SDSS J170745+302056: a low surface brightness galaxy in a group

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On the basis of the SDSS survey and spectral observations with the 6-m telescope of SAO RAS, we have performed a detailed study of SDSS J170745+302056. By combination of its characteristics – exponential surface brightness distribution, central surface brightness of stellar disk $\mu_0(B) = 23.25/\square''$, blue colors, low metallicity and low star formation rate – the galaxy is a typical low surface brightness spiral galaxy. Exponential scalelength of the galaxy is $\approx 3$ kpc, its optical diameter exceeds 20 kpc. SDSS J170745+302056 is a member of a group of five galaxies and probably it is in interaction with UGC 10716. The existence of a large low surface brightness galaxy in such a dense environment is very unusual.

Keywords: galaxies, interacting galaxies, photometry, morphology

1. Introduction

Low surface brightness ( LSB) spiral galaxies are objects with central surface brightnesses of their stellar disks fainter than $23''/\square''$ in the $B$ band (Impey and Bothun 1997). This means that even the central regions of such galaxies are fainter than the night sky background. LSB galaxies exhibit a very wide spread in morphology, sizes, and masses, but disk galaxies of late morphological types are encountered most frequently among them. LSB galaxies are rich in gas; relatively low metallicities, blue colors, and moderate star formation rates are typical for them (see, e.g., van der Hulst et al. 1993; McGaugh 1994; de Blok et al. 1995). There is some evidence that dark halos dominate in the dynamics of such galaxies (de Blok and McGaugh 1997).

Despite their low surface brightnesses and luminosities, the LSB galaxies are an appreciable component of the Universe. For example, in the local Universe about a half of all galaxies with a neutral hydrogen mass exceeding $10^8 M_\odot$ may belong to the LSB ones (Minchin et al. 2004). Their contribution to the dynamical mass density produced by all galaxies reaches $\sim 20\%$, the contribution to the density of baryonic matter is $\sim 10\%$, they contribute about a third to the total HI density in the nearby Universe (Minchin et al. 2004).

The origin and evolution of LSB galaxies remain largely unclear. A number of causes were suggested to explain their peculiarities (primarily a large amount of gas and blue colors in combination with a low star formation efficiency), such as, for example, the formation of LSB galaxies inside relatively late-formed dark halos with a large spin (Jimenez et al. 1998) or a low metallicity of the interstellar medium preventing an efficient cooling and creating a deficit of cold molecular gas which is fuel for star formation (Gerritsen and de Blok 1999). In recent years, the most popular model has been the scenario of small short starbursts randomly distributed over the galactic disk (de Blok et al. 1995; Gerritsen and de Blok 1999; Vorobyov et al. 2009). The mechanism controlling the sporadic star formation in LSB galaxies is unknown, but this model is capable of reproducing many of their characteristics, including their blue colors and low metallicities (Vorobyov et al. 2009).
Our paper is devoted to an observational study of the LSB galaxy SDSS J170745+302056. In the second section of the paper we present the results of its detailed study based on SDSS data and our own spectroscopic observations, and in the third section we consider its spatial environment. All magnitudes in the paper are given in the AB system.

2. General characteristics of SDSS J170745+302056

2.1. Observations and spectroscopic parameters

SDSS J170745+302056 was discovered serendipitously during spectroscopic observations of the galaxy UGC 10716. The observations of UGC 10716 were performed in July 2013 as part of our program aimed at studying edge-on spiral galaxies with strongly warped stellar disks (Reshetnikov et al. 2016). A spectrum of the galaxy in the red region (5700 – 7500 Å) with the slit position angle P.A. = 12° was taken with the SCORPIO instrument (Afanasiev and Moiseev 2005) at the 6-m SAO RAS telescope (the parameters of these observations and the data reduction are described in Reshetnikov et al. 2016). Apart from UGC 10716, the spectrograph slit crossed a faint galaxy about 80″ north of it. This galaxy, SDSS J170745+302056, is barely seen on the original SDSS frames but becomes prominent when increasing the contrast (Fig. 1).

