$ | $-20.28 \pm 0.14$ | 33  | $-1.21 \pm 0.09$ | $-12.17 \pm 0.07$ | 4   | 9.78 $\pm 1.12$ | 25  | 0.81 $\pm 0.01$ | 1.21 $\pm 0.01$ |
| S0 (all)   | 48  | $-24.24 \pm 0.11$ | 11.02 $\pm 0.04$ | $-20.38 \pm 0.12$ | 37  | $-1.19 \pm 0.07$ | $-12.25 \pm 0.06$ | 12  | 9.27 $\pm 0.16$ | 36  | 0.75 $\pm 0.02$ | 1.10 $\pm 0.05$ |
| E (no sat) | 21  | $-24.08 \pm 0.19$ | 10.96 $\pm 0.08$ | $-20.19 \pm 0.21$ | 18  | $-1.12 \pm 0.11$ | $-12.04 \pm 0.12$ | 2   | 9.33 $\pm 0.11$ | 5   | 0.82 $\pm 0.02$ | 1.22 $\pm 0.03$ |
| S0 (no sat)| 25  | $-24.25 \pm 0.15$ | 11.03 $\pm 0.06$ | $-20.38 \pm 0.15$ | 22  | $-1.17 \pm 0.10$ | $-12.21 \pm 0.07$ | 6   | 9.26 $\pm 0.18$ | 16  | 0.73 $\pm 0.03$ | 1.17 $\pm 0.10$ |
| E (sat)    | 22  | $-24.23 \pm 0.18$ | 11.02 $\pm 0.07$ | $-20.36 \pm 0.20$ | 15  | $-1.32 \pm 0.13$ | $-12.32 \pm 0.08$ | 2   | 10.23 $\pm 3.10$ | 20  | 0.80 $\pm 0.01$ | 1.21 $\pm 0.02$ |
| S0 (sat)   | 23  | $-24.22 \pm 0.16$ | 11.02 $\pm 0.06$ | $-20.38 \pm 0.17$ | 15  | $-1.22 \pm 0.09$ | $-12.31 \pm 0.09$ | 6   | 9.28 $\pm 0.25$ | 20  | 0.76 $\pm 0.02$ | 1.11 $\pm 0.04$ |

$dm < 1$

| E         | 4   | $-22.68 \pm 0.68$ | 10.40 $\pm 0.27$ | $-19.45 \pm 0.51$ | 3   | $-1.00 \pm 0.46$ | $-11.18 \pm 0.49$ | 2   | 9.56 $\pm 0.20$ | 3   | 0.82 $\pm 0.14$ | 1.16 $\pm 0.17$ |
| S0        | 16  | $-23.61 \pm 0.17$ | 10.77 $\pm 0.07$ | $-20.17 \pm 0.14$ | 10  | $-0.54 \pm 0.17$ | $-11.32 \pm 0.21$ | 8   | 9.52 $\pm 0.13$ | 14  | 0.59 $\pm 0.05$ | 0.91 $\pm 0.07$ |

$dm \geq 1$

| E         | 40  | $-20.64 \pm 0.25$ | 9.58 $\pm 0.10$ | $-17.74 \pm 0.20$ | 23  | $-1.18 \pm 0.11$ | $-10.95 \pm 0.14$ | 10  | 9.17 $\pm 0.15$ | 35  | 0.54 $\pm 0.04$ | 0.80 $\pm 0.05$ |
| S0        | 30  | $-21.07 \pm 0.30$ | 9.76 $\pm 0.12$ | $-18.19 \pm 0.26$ | 20  | $-1.05 \pm 0.08$ | $-10.66 \pm 0.14$ | 10  | 9.19 $\pm 0.07$ | 26  | 0.50 $\pm 0.04$ | 0.75 $\pm 0.06$ |

