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Destruction of Galaxies as a Cause of the Appearance of Stellar Streams

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Abstract—The interaction of galaxies in clusters with the intergalactic gaseous medium and other galaxies is considered. The causes for the appearance of gaseous and stellar "tails" and stellar "copies" of galaxies during their movement in a dense gaseous medium in the cores of clusters and during the tidal destruction of colliding galaxies are studied. The possible role of star formation and direct collisions of gas-rich galaxies leading to the emergence of low surface brightness galaxies (LSBGs), as well as the destruction of old and the formation of new galaxies is indicated. The possible contribution of the destruction of galaxies and satellites of massive galaxies by star formation bursts occurring in them to the appearance of stellar streams of galactic scales is noted. Stellar streams eventually enter the thick stellar disks and bulges of massive galaxies. Stellar streams, as a product of the decay of satellite galaxies, may contain the remaining dense star clusters and include stars, exoplanets, and interstellar comets.

Keywords: galaxies, stellar streams, star clusters, planetary systems

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1. INTRODUCTION

1.1. Galaxy Clusters

Galaxy clusters are a fundamental structural element of the Universe that accumulates the bulk of its matter. Most of the observed galaxies form clusters with masses of 10^{12}–$10^{15}\,M_\odot$ and radii from 30 to 1000 kpc [1]. The characteristic motion velocities of galaxies in clusters are 300–1000 km/s. The initial mass function (MF) of galaxies and galaxy clusters can be represented as $dN \sim M^{-2}dM$ [2]. The galaxies within the clusters are immersed in a gas-stellar medium. Approximately 30% of the stars inhabiting the clusters do not belong to galaxies; these stars show a noticeable concentration toward the centers of their clusters [3]. Their origin is associated with the destruction of galaxies. According to observations, the gas component accounts for only a few percent of a cluster's mass. The gas density ranges from 10^{-2} cm^{-3} in the cluster core to 10^{-4} cm^{-3} at its periphery [4]. The gas in the cluster core is heated by the motion of galaxies and SN Ia explosions to a temperature of approximately 10^7 K [5, 6], which is confirmed by the observed X-ray emission of galaxy clusters with luminosities $L_{\rm x}$ up to 5×10^{45} erg/s [4].

In many cases, the sizes of galaxies are comparable to the sizes of the clusters containing them, so the motion of galaxies in clusters inevitably leads to their recurrent encounters and collisions. As a result of the tidal interaction of close galaxies, such observable manifestations as gas-stellar spirals, tails, and stellar streams take place. Tidal effects were studied in [7–11]. In [12], along with an extensive review of the results of previous studies, the first attempts were made to numerically simulate tidal phenomena in the world of galaxies and, in particular, structures arising in the course of their interaction.

Further, we consider the processes of collisions and mergers of galaxies as a possible source of the population of galactic stellar bulges and disks, and the retrograde rotation of some stars as a sign of galaxy mergers. Section 2 discusses the processes of galaxy mergers that lead to the formation of stellar streams. Section 3 presents the properties and variants of the origin of the observed stellar streams that comprise the population of stellar bulges and disks. In Section 4, we consider the possible causes of the destruction of galaxies. Section 5 discusses the role of dynamic braking in the process of galaxy mergers. Section 6 presents the results of numerical calculations of different variants of the destruction of a galaxy satellite. At the end of the study, we present the estimates of the parameters of the stellar streams, discussion of the results, and conclusions.

1.2. Role of Intergalactic Gas in the Evolution of Galaxies

The observed galaxies are immersed in a relatively dense intergalactic gas with a density $n_{\rm H}$ = 10^{-3}–

10^{-2} cm^{-3} [13]. The interaction of this gas with the gaseous component of moving galaxies can lead to the appearance of stellar tails in the galaxies. Such galaxies are called "jellyfish" [14, 15]. The stellar tails of jellyfish galaxies are bimodal. Some of these tails owe their appearance to the loss of dense peripheral gas by the galaxy due to the pressure of intergalactic gas incident at a speed up to 1000 km/s, followed by star formation in the lost gas [16]. The other part may be a product of star formation in a dense intergalactic gas with a density n_H flowing around a moving galaxy. The condition for the cooling of the gas when a disk galaxy moves at a velocity on the order of parabolic velocity at its edge looks as follows:

$$n_\mathrm{H} > \frac{0.005}{K^2}(M_{11})^{1/4}\ \mathrm{cm}^{-3}, \qquad (1)$$

where K is the coefficient in the relation $R = 10^4 K M_{11}^{1/2}$. Here, R is measured in pc, and M_{11} is the mass of the galaxy in units of $10^{11}\ M_\odot$ [17]. It is clear from relation (1) that cooling of intergalactic gas and star formation in it is possible in low-mass galaxies at $K \simeq 2–3$ (low surface brightness) that move in the dense cores of their clusters, which is exactly what is observed. The relationship between the radius and mass for galaxies, star clusters, and galaxy clusters follows from the analysis of observational data, and it is valid for most galaxies with an accuracy on the order of a factor of three.

Observations show that the sizes of LSBGs are increased several times relative to their usual sizes [18]. The low surface density of such galaxies facilitates the loss of gas due to the pressure of the oncoming gas of the medium [19]. In this case, not only the loss of gas can occur, but also their complete destruction in the gravitational field of massive galaxies and dense cores of galaxy clusters. The destruction of such galaxies can lead to the formation of stellar streams. At the same time, stellar streams can contain dense star clusters. Thus, the observed stellar streams of the considered origin may be of interest as markers for the search for new star clusters belonging to other galaxies.