The spectrograph slit passed almost through the nucleus of SDSS J170745+302056, approximately at 1″ from the bright knot near the image center. The Hα emission line, from which we found the radial velocity of the galaxy to be $V_{sys} = 9453 \pm 5$ km/s, and noticeably weaker [NII], [SII], and HeI lines are clearly seen in its spectrum (see the integrated spectrum of the central part of the galaxy in Fig. 2). This velocity is lower than the radial velocity of the nucleus of UGC 10716 by 232 km/s. Given that SDSS J170745+302056 and UGC 10716 are close in projection, it can be concluded that they form a bound system or, as will be shown below, enter into a common group of galaxies.

The observed line fluxes from the integrated spectrum of the galaxy are listed in Table 1. Using the calibration from Marino et al. (2013), from the ratios of the [NII]λ6583 Å and Hα intensities we estimated the gas metallicity in the galaxy to be $12+\log(O/H) = 8.20 \pm 0.05$ or $\approx 1/3$ of the solar value. It should be noted, however, that we estimated the above error in the oxygen abundance based on the formal errors in the line fluxes from Table 1. The error of our metallicity estimation method reaches a factor of $\sim 2$, so that the actual error can be higher by several times.

The adopted photometric distance to the galaxy is 133 Mpc (see Section 3 of this paper), giving a linear scale of 0.61 kpc/′. 

![Fig. 1. The high-contrast combined (g + r + i) image of UGC 10716 (large edge-on galaxy) and SDSS J170745+302056 (small galaxy at the top). The straight line indicates the spectrograph slit position. The frame is 1.′55 × 2.′93 in size.](image)
Fig. 2. Observed spectrum of the central region of SDSS J170745+302056.

Table 1. Line fluxes in the spectrum of SDSS J170745+302056

| Line        | Flux, $10^{-16}$ erg/s/cm²/Å |
|-------------|-------------------------------|
| Hα          | 5.5 ± 0.2                     |
| [NII] λ6584 | 0.37 ± 0.07                   |
| [SII] λ6717 | 0.83 ± 0.09                   |
| [SII] λ6731 | 0.47 ± 0.08                   |
| He I λ5876  | 0.39 ± 0.08                   |
| [NII] λ6548 | 0.12 ± 0.08                   |

2.2. Photometric characteristics

The basic observed characteristics of SDSS J170745+302056 are summarized in Table 2. The integrated apparent magnitudes of the galaxy were derived from the original SDSS frames by integrating the flux within an elliptical aperture with a semimajor axis of 22″. (At the preliminary stage we subtracted the background found by a large region around the galaxy and masked the nearby stars.) On the whole, these magnitudes are close to those in SDSS: the mean difference between the SDSS data in five filters and our measurements is $+0.05 \pm 0.18$.

SDSS J170745+302056 has an irregular morphology (Figs. 1 and 3) and, therefore, we used averaging along ellipses to construct its photometric profiles. The positions of the centers of the ellipses and the position angles of their major axes were identical in all color bands. The cuts in the g, r, and i filters constructed in this way are shown in Fig. 3. The semimajor axis of the ellipse and the corresponding mean surface brightness are plotted along the horizontal and vertical axes of the figure, respectively. Since the galaxy is blue, the cuts in different bands overlap, and, therefore, for convenience, the data in the r and i filters in Fig. 3 were shifted toward higher brightnesses.

Table 2. Observed characteristics of SDSS J170745+302056

| α (2000) | 17:07:45.80 |
|----------|-------------|
| δ (2000) | +30:20:56.2 |
| u        | 19.63 ± 0.16|
| g        | 18.72 ± 0.06|
| r        | 18.46 ± 0.06|
| i        | 18.38 ± 0.10|
| z        | 18.52 ± 0.36|
| D (Mpc)  | 133         |
| Scale    | 0.61 kpc/1″ |
| $M_B$    | −16.9       |
| $d(\mu_g = 26.5)$ | 36″ (22 kpc)|
| $\mu_0(g)$ | 23.28 ± 0.05|
| $\mu_0(r)$ | 22.91 ± 0.10|
| $\mu_0(i)$ | 22.86 ± 0.06|
| $h(g)$   | 6.94 ± 0.2  |
| $h(r)$   | 4.99 ± 0.2  |
| $h(i)$   | 5.95 ± 0.2  |
| $12 + \log(O/H)$ | 8.20 ± 0.05|
To a first approximation, the averaged brightness distribution of SDSS J170745+302056 is described by an exponential law with a scale length \( h = 5.6' \pm 0.75' = 3.4 \) kpc (the value averaged over three filters). The galaxy’s surface brightness in the \( u \) and \( z \) bands fluctuates strongly, but, on the whole, it can also be fitted by an exponential disk model with a scale length of \( 6.8' \pm 0.5' \) (or \( 5.6' \pm 0.5' \)) in the \( u \) and \( z \) bands. A slight brightness excess that is most likely related to the extended structure north of the galactic center is noticeable in the photometric profiles at a distance of \( \sim 10'' - 15'' \). If this feature in the profiles is eliminated, the exponential disk scale length decreases to \( h = 5.1' \pm 0.8' = 3.1 \) kpc (the value averaged over the \( g \), \( r \), and \( i \) filters), while the central surface brightness remains virtually without changes. Table 2 gives the values of \( h \) and \( \mu_0 \) found from the brightness profiles without eliminating the excess region.

