Observational insights on the formation scenarios of giant low surface brightness galaxies

Anna Saburova\textsuperscript{1,2}, Igor Chilingarian\textsuperscript{3,1}, Anastasia Kasparova\textsuperscript{1}, Olga Sil’chenko\textsuperscript{1}, Ivan Katkov\textsuperscript{4,5,1}, Kirill Grishin\textsuperscript{1}, and Roman Uklein\textsuperscript{6}

\textsuperscript{1} Sternberg Astronomical Institute, M.V. Lomonosov Moscow State University, Universitetskyy pr., 13, Moscow 119234, Russia, saburovaann@gmail.com
\textsuperscript{2} Institute of Astronomy, Russian Academy of Sciences, Pyatnitskaya st., 48, Moscow 119017, Russia
\textsuperscript{3} Center for Astrophysics — Harvard and Smithsonian, 60 Garden Street MS09, Cambridge, MA 02138, USA
\textsuperscript{4} New York University Abu Dhabi, PO Box 129188 Abu Dhabi, UAE
\textsuperscript{5} Center for Astro, Particle, and Planetary Physics, NYU Abu Dhabi, PO Box 129188, Abu Dhabi, UAE
\textsuperscript{6} Special Astrophysical Observatory, Russian Academy of Sciences, Nizhniy Arkhyz, Karachai-Cherkessian Republic 357147, Russia

Abstract. Giant low surface brightness galaxies (gLSBGs) with the disk radii of up to 130 kpc represent a challenge for currently accepted theories of galaxy formation and evolution, because it is difficult to build-up such large dynamically cold systems via mergers preserving extended disks. We summarize the in-depth study of the sample of 7 gLSBGs based on the results of the performed spectral long-slit observations at the Russian 6-m BTA telescope of SAO RAS, surface photometry and H\textsubscript{i} data available in literature. Our study revealed that most gLSBGs do not deviate from the Tully-Fisher relation. We discovered compact elliptical (cE) satellites in 2 out of these 7 galaxies. Provided the low statistical frequencies of gLSBGs and cEs, the chance alignment is improbable, so it can indicate that gLSBGs and cE are evolutionary connected and gives evidence in favor of the major merger formation scenario. Other formation paths of gLSBGs are also discussed.

Keywords: galaxy evolution, low surface brightness galaxies

Introduction. Giant low surface brightness galaxies (GLSBGs) deserve special interest since they harbor the largest rotating disks in the Universe. These galaxies have baryonic masses reaching $10^{11}M_\odot$ and dynamical masses $\sim 10^{12}M_\odot$. 
Currently accepted galaxy formation scenarios have hard time explaining their properties because for the mass assembly at such scale one typically needs dozens of minor and major mergers, which would likely destroy the disk, zero out the total angular momentum and turn a galaxy into a giant elliptical. Only a couple of dozens gLSBGs were found since the discovery of the prototypical galaxy Malin 1 in the 80s by Bothun et al. (1987) so they are considered extremely rare. The question of the gLSBGs formation remains open (Kasparova et al. 2014; Galaz et al. 2015; Hagen et al. 2016; Boissier et al. 2016; Saburova 2018; Saburova et al. 2021) despite their importance as a “stress test” for the ΛCDM cosmology. An in-plane major merger of two giant spiral galaxies with fine-tuned orbital parameters can end-up in a system resembling a gLSBG (Saburova 2018). So does a triple major merger with two gas-rich galaxies when a host’s hot halo gas cooling is triggered by the cold gas supply from the infalling systems and later forms a giant extended disc (Zhu et al. 2018). The analysis of the results of EAGLE simulations shows that the most extended LSB disks are formed by mergers (Kulier et al. 2020). Accretion of cold gas from a cosmic filament or gas-rich satellites (Penarrubia et al. 2006) on-to a pre-existing high-surface brightness galaxy (Saburova et al. 2019) can also foster a giant disk. The unusually sparse dark matter halo can also lead to the formation of giant LSB disc (Kasparova et al. 2014). In this paper we briefly summarize the efforts that we made to understand the formation scenario of gLSBGs by observing a sample of 7 gLSBGs: Malin 1, Malin 2, NGC 7589, UGC 1378, UGC 1382, UGC 1922, and UGC 6614.