2. MERGING OF GALAXIES DURING COLLISIONS

2.1. Stellar Streams at the Periphery of Galaxies

The commensurability of the size of galaxies with the size of their clusters and the high velocities of their movement within the clusters lead to their direct collisions, which occur rather often during their lifetimes. The characteristic relative velocities of collisions in massive clusters of galaxies are ~10^3 km/s. This value exceeds the characteristic parabolic velocities at the edge of galaxies (~10^2 km/s), which leads such collisions to the scattering of gaseous components [20] and "free" flight of stellar components. Some collisions occur at low relative velocities, comparable to parabolic or less, which leads to the merging of the colliding components and an increase in their mass [21]. The frequency of such collisions in clusters is constant over time [22].

It is known that galactic mergers can produce disk galaxies with stellar nuclei rotating in the direction opposite to the rotation of their stellar disks. The first discovered example of such galaxies is IC 1459, whose nucleus (~300 pc) rotates at a velocity of 179 km/s, while the disk (at a velocity of ~45 km/s) rotates in the opposite direction [23]. This phenomenon was later discovered in a number of other galaxies of various types [24]. It is also possible that some of the galaxies with retrograde rotation of the nuclei with respect to the disk are products of the accretion of dense intergalactic gas from cluster cores accompanied by star formation. However, the high rate of collisions between galaxies in clusters draws attention primarily to collisions as a possible cause of collisional galaxy mergers.

A detailed kinematic and chemical analysis of the vicinity of our Galaxy within ~50 kpc was performed in [25]. This made it possible to establish that most stars in the Galactic halo at distances above 10 kpc from the galactic center (GC) belong to stellar streams. The sources of these streams are low-mass satellite galaxies disrupted by the tidal forces of our Galaxy. The chemical composition and kinematic parameters made it possible to identify eleven stellar streams with $-2.5 <$ [Fe/H] < -0.5 and $0.1 <$ [Fe/H] < 0.4, which contain approximately 90% of all stars in the Galactic halo. Up to half of these streams have retrograde rotation. These results clearly demonstrate the conditions for the formation of vast halos of massive galaxies and stellar streams as decay products of their satellites.

2.2. Outer Halo Structure as a Sum of Stellar Streams

The noticeable concentration of halo stars in stellar streams indicates that their lifetime exceeds the Hubble time (see our estimate below). The confirmation of this increased concentration can be seen in [26], where the positions of 1500 low-metallicity ([Fe/H] < -2) stars in the Galactic halo are considered. Although, as is known [27], stellar streams have also been found in the inner parts of the Galaxy.

Thus, the disintegration of the satellite galaxy leads over time to the formation of a stellar stream along the original orbit of the satellite. Let us estimate the lifetime of a stellar stream within a simple model. The lifetime of a stream is understood as the time required for the velocity of all its member stars to change by an order of magnitude of the dispersion of their initial velocities w. Let a galaxy with mass M and radius R be represented by a system of gravitating objects with mass m each. The radius of the zone within which an object flying with a velocity $u = \sqrt{\frac{GM}{R}}$ changes the velocity of the surrounding stars by w is equal to $r = \frac{Gm}{uw}$, where G is the gravitational constant. The time required for flying objects to cover the entire volume of the galaxy and thus destroy the stellar stream will be equal to $\tau = \frac{R^{5/2}w^2}{G^{3/2}mM^{1/2}}$. The mass and radius of the galaxy are related as $M \approx 0.2R^2$ [17]. As a result, we obtain an estimate of the time required for the destruction of the stellar stream by the stars of the galaxy:

$$\tau = \tau_d\left(\frac{M}{m}\right)^{1/2} \cong 3\times10^7 M_{11}^{1/2}\left(\frac{M}{m}\right)^{1/2} \text{ years,} \qquad (2)$$

where $\tau_d \cong R^{3/2}M^{-1/2}G^{-1/2}$, $M_{11} = M\times10^{-11}/M_{\odot}$. It is obvious from (2) that the lifetime of stellar streams produced by the decay of clusters and low-mass satellite galaxies under the influence of stars of the field (with a characteristic mass equal to the solar mass) significantly exceeds the Hubble time. It is important to note that this is what ensures the aforementioned preservation of all stellar streams in the Galaxy [25] throughout its evolution. However, as follows from relation (2), when galaxies of comparable masses merge, “turbulization” of streams is possible.

2.3. Collisions of Galaxies in Clusters and Their Consequences

Galaxy collisions are a common occurrence for galaxies in known clusters. Let us show how this follows from simple estimates. Let us take the mass of a cluster of galaxies to be M, and the number of galaxies of equal mass to be N. The masses of the galaxies that comprise the cluster and the mass of the cluster itself determine its size $r \approx 2m^{1/2}$ [17]. In this case, the characteristic time τ between collisions of galaxies in the cluster will be $\tau = 10^9 M_{15}^{1/4}$ years, where M_{15} is the mass of the cluster measured in units of $10^{15}\,M_{\odot}$. As a result, over the Hubble time (i.e., during a lifetime), each of the cluster galaxies will experience several collisions with other galaxies in the cluster. The outcomes of such collisions depend on the nature of the galaxies and the relative velocity of the colliding galaxies. For example, some of the colliding galaxies can supply extragalactic stars to the cluster field. Let us consider the effects of collisions that lead to the appearance of stellar streams in galaxies and their clusters.