The columns of Table 3 give: (1)—status the galaxies; (2)—number of galaxies corresponding to columns (3)–(5); (3)—absolute $K$-band magnitudes corrected for extinction according to Melnyk et al. (2017); (4)—logarithmic stellar masses (in the units of the solar mass); (5)—absolute $B$-band magnitudes adopted from HyperLEDA database corrected for extinction; (6)—the number of galaxies corresponding to columns (7) and (8); (7)—logarithmic star-formation rates $SFR$ (in the units of $M_{\odot}yr^{-1}$); (8)—logarithmic specific star-formation rates $sSFR$ (in the units of $yr^{-1}$); (9)—the number of galaxies corresponding to column (10); (10)—logarithmic HI masses $M_{HI}$ (in the units of the solar mass); (11)—the number of galaxies corresponding to columns (12) and (13); (12), (13)—galaxy colors from the SDSS survey.
detailed study. We show its PanSTARRS-1 image in Fig. 1. The size of the field is 100′′ × 100′′, North is at the top and East is on the left. This object may be a galaxy with what is well known as conspicuous “X-shaped structure”. Savchenko et al. (2017) performed detailed photometry for 22 such objects seen edge-on. A comparison of the results of simulations demonstrates their qualitative agreement with observations and supports the “bar-driven” scenario of the formation of X-shaped-structures.

3. RESULTS OF A SEARCH FOR SATELLITES/NEIGHBORS AND DESCRIPTION OF THEIR PROPERTIES

We found in the NED database 112 satellites for 47 isolated galaxies within the radial velocity difference |dV| = 500 km s⁻¹ and projected separation Rp = 750 kpc between the satellite and KIG galaxy. Two galaxies — KIG 555 and KIG 556 — have radial velocities on the order of 1000 km s⁻¹ (and 4 and 18 satellites, respectively); we exclude them from consideration because they reside at the periphery of Virgo cluster.

The 46+45 isolated galaxies have a total of 90 satellites/neighbors, i.e., there is about one companion for every isolated galaxy. This number is about three times less than Madore et al. (2004) obtained for isolated E-type galaxies with V ≤ 2000 km s⁻¹. The ratio of the number of satellites to that of isolated galaxies is higher within the closer volume because of selection effect (Habas et al. 2020). Argudo-Fernandez et al. (2014) analyzed 386 isolated KIG galaxies without subdividing them into early- and late-type systems. A total of 340 (88%) of these galaxies have no physically bound satellites. The remaining 46 galaxies have one to three satellites. We compare the data from our Tables 1 and 2 with Table 1 by Argudo-Fernandez et al. (2014) and found that there are total of 12 galaxies common with ETG galaxies without satellites and common 27 galaxies with ETG galaxies having satellites. Of these 11/12 (92%) are listed in our Table 1 and 13/27 (48%), in our Table 2. We can conclude that the results of the comparison are quite good given different approaches to finding satellites.

Fig. 2 shows the distribution of isolated early-type galaxies N_{KIG} by the number of satellites.

It follows from Table 2 that satellites and neighbors of isolated galaxies have morphological type estimates ranging from elliptical to irregular. The distribution of their types sharply differs with a greater fraction of both later-type systems and systems with stronger emission lines) among satellites than among neighbors, namely:

- satellites: E/S0—29%; S0a/Sc—23%; Scd/Sdm—14%; Sm/Ir—17%; BCD—17%
- neighbors: E/S0—20%; S0a/Sc—55%; Scd/Sdm—20%; Sm/Ir—0%; BCD—5%.

The last four rows of Table 3 list the average properties and the corresponding standard errors for satellites (the last two rows) and neighbors of isolated galaxies. Although in some cases the small sample size makes it impossible to draw a definitive conclusion, certain trends show up: neighbors are significantly brighter and more massive than satellites, and have greater gas amount (which is evident from the criteria used to separate them). Satellites, on the other hand, have somewhat higher star-formation rates and, on the average, are bluer than neighbors.

Fig. 3 shows the distribution of the absolute values of radial velocity differences and projected separations between the KIG galaxies and their satellites, |dV|, km s⁻¹, and Rp, kpc. Satellites and neighbors are shown in the inset using different symbols.

Neighbors, on the average, are located farther than satellites. One can assume that neighbor galaxies are not gravitationally bound to KIG galaxies, but belong to a common cosmic filament-like structure.