The results of long-slit spectral observations. We performed spectral long-slit observations at the 6-m BTA telescope of SAO RAS using SCORPIO and SCORPIO-2 spectrographs (Afanasiev & Moiseev 2005, 2011). The details of the data reduction and analysis could be found in Saburova (2018); Saburova et al. (2019, 2021). The most prominent result of these observations is the discovered kinematically decoupled components in UGC 1922 and UGC 1382. In UGC 1382, the global gaseous disk counter-rotates with respect to stars, and this suggests the external origin of gas in the extended disk. Stellar populations in the central parts of 5 of the 7 gLSBGs are old and metal-rich supporting the scenario of accretion of gas onto a pre-existing high surface brightness galaxy.

The discovery of the cE satellites. The inspection of the archival HST images of the class prototype Malin 1 allowed us to make an important step towards understanding of the nature of gLSBGs. Malin 1 appeared to have two satellites which reminded the low-mass dense compact elliptical galaxies (cE) (see Fig. 1). The cEs are rare low-mass systems (~ 0.5% of dwarf galaxy population)
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Fig. 1. The colour composite images of UGC 1382 from HSC (left panel) and Malin 1 (right panel) from the CFHT-Megacam Next Generation Virgo cluster Survey in $u$, $g$ and $i$-bands taken from Junais & Boissier (2019). Arrows demonstrate the position of cE satellites

with small sizes ($r_e < 1$ kpc) and high densities typically hosting old metal-rich stars Chilingarian et al. (2009); Ferre-Mateu et al. (2021). They likely originate from tidal stripping Bekki et al. (2001) of massive disky progenitors losing 90–95% of stellar mass Chilingarian et al. (2009); Price et al. (2009); Norris et al. (2014); Chilingarian & Zolotukhin (2015); Ferre-Mateu et al. (2021). The structural analysis of the Hubble WFPC2 data using GALFIT confirmed the cE classification, and the re-analysis of published optical spectra from the Russian 6-m telescope confirmed that these cE were indeed the satellites of Malin 1. Further visual inspection of high-quality optical image of UGC 1382 from Subaru Hyper-SuprimeCam Strategic survey revealed additional cE-satellite of gLSBG, the SDSS spectral data confirmed the physical association. As the next step we significantly extended our sample of gLSBGs by visual inspection of HSC and DECaLS data (Saburova et al. in prep.) and discovered more cE+gLSBGs systems (Chilingarian et al. in prep.). Given the statistical frequencies of gLSBGs and cEs, the chance of alignment is improbable thus cE and gLSBGs must be evolutionary connected which gives more arguments in favor of merger scenario at least for some of gLSBGs.

The baryonic Tully-Fisher relation (BTFR Sprayberry et al. 1995; McGaugh & Schombert 2015) between gas+stellar mass and rotation velocity of galaxies is a useful tool for the diagnostic of the formation paths of galaxies. We found out that 6 out of the 7 gLSBGs lie on the high-mass extension of the BTFR which
is also the case for the most luminous spiral galaxies (Di Teodoro et al. 2021). This suggests that gLSBGs are scaled-up versions of less massive disks.

The parameters of dark matter halos of gLSBGs that we were able to derive from HI + optical rotation curves show dichotomy. Some gLSBGs have high radial scales of the dark halo density profile, while some others do not. Hence, the gLSBG class is in fact inhomogeneous, and there might exist different formation channels. At the same time according to our findings (Saburova et al. 2021), most gLSBGs have external origin of the material for their extended disks (merger and accretion scenarios).

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