https://doi.org/10.15407/knit2024.04.081
UDC 524.7+52-735, UDC 521.91:524.3(083.5)+524.6–34

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AN ADVANCED APPROACH TO THE DEFINITION OF THE “MILKY WAY GALAXIES-ANALOGUES”

Our Galaxy — the Milky Way — has certain features of the structure and evolution. The morphological, photometric, kinematic, and chemodynamical properties are usually considered in search for the Milky Way galaxies-analogues (MWAs). The discovery of MWA galaxies with a larger number of simultaneous selection parameters, as well as more stringent constraints on a given parameter, yields a sample of MWA galaxies with properties closer to the true properties of the Milky Way. So, in general, such MW parameters as the morphological type, luminosity, color indices, structural parameters (size, bar, bulge, thin and thick disks, inner ring, halo), bulge-to-total ratio, stellar mass, star formation rate, metallicity, and rotation velocity were used in various combinations for comparison with other galaxies. However, the offset of some MW features in the multi-parameter space of MWAs features should be significant.

The paper aims to give a brief overview of the problematics and to present our approach for studying Milky Way and MWAs matching characteristics (this project is supported by the National Research Fund of Ukraine). We propose to enlarge as much as possible the number of Milky Way features and compile various samples of MWAs in our co-moving cosmological volume for their further optimization. Such features can include 3D-kinematics of star's movement in certain regions, low oxygen content on the periphery, low nuclear activity, and the lack of significant merging over the past 10 Gyrs (isolation criterion). This approach will make it possible to widely formulate the necessary and sufficient conditions for the detection of MWA galaxies as well as to reveal other MW multiwavelength features.

Keywords*: Galactic and extragalactic astronomy — Galactic morphology — Active galactic nuclei — Milky Way — Stellar kinematics — Cosmological evolution.*

Цитування: Vavilova I. B., Fedorov P. M., Dobrycheva D. V., Sergijenko O., Vasylenko A. A., Dmytrenko A. M., Khramtsov V. P., Kompaniiets O. V. An advanced approach to the definition of the “Milky Way galaxies-analogues”. *Space Science and Technology.* 2024. **30**, No. 4 (149). P. 81—90. https://doi.org/10.15407/knit2024.04.081

1. INTRODUCTION

The morphological, kinematic, and multiwavelength properties of the Milky Way (MW), the structure of spiral arms, the chemical evolution, the low activity of a supermassive black hole, the cosmological origin, and the placement of the Milky Way with neighboring galaxies in the cosmic web are essential questions of modern astrophysics.

Is the Milky Way really a typical giant spiral galaxy, and if not, how is it different, and how many the MW-like galaxies are? The fact that the Milky Way has general ratios between various parameters, which are characterized for the spiral galaxies, suggests that the MW is not highly unusual among galaxies. So, the anthropic principle is true, at least as a first-order approximation. This justifies the selection of Milky Way galaxies-analogues (MWAs) using any MW parameters (stellar mass, luminosity, star formation rate, bulge-to-disk ratio, disk scale length, rotation velocity, and morphology are usually considered). However, the offset of some MW features in the multi-parameter space of MWAs features should be significant.

In the earlier works, only the obvious morphological and photometric parameters were to be taken into account as the MW indicators for MWAs. For example, in the seminal article for this research field, De Vaucouleurs and Pence [9] calculated isophotal R_{25} = 11.5 kpc and effective R_{eff} = 5.1 kpc radii as optical scale lengths, inner ring diameter $D(r)$ = 6 kpc, luminosity values $M_T(B) = -20.1$ and class II, color $(B - V)_T = 0.53$ and hydrogen indices in a frame of the two-component MW structure model (spheroidal for bulge and exponential for disk). It allowed them to identify four nearby galaxies NGC 1073, NGC 4303, NGC 5921, and NGC 6744 as possible MWAs.

Mutch et al. [40] compiled a list of MWAs using the stellar mass and the structural parameter as the selection criteria, where the latter parameter corresponds to the profile of the de Vaucouleurs brightness distribution. Licquia et al. [34] selected a sample of MWAs from the SDSS-III DR8 based on their stellar mass and the current star formation rate. Boardman et al. [4] presented a sample of 62 MWA galaxies from the MaNGA with selection criteria as the stellar masses and bulge-to-disk ratio. We note that the selection of MWA galaxies using only two MW characteristics is a typical approach and consistent with the anthropic principle that the Milky Way is not unusual among other galaxies.