Fig. 4 shows the specific star-formation rate plotted as a function of stellar mass separately for satellites, neighbors, and isolated galaxies. Only the upper limit for the FUV flux is known for about 40% of KIG galaxies. (We do not show separately the results of log(sSFR) computations for these systems in the figure.) We determine the masses of galaxies from their K-band
Table 4. Properties of KIG galaxies and their nearest neighbors for the determination of orbital masses of isolated galaxies

| KIG | $M_K$ | $dM_{12}$ | $dV$ | $R_p$ |
|-----|-------|-----------|------|------|
|     |       | magn | km s$^{-1}$ | kpc |
| (1) | (2)   | (3)   | (4)  | (5)  |
| 228 | $-24.21$ | 3.0   | 271  | 163  |
| 264 | $-24.07$ | 1.7   | $-110$ | 307  |
| 303 | $-24.23$ | 3.1   | 46   | 194  |
| 303 | $-24.23$ | 1.9   | 130  | 306  |
| 396 | $-22.60$ | 3.8   | 44   | 217  |
| 413 | $-23.17$ | 1.2   | 39   | 289  |
| 413 | $-23.17$ | 2.5   | 278  | 306  |
| 437 | $-24.62$ | 2.4   | 102  | 178  |
| 480 | $-23.21$ | 3.4   | 128  | 208  |
| 517 | $-24.16$ | 3.1   | 62   | 140  |
| 557 | $-25.05$ | 2.3   | $-198$ | 215  |
| 557 | $-25.05$ | 1.7   | $-72$ | 222  |
| 557 | $-25.05$ | 3.7   | 237  | 261  |
| 578 | $-24.31$ | 3.1   | 7    | 161  |
| 595 | $-24.94$ | 1.9   | $-174$ | 43   |
| 595 | $-24.94$ | 3.1   | $-385$ | 56   |
| 596 | $-23.82$ | 1.2   | 118  | 209  |
| 602 | $-25.04$ | 2.7   | $-136$ | 322  |
| 703 | $-23.09$ | 2.6   | 40   | 191  |
| 722 | $-25.42$ | 3.8   | 122  | 186  |
| 768 | $-23.40$ | 1.9   | $-2$  | 302  |
| 771 | $-24.54$ | 2.8   | $-247$ | 13   |
| 771 | $-24.54$ | 2.8   | 218  | 118  |
| 771 | $-24.54$ | 2.0   | 47   | 261  |
| 771 | $-24.54$ | 2.7   | $-261$ | 288  |
| 1042| $-24.52$ | 1.3   | $-420$ | 261  |
| Mean | $-24.25 \pm 0.14$ | 2.53 $\pm 0.15$ | $-5 \pm 30$ | 208 $\pm 17$ |
luminosities assuming that \( M^*/L_K = 1M_\odot/L_\odot \) (Bell et al. 2003).

As expected, early-type galaxies in the KIG have quenched star formation, about the same as we obtained for isolated early-type galaxies in the 2MIG catalog (see Melnyk et al. (2015), Table 1). Satellite galaxies show a weak decrease of star-formation rate with increasing stellar mass, whereas neighbor galaxies, whose magnitudes are approximately equal to those of “host” galaxies, occupy an intermediate locus in the distribution in Fig. 4 (see also Table 3).

4. COMPARISON OF THE PROPERTIES OF EARLY-TYPE KIG GALAXIES WITH AND WITHOUT SATELLITES/NEIGHBORS

Fig. 5 shows the distribution of radial velocities \( V_{LG} \) of isolated early-type galaxies: (a) galaxies without satellites; (b) galaxies with satellites/neighbors with velocity differences \( |dV| < 500 \) km s\(^{-1}\) and projected separations \( R_p < 750 \) kpc with respect to the “host” galaxy. The fact that the mean values of the radial velocity distributions shown in panels (a)
Figure 3. Distribution of the radial velocity differences moduli $|dV|$, km s$^{-1}$ and projected separations $R_p$, kpc, between the KIG galaxies and their companions. The designations are shown in the inset.

Figure 4. Dependence of specific star-formation rate $sSFR$, on stellar mass $M^*$. The designations of galaxies are shown in the inset.

and (b) (8580 ± 560 and 8184 ± 570 km s$^{-1}$, respectively) indicate that KIG galaxies of both subclasses occupy about the same volume within the quoted errors with galaxies without satellites being, on the average, somewhat more distant because of only one outlier galaxy KIG 701 with $V_{LG} = 24227$ km s$^{-1}$. Note that isolated early-type galaxies have significantly greater average radial velocity than all KIG galaxies whose mean radial velocity is $\langle V_{LG} \rangle = 6624$ km s$^{-1}$ according to Verley et al. (2007a).