The observed central surface brightness of the SDSS J170745+302056 disk (Table 2) after its correction for extinction in the Milky Way (Schlafly and Finkbeiner 2011), applying the k-correction (Chilingarian et al. 2010), and the recalculation to the \( B \) filter (Blanton and Roweis 2007) is \( \mu_0(B) = 23.25^m/\square'' \). Consequently, the galaxy is indeed a LSB one. The galaxy is not bright, its absolute \( B \) magnitude is \(-16.9\), but it cannot be attributed to dwarf objects by its diameter \( \sim 20 \) kpc.

The metallicity of SDSS J170745+302056 corresponds to typical values for LSB objects (e.g. McGaugh 1994; Kuzio de Naray et al. 2004). The characteristics of SDSS J170745+302056 satisfy the luminosity – metallicity relation for spiral galaxies (Kuzio de Naray et al. 2004).

2.3. Analysis of the colors

Figure 4 shows the positions of the corrected colors for SDSS J170745+302056 on color–color diagrams. On the right panel the observations in the \( NUV \) filter (\( \lambda = 0.23 \mu m \)) based on data from the GALEX space telescope (Martin et al. 2005) were added to the optical photometry. The dashed lines on the panels indicate the dependences for the colors of normal galaxies. On the left panel we used the SDSS data for bright E–Im type galaxies (Fukugita et al. 2007). On the right panel we added the \( NUV - r \) color index according to the empirical dependence from Chilingarian and Zolotukhin (2012) to the \( g - r \) color index from Fukugita et al. (2007) for galaxies of the same morphological types. We see that the integrated colors of SDSS J170745+302056 are very blue, \((g-r)_0 = +0.26 \pm 0.08\), \((u-g)_0 = +0.72 \pm 0.17\), and \((NUV-r)_0 = +1.61 \pm 0.17\), and are outside the color sequences for the Hubble sequence of galaxies.

The crosses in Fig. 4 indicate the characteristics of edge-on LSB galaxies from Du et al. (2017). These galaxies have metallicities, luminosities, and sizes comparable to those of SDSS J170745+302056. As can be seen from Fig. 4, the LSB galaxies are located on the color–color diagrams approximately
Fig. 4. Left: the colors of SDSS J170745+302056 on the \((g−r)−(u−g)\) color–color diagram (blue circle with error bars). The dashed line is the color sequence for normal galaxies (Fukugita et al. 2007). The dotted line is the evolutionary track for the model with constant star formation (see the text). The diamonds indicate the colors of the model for an age of 6.5 Gyr. The circle marks the position of the galaxy UGC 12695. Right: the colors of SDSS J170745+302056 on the \((g−r)−(NUV−r)\) color–color diagram. The dashed line indicates the colors of normal galaxies (Fukugita et al. 2007; Chilingarian and Zolotukhin 2012). The remaining designations are the same as those on the left panel. The red crosses on both panels indicate the characteristics of LSB galaxies from Du et al. (2017).

along the color sequence for normal galaxies, but with a shift toward bluer colors. On these diagrams SDSS J170745+302056 lies at the edge of the distributions for LSB galaxies. The circle on the \((g−r)−(u−g)\) plane indicates the colors of UGC 12695, one of the bluest known LSB galaxies (O’Neil et al. 2000). Figure 4 suggests that SDSS J170745+302056 belongs to very, but not extremely blue LSB galaxies.