The discovery of MWA galaxies with a larger number of simultaneous selection parameters, as well as more stringent constraints on a given parameter, yields a sample of MWA galaxies with properties closer to the true properties of the Milky Way. So, in general, such MW parameters as the morphological type, luminosity, color indices, structural parameters (size, bar, bulge, disk), bulge-to-total ratio, stellar mass, and rotation velocity were used in various combinations for comparison with other galaxies.

On the other hand, when we use more selection criteria, we add little or no MWA galaxies (see, Boardman et al. [5]). For example, Fraser et al. [20] found only 176 MWA galaxies among over a million of the SDSS DR7 galaxies, selecting them by stellar mass M_*, morphology, and bulge-to-disk ratio and using Galaxy Zoo morphological classification. They concluded that the Milky Way is a galaxy with a low star formation rate log $(\mathrm{SFR}_{MW}/M_{Sun}\ \mathrm{yr}^{-1}) = 0.22$, but it is not unusual when compared to similar galaxies (the same as [61] who estimated this value as 0.25). Boardman et al. [4] did not find MWA galaxies in the MaNGA survey when they combined four parameters: stellar mass, star-formation rate, bulge-to-disk ratio, and disk scale length. Tuntipong et al. [61] used four selection parameters (stellar mass M_*, star formation rate SFR, bulge-to-total ratio B/T, and disk effective radius R_{eff}) for identifying MWAs in the SAMI Galaxy Survey. Combinations of all the parameters allowed them to find 10 MWAs in the GAMA and Cluster regions of the SAMI survey and to outline that B/T is the least important out of them. We also note that MW has stable rotation periods: for the general spiral pattern of 220—360 Myr [21], for the bar pattern of 160—180 Myr [57], and for the Sun's Galactic position of 212 Myr [50].

Pilyugin et al., in a series of works [43, 44, 46], developed the newest approach for the MWAs selection. The oxygen abundance characterizes an astration level (a fraction of matter converted into a star) and, consequently, is an indicator of how far a galaxy has gone forward in its (chemical) evolution. They considered a sample of about 500 galaxies from the

MaNGA survey with selection criteria for three parameters (stellar mass M_*, optical radius R_{25}, rotation velocity V_{rot} to determine the oxygen abundance in the center $(O/H)_0$ and at the isophotal radius $(O/H)_{R25}$. They found that the $(O/H)_{R25}$ in the Milky Way is appreciably lower than in other galaxies with similar value at the center $(O/H)_0$. So, they revealed that the most prominent feature of the MW is the low metallicity at the periphery and identified four galaxies (NGC 3521, NGC 4651, NGC 2903, and MaNGA galaxy M-8341-09101) that can be considered as Milky Way twins.

Such results suggest that some MW parameter(s) can be unusual or their combination can be rare. In this sense, we propose an advanced approach to the search of MWAs by pointing out as much as possible indicators of MW features (Section 2). It allows to enlarge selection criteria for MWA definition as well as to consider wider at what the properties of MW look like to the outside extragalactic observer. The aim of our article is to present the project “The Milky Way galaxies-analogues” (2024—2026) supported by the National Research Fund of Ukraine.

2. CONCEPT OF AN ADVANCED APPROACH

Being a typical barred spiral galaxy, the Milky Way has several meaningful observational features of its evolution. In our opinion, using multiple selection criteria for finding MWAs is a more effective approach, which enlarges the common picture of MW and MWAs’ physical properties, diminishes potential biases in MWA studies, and enriches our knowledge for identifying and optimizing the necessary/sufficient conditions for the definition of MWAs galaxies.

Below, we clarify and briefly discuss the MW parameters and observational features both mostly considered (Section 2.1) and those we would like to propose (Section 2.2, 2.3) for MWAs’ search.

2.1. Morphological and photometric parameters, scale length of structures, metallicity, stellar mass, and star formation rate. The ***morphological type*** of our Galaxy was determined as SAB(rs)bc [9]. The SBc type ($T = 4$) is usually considered for the study of MWAs.