Clear evidence that our Galaxy actively absorbed some of its satellites in the past epochs is the existence of an extensive population of stars with spatial retrograde rotation (i.e., reverse rotation) of the main mass of the disk and bulge of the Galaxy. The first to notice such stars were Parenago [28] and Vorontsov-Vel’yaminov [29]. Modern studies have shown that the retrograde stellar population of the Galactic consists of the products of absorption of low-mass satellites by the Galaxy. In addition to kinematics, this population is distinguished by a low abundance of heavy elements [30, 31]. The latter is natural for stars of low-mass satellite galaxies absorbed by our Galaxy in the course of its evolution.

The study of the kinematics of Galactic halo stars with a low metal abundance [Fe/H] < -1.0 made it possible to find several distinguished groups of stars with similar orbital parameters [32]. As it turned out, these groups are streams of stars: the decay products of satellite galaxies absorbed by our Galaxy in the past. They clearly demonstrate the features of the assembly process of the stellar bulge and the halo of our Galaxy: halo stars with [Fe/H] < -2.5 are the sum of two almost equal populations with forward and backward orbital rotation around the GC [33]. Most of these stars previously belonged to satellites absorbed by the Galaxy during its formation. A detailed analysis of 23 stellar streams of the Galaxy made it possible to find dwarf galaxies: the precursors of some of these streams [34]. We should mention that eight of the noted streams turned out to be associated with massive globular clusters, probably the former members of the destroyed satellites of the Galaxy.

A detailed analysis of the orbits and chemical composition of 54 low-mass satellite galaxies and globular clusters of our Galaxy [35] showed that at [Fe/H] ≥ -1.0 most of them have a common galactic direction of rotation, a relatively low eccentricity of their orbits (less than ~0.3), and the planes of their orbits are close to the plane of the Galaxy. Satellites with [Fe/H] < -1.0 often have orbits with high eccentricity and retrograde direction of rotation around the GC. The planes of their orbits deviate significantly from the plane of the Galaxy. We should also add that the pericenters of the orbits of the studied satellites are in the range of 0.5 to 30 kpc, and the apocenters are in the range of 2 to 100 kpc [35]. Another evidence of the active role of mergers in the evolution of the Galaxy is the presence of stars in the Galaxy with velocities close to or exceeding the escape velocity of ~445 km/s [36].

Let us consider the observed consequences of collisions and mergers of galaxies. Figures 1 and 2 show the scenarios of these processes. Most galaxies are members of their dense clusters. The example of our Galaxy shows that massive galaxies are immersed in a cloud of their satellites, the number of which reaches multiple tens [37]. During the evolution of a cluster, high-velocity collisions clear galaxies of gas, which may be the cause for the appearance of S0 galaxies [38]. These circumstances make the encounters and collisions of galaxies ordinary events in their lives.

Collisions with low relative velocities and gravitational deceleration lead to the merger of galaxies, and the latter leads to several observed consequences, for example, retrograde rotation of part of the stars in gal-

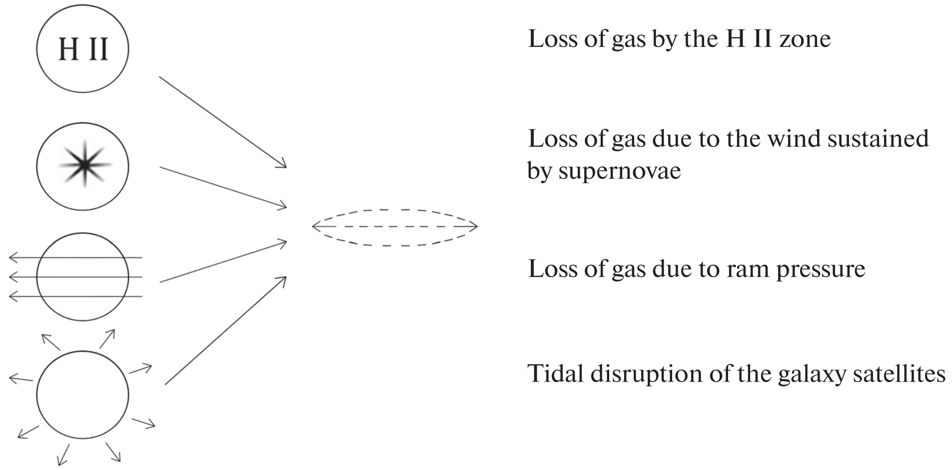

Fig. 1. Variants of the destruction of galaxies with their transformation into stellar streams.

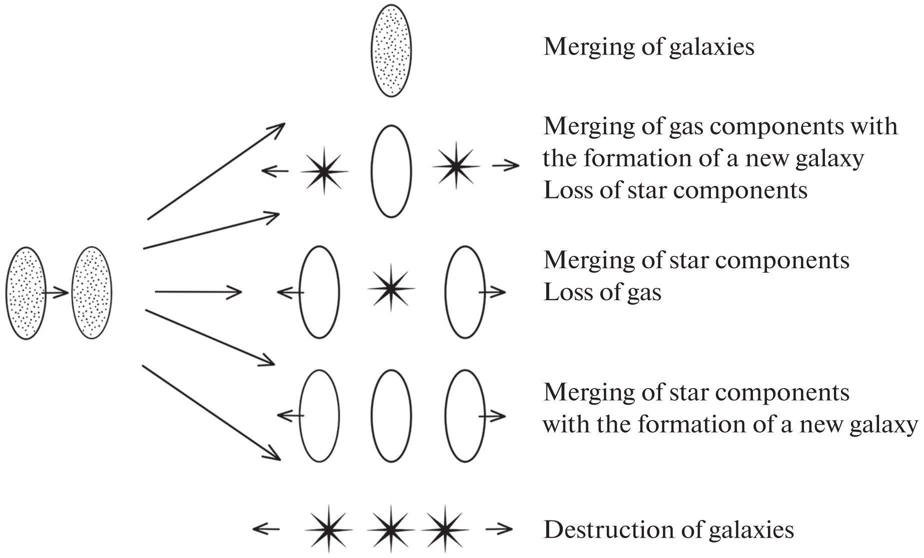

Fig. 2. Scenarios of disc galaxy collisions.