To interpret the observed colors of SDSS J170745+302056 using the GALEV software package\(^2\) (Kotulla et al. 2009), we considered a simple evolutionary model. This model is based on the assumption about a constant star formation rate over the entire lifetime of the galaxy. This assumption, of course, greatly simplifies the actual star formation history, but for many LSB galaxies it can hold, even if approximately (Schombert and McGaugh 2014). Applying a more complex and refined modeling to a scarce observational data set and relatively high measurement errors was deemed premature.

To estimate the star formation rate in SDSS J170745+302056, we used its ultraviolet luminosity in the FUV (\(\lambda = 0.15 \, \mu m\)) and NUV filters from the GALEX data. (The luminosity in this range traces the star formation on a time scale of \(\sim 10^8\) years.) We recalculated the luminosities to the star formation rate based on the calibrations from Wijesinghe et al. (2011). The star formation rate was found from the data in the FUV and NUV filters to be 0.04 and 0.05 M\(_\odot\)/yr, respectively.

This estimate is consistent with the estimates based on the observed flux in the H\(\alpha\) emission line in our spectroscopic observations (Table 1). Using the calibration from Kennicutt (1998), given the extinction in the Milky Way and the adopted distance, we obtain the current star formation rate, 0.01 M\(_\odot\)/yr. Of course, this value is a lower limit, for example, other star-forming regions through which the spectrograph slit did not pass can also be present in the galaxy.

Assuming the star formation rate in SDSS J170745+302056 to be constant and equal to 0.05 M\(_\odot\)/yr, we computed the long-term evolution of its colors. Other components of the model were: the Salpeter initial mass function, emission lines contribution, the absence of internal extinction in the galaxy.
galaxy, and consistent evolution of the chemical composition (Kotulla 2009). The final tracks on the color–color diagrams are indicated by the dotted lines (Fig. 4).

On both diagrams the model tracks pass near the colors of SDSS J170745+302056. The best agreement between the model and actual colors is achieved for a time of 6.5 Gyr after the onset of star formation (the diamonds in Fig. 4). By this time, the stellar mass $M_*$ in the galaxy (the diamonds in Fig. 4). The actual observed metallicity of SDSS J170745+302056 is approximately a factor of 3 higher than this value. However, given the error in determining the metallicity in the galaxy and that the model used is approximate, the question about the agreement between the model and observations remains open. The stellar mass of SDSS J170745+302056 can be estimated from its multicolor photometry. Using the calibrations from Bell et al. (2003) and Zibetti et al. (2009) and various colors, we found the stellar mass of the galaxy to reach $(2 - 6) \cdot 10^8 M_\odot$. This value is consistent with the model above.

3. The spatial environment of SDSS J170745+302056

SDSS J170745+302056 is not far from the large and bright spiral galaxy UGC 10716 (Fig. 1). The projected distance between the centers of the galaxies is 84′′ or 51 kpc. As we have shown previously, the radial velocities of the galaxies are relatively close, which may be indicative of their interaction. Additional arguments for the possibility of an interaction between these galaxies can be the stellar disk warp in UGC 10716 (Reshetnikov et al. 2016) and the peculiar morphology of SDSS J170745+302056. Furthermore, the combined image of SDSS J170745+302056 shows signatures of a small tidal tail branching off from the northern edge of the galaxy toward UGC 10716 (Fig. 3).

According to Berlind et al. (2006), UGC 10716 is a member of a group of three (from a sample of objects with absolute magnitudes $M_r < -18$, group 5002) or four (from a sample with $M_r < -19$, group 9524) galaxies. Apart from UGC 10716, the group includes PGC 059633 (the brightest member of the group), UGC 10714, and SDSS J170726.32+301316.7 (Berlind et al. 2006). A check based on SDSS data shows that SDSS J170726.32+301316.7 has no measured redshift and is most likely is a more distant background object that does not belong to this group. On the other hand, the irregular galaxy SDSS J170730.04+301356.8 not far from UGC 10714 and the galaxy SDSS J170745+302056 being studied in this paper should be included in the group. The corrected and expanded list of group members is presented in Table 3. The data in the table were collected from SDSS and NED.