Main structural parameters: giant disk galaxy having four {two ?} spiral arms with twist angles, bar, bulge, inner ring, and halo.

Metallicity as a key parameter of chemodynamical evolution reveals many factors that define the MW’s structural parameters. Hammer et al. [26] found a systematic offset in the position of the Milky Way in the parameter space within 1σ for all Tully-Fisher ratios, which shows a significant deficiency in stellar mass, angular momentum, disk radius, and Fe/H in the stars in the periphery region at a given V_{rot}. In contrast, McGaugh [37] suggests that the Milky Way is a normal spiral galaxy obeying the Tully—Fisher and the size-mass relation. Licquia et al. [33] examined the three-dimensional diagram (V_{rot} — luminosity — radius) and found that the Milky Way lies farther from this relation than around 90 % of other spiral galaxies, yielding evidence that the MW is extremely compact for its rotation velocity and luminosity possessing a cold bar [52]. In this context, we also note the recent work by Queiroz et al. [51] with the GAIA data on the differences of the stellar population in the MW bar and bulge.

The chemical properties of the MW are not typical in several aspects. On the one hand, the MW is one of the most oxygen-rich spiral galaxies in the sense that the metallicity in the center is close to the maximum attainable value [47]. On the other hand, the oxygen abundance along the optical radius is noticeably lower than in galaxies with a similar central metallicity [46]. At the same time, the MW has a very steep metallicity gradient compared to most giant spiral galaxies, in which the change in oxygen excess along the optical radius is quite small [45].

Chandra et al. [6] considered the MW three-phase chemodynamical evolution exploring a sample of 10 million red giant stars with low-resolution Gaia XP spectra and operating with angular momentum as a function of metallicity. They compared it with those of MWAs from the Illustris (TNG50) cosmological simulation taking into account these three MW evolutionary phases: the disordered protogalaxy, the kinematically hot old disk, and the kinematically cold young disk. They proposed three physical mechanisms for explanation (spinup, merger, and cooldown), which satisfies conditions of the Gaia-Sausage-Enceladus (GSE) last major merger with our Galaxy at $z \sim 2$. In the frame of this three-phase scenario, Semenov et al. [56] proposed an explanation of yet one MW feature: the MW disk was formed quite early, within the first few billion years of its evolution. It is consistent with the overall population of MWA-mass disk galaxies. We note that the thicknesses of thin and thick disks 220—450 pc and 2.6 kpc are usually considered, respectively [3].

Among other MW chemodynamical features, which were compared with MWAs obtained in TNG50 cosmological simulations, we note recent fundamental research by Rix et al. [54]. Using Gaia XPspectra, they found a universal feature for MW and MWAs: their extremely metal-rich giant stars ($M/H_{XP} > 0$) are mostly concentrated in a compact central dynamically hot knot with $R < 1.5$ kpc. Taking into account that MW metal-poor stars are also concentrated in the central few kiloparsecs region, future studies with the SDSS-V, as these authors write, will allow us to estimate the stellar population more precisely. Another "side" of our Galaxy, the halo at 10—80 kpc, was studied by Han et al. [27] with the H3 Survey data. They found the strong kinematic asymmetries of distributions and, consequently, cold and kinematically hot fractions of stars with radial velocity dispersions of 70 km/s and 160 km/s, respectively.

As for the ***inner ring*** feature, Wylie et al. [70] in their recent meticulous work with a sample of APOGEE DR16 inner Galaxy stars, studied the outer bar region. They considered the orbits of stars in the ‘‘state-of-the-art bar-bulge potential with a slow pattern speed", constructing the maps of their metallicity [Fe/H], density, and ages. They conclude that the MW inner ring-like structure is, on average middle-age and has a metal-rich gradient along the bar's major axis. Their position is between the planar bar and corotation.

The following ***photometric parameters, stellar mass, star formation rate*** are usually taken into account for the search of MWAs: luminosity class (II); isophotal diameter D_{25} = 26.8 kpc [23] with adopting a central surface brightness μ_0 = 22 B-mag/arcsec^{-2} and a disk scale length h = 5 kpc; the isophotal radius is usually adopted as R_{25} = 12 kpc; the stellar disk up to 1.35 kpc [53].