axies [24, 39] and the appearance of double galactic nuclei [40]. A detailed analysis of the chemical composition of the stars made it possible to establish that the retrogradely rotating stars of the Galaxy have metallicity an order of magnitude lower than the rest of the stars [41]. In addition, the merger of galaxies explains the presence of double and off-center nuclei in a significant number of observed galaxies [40]. Accretional activity of some quasars is provided by mergers of dense nuclei of colliding galaxies [42]. The formation of new galaxies from the gas components of colliding galaxies (Fig. 2) may in the future explain the appearance of galaxies without a dark halo [43].

3. STAR STREAMS AS PRODUCTS OF DESTRUCTION OF GALAXIES AND THEIR SATELLITES

3.1. Destruction of the Stellar Component of Galaxies

The widespread occurrence of relatively narrow stellar streams located near galaxies raises the question of the conditions for their appearance [27]. A possible scenario for the appearance of such streams is associated with the destruction of one of the interacting galaxies (Fig. 1). Observations have shown [44] that up to 20% of the light from stars in clusters of galaxies belongs to the continuous stellar background of these clusters and cannot be directly associated with galaxy members of the clusters. For various reasons, a significant part of galaxies in clusters disintegrate in the course of their evolution, thus forming a continuous stellar background of the cluster.

The Leo Ring cloud is an example of the gaseous component of a galaxy destroyed in collision [45]. Here, a giant gas ring (with a radius of approximately 10^5 pc) of neutral hydrogen is devoid of stars and has an almost solar abundance of metals. The mass of neutral hydrogen in this ring is $\sim 2 \times 10^9 M_{\odot}$, and the expansion rate is ~100 km/s, which corresponds to an age of $\sim 10^9$ years. The occurrence of such a ring may be caused by a burst of star formation in the disk precursor galaxy or a collision of two galaxies at hyperbolic velocities. These processes could significantly reduce the mass of the galaxy, "freeing" its gas component.

The role of a galaxy cluster in the stellar halo formation of massive galaxies was quantitatively estimated in [46] using the example our Galaxy. The study of degenerate dwarfs close to the Sun made it possible to establish that approximately 15% of them are relatively young (their age is several billion years), but they have high spatial velocities corresponding to the stars of the Galactic halo. Since the formation of "native" halo stars was completed approximately 10–12 Gyr ago, young degenerate halo stars are probably the decay products of young dwarf satellites of the Galaxy that were absorbed by it in the course of evolution.

3.2. Intergalactic Stellar Streams, Magellanic Clouds and the Andromeda Nebula

Let us consider the possible causes and scenarios for the destruction of the stellar component of the galaxy with its transformation into a stellar stream during evolution or collision with another galaxy. The question of the existence of a stellar stream was first risen by M. Flammarion, who found a linear group of stars and nebulae in the Pleiades associated in some way with that cluster [47]. The answer to the question of the nature of stellar streams in galaxies and their surroundings is also not new. Nearly a hundred years ago, the synchronous spatial motion of stars was attributed to the disintegration of star clusters [48–50]. In recent years, due to significant improvement in observational and theoretical instrumental capabilities, the observational study of the morphology of tidal phenomena and the physics of stellar streams, including those located near galaxies, has attracted great and comprehensive attention. Particular attention is paid to the so-called Magellanic Stream, a gas-stellar structure that links the Magellanic Clouds and our Galaxy. It covers approximately 200 degrees of the southern sky [51] and includes star clusters, along with gas and stars. Numerical modeling makes it possible to establish a picture of the formation of this structure during the past encounter of the Magellanic Clouds with our Galaxy [52, 53]. It is possible that the Magellanic Clouds approached the Galaxy regularly, which complicates the observed picture and, naturally, the attempts to interpret it using models. The study of the Magellanic Stream and other stellar streams makes it possible to see the picture of tidal phenomena in the world of galaxies "from the inside," assessing the role of the dark component of the Galaxy in its morphology.

Examples of disintegrating globular clusters observed as extended structures resembling "star spears" in their outlines (Palomar 5 and Palomar 15) with sizes of tens of parsecs [54, 55] give a picture of the consequences of tidal destruction of relatively weakly connected stellar systems. In addition, it is possible that these clusters are nuclei of tidally disrupted dwarf galaxies. The latter continuously replenish the stellar population of the Galactic halo. Currently, there are more than 40 stellar streams known in the Galaxy [56]. The study of the stars in the Galactic halo with $[\mathrm{Fe/H}] < -2.0$ makes it possible to find kinematic stellar streams among them [26]. An analysis of the [O/Fe] and [Fe/H] values of the halo stars led to the discovery of groups of stars with low metallicity, distinguished by their chemical composition, belonging in the past to nearby low-mass galaxies. The bimodality of the distribution of low-metallicity stars in the [O/Fe] ratio [26] is a likely consequence of the mixing of the oldest stars in the Galaxy with the stars of the companion galaxies it absorbed [57]. They are continuously absorbed by our Galaxy during its evolution in the Local Cluster [58].