It follows from the data in Table 3 (rows 3–6) that the mean absolute magnitudes, specific star formation rates, hydrogen masses, and colors of isolated E-galaxies and S0-type galaxies do not differ within the quoted errors.
5. DETERMINATION OF ORBITAL MASSES OF ETG KIG GALAXIES FROM MOTIONS OF THEIR SATELLITES

After cleaning the sample of isolated galaxies by types and excluding two galaxies located in the neighborhood of Virgo cluster with \( V_{\text{LG}} \sim 1000 \text{ km s}^{-1} \), there remain a total of 90 satellites/neighbors with \(|dV| < 500 \text{ km s}^{-1}\) and \(R_p < 750 \text{ kpc}\) with respect to the “host” galaxy. Fig. 3 shows their distributions in the \(|dV|, R_p\) plane. As is evident from the figure, at \(R_p > 400 \text{ kpc}\) neighbors appear that are comparable in brightness with KIG galaxies. Such cases are hardly of any use for estimating the orbital masses. On the other hand, the projected virial halo radius for our Milky Way galaxy and M31 with their \(K\)-band luminosities \(L_K \sim 5 \times 10^{10} L_\odot\) is of about 250 kpc (Tully 2015). The average luminosity of an ETG galaxy with satellites from Table 2 is \(L_K \sim 1.0 \times 10^{11} L_\odot\), i.e., twice higher. Given that the mass of the halo is proportional to the cube of the virial radius, the virial radius of a typical KIG ETG galaxy may be as large as about 330 kpc. Therefore hereafter we consider only the KIG galaxies with satellites with \(R_p < 330 \text{ kpc}\), and there a total of 26 such cases. We summarize the results in Table 4. Its columns give: (1)—the number of the galaxy in the KIG catalog; (2)—corrected absolute \(K_s\)-band magnitude from NED; (3)—the difference of the absolute \(K\)-magnitudes between the satellite and KIG galaxy; (4)—the difference of radial velocity between the satellite and the KIG galaxy in \(\text{km s}^{-1}\); (5)—the mutual projected separation \(R_p\) in \(\text{kpc}\). The last row gives the average parameter values and their standard error.

The data from Table 4 lead us to conclude that:

- a “typical” satellite is ten times fainter than its KIG host galaxy, i.e., for these bound systems the Keplerian approach can be used to determine the mass of the central dominating galaxy from the motions of its small satellites;
- the mean difference of the radial velocities of satellites is close to zero, \(\langle dV \rangle = -5 \pm 30 \text{ km s}^{-1}\), and this fact supports their physical connection with the corresponding KIG galaxies;
- at \(\langle M_K \rangle = -24.25 \pm 0.14\) a KIG ETG galaxy has a luminosity of \(\log(L_K) = 11.01 \pm 0.06\), or \(L_K = (1.03 \pm 0.15) \times 10^{11} L_\odot\), which is twice higher than the luminosity of the Milky Way.

Under the assumption of random orientation of satellite orbits with a mean orbital eccentricity of \(\langle e \rangle = 0.7\) (Barber et al. 2014) the mass of the central object can be written as \(M_{\text{orb}} = (16/\pi G)\langle dV^2R_p \rangle\), where \(G\) is the gravi-
tational constant. Based on the data for 26 satellites listed in Table 4 we estimated the orbital mass as

\[ M_{\text{orb}} = (7.56 \pm 2.36) \times 10^{12} \, M_\odot, \]

i.e. a halo mass to the average \( K \)-band luminosity ratio for E- and S0-type KIG galaxies of

\[ M_{\text{orb}}/L_K = 74 \pm 26. \]

This ratio is close to the corresponding ratios \( M_{\text{orb}}/L_K = 38 \pm 22, 82 \pm 26, \) and \( 65 \pm 20 \) for the massive Local-Volume ETG galaxies NGC 3115, NGC 5128, and NGC 4594, respectively (Karachentsev and Kudrya 2014, Karachentsev et al. 2020). At the same time, the average orbital mass to \( K \)-band luminosity ratio for apparently bulgeless spiral galaxies is as low as \((20 \pm 3) M_\odot/L_\odot\) (Karachentsev and Karachentseva 2019).