The ***mass*** of our Galaxy has various estimates depending on methods and entire region for this estimate: from 8.5×10^{11} M_{Sun} [42] to 1.4×10^{12} M_{Sun} [24]. The virial mass at Galactocentric distance less than 21.1 kpc is M_{vir} = 0.2×10^{12} M_{Sun} (see, for example, Watkins et al. [69] for estimation by halo globular clusters motion); stellar mass M_*= 5×10^{10}M_{Sun} (log M_* = 10.7) with linear scale (B/T, R_{eff}) [61]; number of stars N_* = (1—4)×10^{11} when the disk stars were detected with Gaia DR2 even beyond 25 kpc from the MW center; dark matter density at Sun's position M_{DM} = 0.0088 M_{Sun} pc^{-3} [29] but a dark matter area may extend up to ~ 600 kpc [7]; ***star formation rate*** *SFR* = 1.78 ± 0.36 M_{Sun} yr^{-1} [61].

In this context, the Illustris(TNG50) simulation, containing approximately 100 MWA galaxies by mass, could be used to define their evolutionary tracks in order to discover whether there is a typical scenario of evolution that leads to the formation of MWA galaxies or to estimate the probabilities of different scenarios of their formation. The result of this task will be exploited to select the most likely scenario (scenarios) for a search of MWA galaxies at the higher redshifts.

2.2. Nuclear activity, supermassive black hole, 3D-kinematics of stars. We propose to search for such a parameter of the Milky Way in the parameter space, which shows the maximum deviation from the corresponding relation for spiral galaxies. This parameter is used as the main criterion for selecting MWA galaxies. Because the search for MWA galaxies is feasible using any parameters of the MW, we propose to increase their number both for the search for MWAs and for the specification of their properties.

In most of the research, as you see, the MW galaxies-analogues were selected based on two/three parameters: stellar mass and some additional parameter, usually bulge-to-disk (bulge-to-total) ratio, the star formation rate. In addition to these MW features, we would like to highlight the weak nuclear activity and the low mass of the supermassive black hole (SMBH), 3D-kinematics for the rotation velocity, isolation criteria, and several known multiwavelength properties.

The **3D-kinematics of a star's movement** can serve as an indicator for the search for MWAs. In series of works, Fedorov et al. [17—18], Dmytrenko et al. [10], Denyshchenko et al. [8] investigated the region of the Milky Way in the coordinate ranges 120° < < θ < 240°, 0 kpc < R < 16 kpc, –1 kpc < Z < 1 kpc with Gaia EDR3 using samples of red giants and subgiants whose centroids are in the MW plane. For the first time, these authors derived the dependence of their kinematic parameters on the Galactocentric coordinates as well as the parameters for rotational velocity $\partial V_R/\partial\theta$ and $\partial V_\theta/\partial\theta$.

Our approach includes the task of investigating the 3-D kinematics of a large part of the MW based on GAIA DR3 data within the Ogorodnikov — Milne model and using the determined strain and rotation rate tensors to establish the spiral pattern of the MW. The studied galactic space will be bounded by the Galactocentric coordinates of 4 kpc $< R <$ 14 kpc, $140° < \theta < 220°$ and -3 kpc $< Z <$ 3 kpc. This is the region dominated by older stars, which are more evenly distributed than younger blue stars. Using the obtained components of the spatial velocities of the centroids and kinematic parameters, we will able to construct $V_{rot}(R)$ and their slope within this region and to determine the parameters of the spiral arms, including the coordinates of the vertices of various star regions. These results can serve as characteristic features for applying machine learning in tasks of searching MWAs with kinematically cold rotating disk.

Let us also remind that our Galaxy possesses both a ***weak nuclear activity and a small mass of the supermassive black hole***: $M_{SMBH} = 4.61\times10^6\ M_{Sun}$ [2, 22]. The central object Sgr A* usually shows quiescent state, but sometimes does show rapid outbursts or flares of radiation (see e.g. [13, 25], and references therein). This is the case of a low-luminosity galactic nucleus, radiating at $\approx 10^{-8}$ of the Eddington level. In the such regime of activity, the MW core has no typical AGN-like gas-dusty torus but has so-called "circumnuclear disk" (CND) as a torus-like dusty-molecular gas around Sgr A* extending from ~1 pc to ~5 pc (see, e.g. [16, 32, 59]).