The most complete study of stellar streams in our Galaxy to date was carried out in [59] on the basis of the Gaia DR2 and Gaia EDR3 catalogs. Streams associated with eleven globular clusters, including ω Cen, were found. The length of the observed part of the streams ranges from few to one hundred degrees of the celestial sphere. Some of the stellar streams probably do belong to dwarf galaxies disrupted by the tidal forces of our Galaxy. This is evidenced by the low abundance of iron, not exceeding 10% of solar. The authors come to the conclusion that the halo of our Galaxy, woven from the filaments of stellar streams, resembles "a ball of wool." This conclusion is also relevant for the stellar component of the halo and other galaxies, as well as for the stellar environment of the field of galaxy clusters.

The study of the nearest massive neighbor of the Galaxy, the Andromeda Nebula, is indicative [60, 61]. Within 150 kpc of the latter, there are several arc-like stellar formations visible, including six globular clusters. These arcs are likely products of the tidal decay of the Andromeda satellites with the formation of stellar streams up to 120 kpc in length in the halo. Comparison of the halo structures of our Galaxy and the Andromeda Nebula suggests that the destruction of satellites of massive galaxies plays an important role in the morphology of their stellar halos. A detailed study of the periphery of neighboring galaxies revealed that stellar streams of rare forms and different observed brightness are very diverse, which, for example, was demonstrated in [62–66]. They form various types of arcs and rings around their galaxies. The tidal destruction of nearby satellites of galaxies is recognized as the cause of their formation.

4. CAUSES OF DESTRUCTION OF GALAXIES AND THEIR SATELLITES

4.1. Motion Effects of Galaxies in a Gaseous Environment

Let us consider the possible causes of the destruction of cluster galaxies that ultimately lead to the appearance of stellar streams of gravitationally unrelated stars (Fig. 1). Among them are the interaction of galaxies with a dense gaseous medium of galaxy clusters, collisions of galaxies, and bursts of star formation in them leading to the loss of a massive gaseous component. The observed example of the interaction of disk galaxies with the gaseous medium of their clusters is the so-called "jellyfish" galaxies mentioned above. They exhibit an umbrella morphology and active star formation at the edges. An active increase in the observational base for jellyfish galaxies [67] and three-dimensional gas-dynamic models of the interaction of inhomogeneous gas disks of galaxies with a dense gas of the medium [68–70] made it possible to visualize this phenomenon. A list of eleven galaxies of this type is given in [70]. The length of the gas-stellar tails of galaxies reaches 100 kpc, which at a motion velocity of the galaxies of 300 km/s corresponds to the time of their formation of 3×10^8 years. Estimates show that this time is sufficient for the cooling of the heated gas and the formation of stars in the gas flowing around the dense core of the parent cluster of galaxies (1).

The loss of the peripheral regions of the gas disk of galaxies explains the appearance of rings of young stars around such galaxies, which are probably not gravitationally associated with them [15]. The result of this process will be the formation of long narrow stellar tails of galaxies moving in a dense gaseous medium. In addition, it is easy to imagine that rapid movement in a dense gaseous medium can lead to a complete loss of gas by the galaxy. Let us find the condition for this phenomenon. Within a single-zone homogeneous galaxy model, the condition for loss of gas (with an average density ρ_g) by a galaxy due to the pressure of the oncoming gas of the medium with the density ρ_0 will be

$$\frac{v}{v_K} > \left(\frac{\rho_g}{\rho_0}\right)^{1/2}, \tag{3}$$

where v is the spatial velocity of the galaxy, and v_K is the Keplerian velocity at the edge of the galaxy. It is clear from this formula that, under condition (3), fast galaxies with a low surface gas density in the dense gaseous medium of the nuclei of galaxy clusters can indeed lose their gas. It becomes clear that elliptical or S0 galaxies of dense clusters can lose gas not only under the influence of SNeIa, but also due to the "ram pressure" of intergalactic gas (Fig. 1). The rapid removal of galactic gas in the dense cores of galaxy clusters leads to a number of interesting consequences, which are shown in Fig. 1. If the mass of gas in the galaxy was smaller than the mass of stars, then the gas-deprived galaxy would turn into an E or S0 galaxy without star formation and with the wind supported by supernovae of the first type (SNeIa) and the gas pressure of the environment. Observations support the possibility of formation of at least part of E galaxies in the course of collisions of their predecessors [71].

If the mass of stars in a moving galaxy was smaller than the mass of gas, the rapid loss of gas by such a galaxy will lead to the decay of its stellar component with the eventual transformation of the latter into a stellar stream along the galactic orbit within its cluster. The mass of gas in disk galaxies of low mass ($M < 10^{10}\,M_\odot$) is often comparable to the mass of their stars [72]. This process is also possible for satellites of massive galaxies, the loss of gas of which is initiated by the strong galactic wind of the latter. This wind can also be caused by a collision of galaxies, which increases the rate of star formation in them and the strength of the galactic wind tenfold [72]. Collisions leading to an increase in the rate of star formation simultaneously lead to a sharp increase in the frequency of supernova explosions associated with the end of the evolution of massive $M \geq 8\,M_\odot$ stars. This can also lead to the loss of gaseous components of colliding galaxies and the subsequent destruction of their stellar components [73] with the transformation of the latter into stellar streams.