Karachentseva et al. (2011) analyzed the velocities and projected separations of dwarf satellites located in the vicinity of 2MIG galaxies and found that the motions of 60 satellites about E- and S0-type galaxies imply a median ratio of \( M_{\text{orb}}/L_K = 63 \), whereas the data for 154 satellites orbiting spiral galaxies yield a median ratio of \( M_{\text{orb}}/L_K = 17 \). This about threefold difference between the dark-to-visible mass ratios is an indication suggesting that the dynamic evolution of early- and late-type galaxies proceeded along essentially different scenarios.

6. CONCLUDING REMARKS

Isolated early-type (E, S0) galaxies and galaxies of the same types residing in groups and clusters may have different dynamic history and structure. A standard sample of elliptical and lenticular galaxies is needed to reveal such differences. In this study we use the Catalog of Isolated Galaxies (KIG, Karachentseva 1973) as such standard sample. It contains 1050 objects, which makes up for about 4% of all Northern-hemisphere galaxies with apparent magnitudes \( m_B \leq 15.7 \) mag. Of these only 165 galaxies were classified as belonging to types E and S0. Hence isolated early-type galaxies are a rather rare (0.6%) category of galaxies in the Zwicky et al. (1968) catalog. The small number of such galaxies is consistent with the idea that E- and S0-type galaxies form as a result of mergers or close interactions of neighbors.

We use modern digital sky surveys (PanSTARRS-1, SDSS) combined with the data of H I-line and far-ultraviolet (GALEX) sky surveys to reclassify 165 early-type galaxies in the KIG. As a result, the number of E- and S0-type galaxies was reduced down to 91. Our classification of these galaxies and the classification performed by other authors are presented in Tables 1 and 2. About 20% of the galaxies of this sample exhibit various peculiarity features (anomalous structure, emissions in optical lines, presence of H I or FUV fluxes).

Lenticular and elliptical galaxies have, on the average, high \( K \)-band luminosities:

\[ \langle \log L_K(S0) \rangle = 11.02 \pm 0.04 \]

and

\[ \langle \log L_K(E) \rangle = 10.99 \pm 0.05 \]

in the solar units. Note that S0-type galaxies appear somewhat bluer

\[ \langle g - r \rangle = 0.75 \pm 0.02, \quad \langle g - i \rangle = 1.10 \pm 0.05, \]

compared to E galaxies with

\[ \langle g - r \rangle = 0.81 \pm 0.01, \quad \langle g - i \rangle = 1.21 \pm 0.01. \]

Our search for satellites of early-type KIG galaxies revealed 90 neighbors with radial velocity differences \( |dV| < 500 \, \text{km} \, \text{s}^{-1} \) and linear projected separations \( R_p < 750 \, \text{kpc} \). Note that half of KIG galaxies have no neighbors with such properties.

We found no appreciable differences in either integrated luminosities or colors of ETG KIG galaxies due to the presence or absence of close neighbors.

An average early-type KIG galaxy is twice more luminous that the Milky Way or M31 and has a characteristic virial radius of about 330 kpc. There are 26 satellites within this radius and their average luminosity is one order of magnitude lower than that of KIG galaxies. The
presence of such small satellites does not contradict the isolation criterion adopted in the KIG.

We assumed that the orbits of 26 satellites are randomly oriented and that their average eccentricity is equal to \( \langle e \rangle = 0.7 \) to infer the average orbital mass of E- and S0-type KIG galaxies, which we found to be

\[
M_{\text{orb}} = (7.56 \pm 2.36) \times 10^{12} M_\odot.
\]

The characteristic orbital mass to luminosity ratio of isolated E- and S0-type galaxies

\[
M_{\text{orb}}/L_K = (74 \pm 26) M_\odot/L_\odot
\]

is consistent with the \( M_{\text{orb}}/L_K \) estimates for isolated early-type galaxies in the 2MIG catalog \((63M_\odot/L_\odot)\), as well as with the \( M_{\text{orb}}/L_K \) estimates for E- and S0-type galaxies in the Local Volume: 38 ± 22 (NGC 3115), 82 ± 26 (NGC 5128), and 65 ± 20 (NGC 4594) in the solar units.

The high halo mass to luminosity ratio for E- and S0-type galaxies compared to the corresponding average ratio \((20 \pm 3)m_\odot/L_\odot\) for bulgeless spiral galaxies is indicative of essential differences between the dynamic evolution of early- and late-type galaxies.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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