2.3. Isolation criterion. We accept as a working hypothesis that the MW's features are caused by its evolution without major merging over the last 10 Gyr. We consider the isolation criterion of MWA galaxies on the scales of neighboring galaxies to study the role of satellites in the evolution of MWA galaxies.

The Milky Way can be considered an isolated galaxy during the long time of its evolution. The results of the high-resolution N-body simulations of last major merger by Naidu et al. [41] allowed in particular to determine both the orbital parameters of merging with two density profile breaks at ~15—18 kpc and 30 kpc as well as distribution of stellar and dark matter mass between GSE and Milky Way.

What is about minor mergers? How do the Magellanic Clouds (the gas reservoirs) influence the evolution of MW? Van den Bergh [62] assumes that the Magellanic Clouds may be interlopers from a remote part of the Local Group rather than true satellites of the Milky Way, i.e., the Large Magellanic Cloud (LMC) is on its first approach to the MW. Font et al. [19] and Jones et al. [28] investigated the significance of satellite effects and analyzed star formation rates in galaxy systems similar to the MW system using the projected distances between galaxies.

What is the future collision of the Milky Way with Andromeda galaxy [14, 63] in around 5 Gyr? Sawala et al. [55] used the Gaia and HST observational data to determine the dynamical process of merging the MW-M31 system. These authors predicted that M33 and LMC, as other members of the Local Group, can make this merger less likely because the LMC orbit runs perpendicular to the MW-M31 system orbit. Moreover, they found that existing uncertainties in the present kinematic and dynamic (masses) data for Local Group galaxies give a 50 % — 50 %probability of MW-M31 merger during the next 10 Gyr. Not only the correct distance moduli determination (see, for example, [15]) and the MW-M31 orbital geometry [1] but also the position of the Local Void lying adjacent to the Local Group [35, 36, 60] and the MW moving away from this void can play a certain role. To study the role of interaction with neighboring (dwarf/normal) satellite-galaxies in the evolution of MWAs, the isolation parameters for nearby galaxies are available (see, Sorgho et al. [58] for the AMIGA project). For example, the isolated galaxies selected from the 2MIG catalog exhibit ***multiwavelength properties***, which are characterized by weak nuclear activity as compared with galaxies in the dense environment [11, 38, 48, 68] and faint luminosity in spectral ranges, especially in radio- and X-ray ranges [49, 64].

The ***multiwavelength data*** for exploiting spectral energy distributions (SED) of MWAs are also gathered in various observational sky surveys obtained by ground-based and space telescopes [65]. Therein, in our opinion, the galaxies most MW-like (MW twins) deserve close attention. For example, the NGC 3521 is one of such MW twins as regarding baryon mass, rotation velocity, scaled disk length, and metallicity. Its multiwavelength observational data, including from the Ukrainian UTR-2 radio telescope in the decameter range [31], will be quite useful both to have a full SED of the NGC 3521 and to explain some MW features as the Galactic background radio emission or the North Polar Spur [39]. The archive of the UTR-2 radio telescope contains large volumes of 24-hour survey data for 4-5 positions on inclination.

An interesting expected result to find the view of the MW from the outside observer can be achieved using machine learning for classification by a range of photometric parameters (morphology details, optical radius, luminosity concentration index to the center, color indices, etc.) and image features (bar and bulge, structure of spiral arms, inclination angle, etc.) classification [12, 30, 66, 67] as well as the obtained 3-D kinematics of the MW red-giant and subgiant stars, and the parameters of multiwavelength radiation of MWAs as additional indicators.

3. CONCLUSION

Our project for searching MWAs includes several research areas: 3D kinematics of stars of the MW; selected multiwavelength properties of MWA galaxies, including NGC 3521 as the most MW-like galaxy; the activity of the nuclei and SMBH masses of MWA galaxies; the gravitational coupling of selected MWA galaxies and the analysis of the significance of the influence of dwarf neighboring galaxies; cosmological simulations of the evolutionary tracks of MWA galaxies; search for the appearance of the MW for the outside observe by machine learning, which is based on the data of MWA-galaxies; the revealing for other features of the MW in comparison with the MWA galaxies.