Einasto et al. [74] found that nearby satellites of the Galaxy belong, as a rule, to E galaxies, while distant satellites are irregular galaxies and disk galaxies with gas and star formation. It is natural to assume that nearby satellites have repeatedly crossed the dense gaseous disk of our Galaxy in the past and have lost their gaseous components, becoming E galaxies. Furthermore, distant satellites, whose orbits lie far from the dense gaseous disk of the Galaxy, retain the possibility to hold gaseous disks in which star formation is sustained. The study of the mass spectrum of satellites of massive galaxies showed that it can be represented by the function $dN/dM \sim M^{-5/4}$ [75]. The reduced slope of the mass function of the satellites, in comparison with the classical one, equal to –2 [2], may indicate the disruption of low-mass satellites in the course of interaction with central galaxies and their absorption by massive galaxies. Thus, collisions of galaxies with the participation of intergalactic gas of a galaxy cluster play an important role in determining the fraction E of galaxies (devoid of gas and star formation) [76].

The destruction of satellites of galaxies can lead to another interesting consequence. It has been repeatedly noted that the number of metal-poor stars in the Galaxy should be expected with closed evolution [77]. It is possible that the absorption of the evolved gaseous component of nearby satellites and intergalactic gas can change the course of the chemical evolution of the galaxy and explain the deficit of stars with low metallicity, thereby solving the well-known "G-dwarf problem."

4.2. Initiation of Bursts of Star Formation in Galaxies

The collision of galaxies can lead to star formation in the total gas with the disintegration of the newly formed star system. Examples of such collisions are the Taffy system (UGC 1294/5) and Arp 194 [78], which show star-forming gas structures between two stellar disks. The destruction of galaxies during their collisional evolution in clusters is a common phenomenon in the world of galaxies, continuously replenishing the extragalactic environment of clusters with stars.

The star formation rate, regulated by hydrogen ionization, was estimated in [79] as $\frac{d\rho_g}{dt} = -5\times 10^7 \rho_g^2$, where ρ_g is the gas density. Considering the observed correlation $M \cong 0.2R^2$ [17], where M and R are the mass and radius of the galaxy, at $M \le 10^7\ M_\odot$, we find that the characteristic star formation time will be shorter than the Keplerian time. As a result, a spherically symmetric galaxy, having lost most of its mass in the form of gas during the initial burst of star formation, can decay, thus turning into a stellar stream. Observations confirm the role of the encounters of galaxies in the activation of star formation in them [80]. The decay of a significant part of low-mass galaxies helps, in addition, to understand the reason for the decrease in the slope of the mass function of galaxies [17].

Thus, a very likely mechanism for the decay of young, gas-rich galaxies is the initial burst of star formation, which is also shown in the diagram in Fig. 1. The conditions for this phenomenon, as indicated above, are the compactness and spherical symmetry of a young galaxy. The latter condition allows us to consider the transfer of the kinetic energy of the envelopes of exploded supernovae to the energy of motion of the gas component of the galaxy to be effective. The characteristic kinetic energy of the envelope of a massive supernova is $\sim 10^{50}$ erg. The gravitational energy of the gas component of the galaxy at $M = 0.2R^2$ [17] is $\sim 10^{59} M_{11}^{3/2}$ erg. If we take the Salpeter initial mass function of stars $dN/dM \sim M^{-2.35}$, we can find that for one massive supernova with a mass greater than $10\ M_\odot$, there is $\sim 100\ M_\odot$ of less massive stars with $M > 1\ M_\odot$. Hence, it follows that with a mass of young stars greater than $M_{11}^{1/2}$ of the fraction of the total mass of the galaxy, the energy of supernovae—the products of a star formation burst—is sufficient to rid such a galaxy of a gas component with a mass of the order of the mass of the galaxy. That is, for galaxies with mass $\sim 10^7\ M_\odot$, the transformation into stars of only ~0.01 of the entire mass of its gas component is sufficient to rid it of the gaseous component and, therefore, destroy its stellar component. Observations show that galaxies with gas masses exceeding the mass of stars are common among galaxies with a total mass below $\sim 10^{10}\ M_\odot$ [81]. The efficiency of this mechanism depends on the degree of symmetry; ordinary disk galaxies release excess supernova energy by means of the polar wind. The stellar component of the galaxies destroyed in this way transforms over time into a stellar stream and replenishes the field of the cluster's intergalactic stars.

A burst of star formation in low-mass satellites of massive galaxies can be triggered by tides. If the satellite's orbit is sufficiently elliptical, the burst can occur upon an increase in the rate of star formation in the pericentric part of the orbit. Probably, this can explain the short, $\sim 5\times 10^8$ years, burst of star formation in the faint ($M_V = -7^m$) dwarf galaxy Eridanus II, a satellite of our Galaxy [82]. Another example is the BOSS–EUVLG1 galaxy [83] with a mass $\sim 10^{10}\ M_\odot$ and star formation rate $\sim 10^3 \frac{M_\odot}{\text{year}}$. The observed rate of gas loss by this galaxy is $\sim 50 \frac{M_\odot}{\text{year}}$. This gas loss rate is sufficient for a significant reduction in the galaxy's mass in a time comparable to its Keplerian time. This can not only significantly expand the galaxy, turning it into an LSBG, but also destroy it, eventually turning it into a stellar stream.

It is interesting that bursts of star formation can be caused by the immersion of galaxies in the dense gaseous medium of the cores of their clusters, as demonstrated by the analysis of forty observed galaxy clusters [84]. A burst of star formation in a spheroidal gaseous protogalaxy with a mass $10^6\ M_\odot$–$10^{11}\ M_\odot$ along with direct collisions of galaxies turns out to be an effective mechanism for the formation of E and S0 galaxies with the subsequent possible destruction of their stellar components.