The mean radial velocity of the group galaxies is 9502 km/s and the corresponding distance to it is $D = 133$ Mpc (this value was used previously to find all of the distance-dependent quantities). The velocity dispersion of the group galaxies is $\sigma = 121$ km/s; its harmonic radius is 151 kpc. The above values are quite typical for the groups identified by various algorithms in the surrounding part of the Universe (Makarov and Karachentsev 2011).

The group crossing time is $\approx 0.1$ of the Hubble time. This means that the group members could repeatedly encounter in the past. It remains unclear how a relatively unevolved and large ($\sim 20$ kpc in diameter!) LSB galaxy could be preserved in such an environment. LSB galaxies are usually located in low-density environment, far from possible star formation triggers (see Rosenbaum et al. 2009 and references therein). Therefore, we can suggest that SDSS J170745+302056 has encountered this group only relatively recently and, possibly, experiences the first encounter with another massive galaxy (UGC 10716). In that case, the large-scale warp of the UGC 10716 plane is most likely related to the interaction with other group members and not with SDSS J170745+302056. Remarkably, excluding SDSS J170745+302056 from consideration barely changes the integrated characteristics of the group. Without SDSS J170745+302056 the velocity dispersion of the group becomes 136 km/s, its harmonic radius is 158 kpc, and the crossing time remains the same.

Recently, a large population of the so-called ultra-diffuse galaxies was discovered in several clusters (van Dokkum et al. 2015; Wittmann et al. 2017) and even groups of galaxies (Makarov et al. 2015). These galaxies have very low surface brightnesses, low metallicities, and their typical sizes reach several kiloparsecs. The origin of such objects in the regions of a high density of galaxies also remains unclear. For example, it is possible that the ultra-diffuse galaxies have unusually massive (for their luminosity) dark halos that protect at

\[ http://ned.ipac.caltech.edu \]
Table 3. Parameters of the group galaxies

| No. | SDSS Name                  | Type  | cz (km/s) | r (mag) |
|-----|----------------------------|-------|-----------|---------|
| 1   | J170654.71+301611.1        | PGC 059633 Sb | 9342     | 13.73   |
| 2   | J170725.22+301330.0        | UGC 10714 Sb | 9526     | 14.28   |
| 3   | J170730.04+301356.8        | Irr    | 9503      | 17.04   |
| 4   | J170744.50+301935.1        | UGC 10716 Sb | 9685     | 14.74   |
| 5   | J170745.80+302056.2        | LSB, Irr | 9453     | 18.46   |

them from the tidal effect of clusters (van Dokkum et al. 2015). Drawing an analogy between ultra-diffuse galaxies and SDSS J170745+302056, we can suggest that the galaxy being studied also possesses a very massive halo that prevents its destruction. On the other hand, compared to SDSS J170745+302056, the ultra-diffuse galaxies are fainter, have, on average, lower surface brightnesses, and, in addition, they contain no gas and exhibit red colors. Consequently, SDSS J170745+302056 and the ultra-diffuse galaxies can be different in origin.

4. Conclusions

Based on our observational data, we studied the galaxy SDSS J170745+302056. By the set of its characteristics, it is a typical blue irregular LSB galaxy. We estimated its age within a simple model with a constant star formation to be $\sim 6.5$ Gyr. This means that it was formed at a redshift $z \sim 0.7$.

The most remarkable feature of SDSS J170745+302056 is that it is a member of a group of galaxies with a crossing time $\approx 0.1$ of the Hubble time. In such a dense environment the galaxy should have repeatedly encountered other group members and experienced tidal perturbations capable of triggering active star formation in it. At the same time, the low surface brightness of SDSS J170745+302056 and its colors may be indicative of the galaxy’s relatively quiet evolution in the past. It is not inconceivable that SDSS J170745+302056 was formed in a region of relatively low ambient density and has only recently encountered the group of galaxies we discuss. Another possible explanation proposed previously for ultra-diffuse galaxies in clusters is that SDSS J170745+302056 possesses an anomalously massive dark halo that protects its disk during its encounters with other group members.

Our results are preliminary ones. More detailed observational data concerning the morphology, kinematics, and HI content of SDSS J170745+302056 are required to clarify its formation and evolution.

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