Samples of candidates for the role of the MWAs should contain the maximum possible number of MW features. This allows for optimizing the necessary and sufficient conditions for revealing MWAs. The number of candidates for MWA galaxies will increase quantitatively, and their study will, in turn, help to understand the appearance and features of the MW as an extragalactic object. Cosmological simulations TNG50, in turn, allow clarifying whether single/different evolutionary tracks lead to the formation of the MWA.

The Milky Way galaxies-analogues provide an alternative insight into the various pathways that lead to the formation of disk galaxies with properties similar to the Milky Way. Such an approach will make it possible to widely formulate the necessary and sufficient conditions for the detection of MWA galaxies as well as to reveal other MW multiwavelength features. In our cosmological co-moving volume, the MWAs can be identified in solving the multi-parameter task of optimizing those quantitative and qualitative characteristics that should be as similar as possible to the MW features. This circumstance reflects the fact that available samples of MWAs contain the galaxies in the redshift range of the Local Universe.

Determining what our Galaxy (our big house) looks like from the outside is of great importance for astrophysics and astronomy's popularization. Mankind has always been interested in whether our place of residence in the Universe is special or whether there are other similar places. First, there was a search for planets near other stars; after discovering the first exoplanets, the search began for terrestrial planets and planetary systems similar to the Solar System. The search for for MWA galaxies is the next step on this path.

Acknowledgments*. The authors gratefully thank Prof. L. S. Pilyugin for the helpful discussion and to the anonymous Referee. The work is supported by the National Research Fund of Ukraine (Project No. 2023.03/0188, 2024—2026).*

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Стаття надійшла до редакції 16.08.2024
Після доопрацювання 17.09.2024 Прийнято до друку 17.09.2024

Received 16.08.2024
Revised 17.09.2024
Accepted 17.09.2024

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ПЕРСПЕКТИВНИЙ ПІДХІД ДО ВИЗНАЧЕННЯ «ГАЛАКТИК-АНАЛОГІВ ЧУМАЦЬКОГО ШЛЯХУ»

Наша Галактика — Чумацький Шлях — має певні особливості будови та еволюції. При пошуку галактик-аналогів Чумацького Шляху зазвичай враховують морфологічні, фотометричні, кінематичні та хемодинамічні властивості. Виявлення галактик-аналогів із більшою кількістю одночасних параметрів відбору, а також більш суворими обмеженнями на певний параметр, дає вибірку галактик-аналогів із властивостями, ближчими до справжніх властивостей Чумацького Шляху. Зазвичай такі параметри Чумацького Шляху, як морфологічний тип, світність, показники кольору, структурні параметри (розмір, бар, балдж, тонкий та товстий диски, внутрішнє кільце, гало), співвідношення світності балджа до загальної, зоряна маса, темп зореутворення, металічність і швидкість обертання використовуються в різних комбінаціях для порівняння з іншими галактиками. При цьому зміщення деяких параметрів Чумацького Шляху у багатопараметричному просторі параметрів галактик-аналогів має бути значущим.

Мета роботи — надати короткий огляд проблематики та представити наш підхід до вивчення таких особливостей Чумацького Шляху та його галактик-аналогів, які збігаються (проєкт підтримується Національним фондом досліджень України). Ми пропонуємо максимально збільшити кількість досліджуваних параметрів Чумацького Шляху та створити різні вибірки галактик-аналогів у близькому космологічному об'ємі для їхньої подальшої оптимізації. Серед таких параметрів — тривимірна кінематика руху зір у заданій області Чумацького Шляху, низький вміст кисню на периферії, слабка активність ядра і відсутність значного злиття за останні 10 млрд років (критерій ізольованості). Такий підхід дозволить сформулювати необхідні та достатні умови для виявлення галактик-аналогів та виявити інші багатохвильові особливості Чумацького Шляху.

Ключові слова: Галактична та позагалактична астрономія — Морфологія галактик — Активні ядра галактик — Чумацький Шлях — Зоряна кінематика — Космологічна еволюція.