For young galaxies and star clusters with masses below $\sim 10^6\ M_\odot$, there is another possibility of the loss of the gas component [85]. This can happen due to the gas being swept away by stellar winds or zones of ionized hydrogen. Considering the relation $M = 0.2R^2$ [17], the characteristic velocity of motion of stars in the galaxy is described by the formula $v \approx 2.5\times 10^7 (M_{11})^{1/4}$ cm/s. The expansion rate of HII zones is approximately 10^6 cm/s. Therefore, removal of more than half of the mass of a system with a mass below $\sim 10^6\ M_\odot$ by the pressure of ionized hydrogen will lead to the disintegration of the stellar component of this system.

The main conclusion of the above analysis is that, regardless of the mechanism of decay of stellar systems (expansion of HII zones as the cause of sweeping out of gas or a burst of star formation with explosions of massive supernovae), a dense gravitationally unbound cloud of stars appears as a result of the collision of gas-rich galaxies. The further evolution of this cloud depends on its environment. The disintegration of a single galaxy in a galaxy cluster leads to the transformation of its stellar component into a stellar stream along the orbit of that galaxy in the cluster. The time of disruption of such a stream due to a collision with a galaxy can be estimated as follows. Let us assume that a stationary galaxy cluster with mass M and radius R consists of identical galaxies with mass m and radius r. Dispersion of velocities of stars in a disintegrated galaxy $v = \sqrt{\frac{Gm}{r}}$, and the velocity of stream stars and cluster galaxies $V = \sqrt{\frac{GM}{R}}$. Let us assume that the condition for the decay of a stellar stream will be a change in the velocities of its members during evolution by the value of the initial dispersion of the stars under the influence of encounters with the cluster galaxies. Simple analytics leads to the following estimate of the lifetime of a stellar stream from a disintegrated galaxy:

$$\tau = \frac{R}{r}\frac{R^{3/2}}{G^{1/2}M^{1/2}} = \frac{R}{r}\tau_d \approx \tau_d\left(\frac{M}{m}\right)^{1/2}, \qquad (4)$$

where G is the gravitational constant, $\tau_d = R/v$ is the characteristic dynamic time of a galaxy cluster. At $M = 0.2R^2$ and $m = 0.2r^2$, this estimate becomes $\tau_d = 4\times 10^{10}\frac{M_{15}^{3/4}}{m_{11}^{1/2}}$ years. Obviously, with the characteristic masses of disintegrated galaxies $10^7\ M_\odot$–$10^{11}\ M_\odot$ and clusters $10^{13} M_\odot$–$10^{15} M_\odot$, this time exceeds the Hubble time. As a result, we come to the conclusion that free stellar streams from disintegrated galaxies can persist over the Hubble time. And the stellar environment of galaxies in their cluster, making up half of its mass, is represented mainly by stellar streams, the degree of evolution of which depends on their age. The observational identification of these streams is complicated by their low brightness [86].

The analysis of the observed stellar streams near galaxies makes clear that some of the streams are located at distances much larger than the optical dimensions of nearby galaxies [65].

4.3. Tidal Destruction of Galaxies

Let us estimate the conditions for tidal destruction of satellite galaxies in the gravitational field of a central galaxy with mass M_0 and radius R_0. The values of the latter are related as $M_0 = 0.2R_0^2$ [17]. Tidal decay begins when the average density of a satellite of smaller mass $\frac{m}{r^3}$ becomes equal to tidal density $\frac{M_0}{R_0^3}$. We will take the satellite radius to be $r = kR_0$. LSBGs often have k values up to 10 [87, 88]. Now, the condition for the satellite to fill its Roche lobe (the condition for the onset of its destruction) becomes as follows: $\frac{d}{R_0} < k\left(\frac{m}{M_0}\right)^{1/3}$, where d is the distance between the galaxies. That is, the destruction of the satellite begins at $k > \left(\frac{M_0}{m}\right)^{1/6}$, which occurs when the small galaxy approaches the central galaxy at a distance shorter than the radius of the latter. This circumstance creates a condition for the formation of stellar streams with a length that noticeably exceeds the apparent dimensions of the galaxies around which they are observed. Compact, high-density galaxies can immerse deep into a massive galaxy without disrupting the galaxy or themselves. This leads to the appearance of galaxies with double nuclei [89], "alien" globular clusters of stars, and "alien" stars in galaxies.

5. TIDAL DECELERATION OF GALAXY SATELLITES

The analysis of the conditions for galaxy mergers and the conditions for the existence of satellites of massive galaxies should consider the conditions of tidal deceleration of their motion in a gravitating medium. This process leads to their capture by massive galaxies. This phenomenon is very common in the world of galaxies. It is possible that the popular, most massive globular cluster ω Cen is the core of a nearby satellite absorbed by our Galaxy.

The magnitude of the deceleration force acting on a body moving in a gravitating medium was first found by Chandrasekhar [90]. It can be estimated using a simple model that follows. Let a point-like body with mass m move with a velocity v in the field of point-like gravitating bodies, the average density of which is ρ. The motion of bodies of the medium within a cylinder with a radius $r = Gm/v^2$ will be perturbed by the gravity of a moving object. As a result, they are concentrated in the trail of the latter. A gravitating force F

arises, which decelerates the movement of the body. Its magnitude $F \approx G\rho m r \approx \frac{G^2 m^2}{v^2}\rho$, where G is the gravitational constant. The characteristic time of deceleration of a moving body or the time it takes for its velocity to change by the value of the velocity itself in a galaxy with mass M is:

$$\tau = \frac{v^3}{G^2 \rho m} \approx \tau_d \frac{M}{m}, \tag{5}$$

where τ_d is the Keplerian relaxation time.

Equation (5), which was obtained by Chandrasekhar in 1943 [90], also includes a logarithmic factor on the order of unity, which considers the rearrangement of the field bodies outside the zone of influence of the moving mass m. Substituting the parameter values characteristic for galaxies into relation (5), we obtain

$$\tau = 3 \times 10^7 (M_{11})^{1/4} \frac{M}{m} \text{ years.} \tag{6}$$

The average density of galaxies increases approaching the galactic nucleus as R^{-2} at a constant rotation velocity of the galaxy.

Therefore, at $\alpha = \frac{R}{R_0}$ Eq. (6) can be written as

$$\tau = 3 \times 10^7 \alpha^2 (M_{11})^{1/4} \frac{M}{m} \text{ years.} \tag{7}$$

The latter condition allows us to understand the general picture of the deceleration of galaxy satellites in the parent galaxy. It is clear that effective deceleration requires a large mass of the decelerated satellite and its proximity to the dense core of the galaxy. The result of the process of deceleration and merging of galaxies can be observable galaxies, the nuclei of which rotate in the direction opposite to the rotation of the galaxy itself.

It should be noted that the absorption of satellite galaxies leads to the expansion of the absorbing galaxies, because the decrease in the kinetic energy of the satellites occurs due to the growth of the internal energy of these galaxies. The result of this process is the appearance of LSBGs [91]. Some of the latter consist of old red stars, while some also include young stars [92]. The absorption of massive satellites along with the loss of gas by galaxies is one of the ways leading to the appearance of LSBGs. The study of distant ($z > 1$) young galaxy clusters revealed that the fraction of LSBGs in them is three times lower than in modern clusters [93]. This is consistent with the collisional mechanism of their formation. Collisions of disk galaxies at hyperbolic velocities are another possibility for the formation of LSBGs [73, 94]. In this case, the total gas component can become a young LSBG, while the stellar components can become red galaxies of this type (Fig. 1).

The analysis of Eq. (6) leads to the conclusion that the characteristic deceleration time strongly depends on the velocity of the decelerated galaxy relative to the main mass of the galaxy. In massive galaxies with $M \geq 10^{10} M_\odot$, most of the mass belongs to the dark halo [43, 95]. As already mentioned, the study of the stellar streams of the Galaxy revealed that some of them move in the direction opposite to the rotation of the stellar component of the Galaxy [96]. This, firstly, indicates the extragalactic nature of some of the stellar streams and, secondly, allows us to hope for a detailed analysis of the kinematics of stellar streams in the Galaxy as a method for estimating the rotation rate of its dark halo.

6. STELLAR STREAM MODELS

6.1. Condition for the Appearance of Stellar Streams

The initial condition for the appearance of stellar streams in galaxy clusters is the collision of the galaxies, leading to their partial or complete disintegration (Fig. 2). The condition for the merger of galaxies is their low relative velocity. The formation of new galaxies is possible if the gas components of disk galaxies have high density. The condition for the decay of collision products of disk galaxies is the positive binding energy of their stellar components. The collision results of two identical disk galaxies with gas components are illustrated in Fig. 2. The outcome of the collision depends on the initial velocity of the galaxies and the fraction of the gas component in the total mass of the galaxy.

The force acting on any body moving in the Galaxy depends on the local gradient of the Galaxy's gravitational potential. The study of the rotation curves of galaxies has clearly shown that the latter cannot be reduced to the potential of a gravitating point, as in the two-body problem, but has a more complex structure [97]. Sometimes, to solve the problem, it was sufficient to "smooth" the potential of a point in the center of the galaxy in order to avoid large accelerations [98]. Considering the constancy of the rotation rate of disk galaxies inevitably leads to the appearance of a logarithmic factor in determining the potential: $\varphi \sim \ln R/R_0$ [99]. Considering the disk character of galaxies leads to the appearance of a two-dimensional potential [100]. Rejection of the one-dimensional potential of a gravitating point significantly complicates the shapes of the orbits of satellites of galaxies in the gravitational field of a massive galaxy [101], contributing, as we will see later, to the disruption of stellar streams in massive galaxies through their expansion. Let us consider the conditions for the appearance of stellar streams in the collision of galaxies. They are based on the condition of the density of the satellite galaxy becoming equal to the tidal local density of the parent galaxy with mass M, or the radius of the satellite galaxy becoming equal the radius of its Roche lobe.

The radius of a satellite galaxy with mass m can be written as $r \approx 2Km^{1/2}$ [17]. Here, K is a parameter which indicates the deviation of the galaxy radius from the standard one. The radius of the Roche lobe r_R of a satellite galaxy within a parent galaxy with a mass M_R is $r_R = 0.4\left(\frac{m}{M_R}\right)^{1/3} d$, where d is the distance from the parent galaxy. Comparing the two radii, provided that the rotational velocity of the parent galaxy is constant, we find that at

$$\frac{M_R}{M} < K^{3/2}\left(\frac{m}{M}\right)^{1/4} \tag{8}$$

the satellite fills its Roche lobe and begins to disintegrate. In the case of elliptical orbits of satellites, this occurs when they are immersed in the dense nuclear regions of the parent galaxies. The density gradient of the satellite galaxy makes this process gradual, as a result of which the satellite first acquires a stellar "spear," and upon the passage of the pericenter of its orbit in the dense core, the satellite decays and turns into a stellar stream. Noteworthy is the large dependence of the satellite immersion depth on its initial density. Globular clusters penetrate even the dense nuclei of galaxies, while low-density galaxies are disrupted at the periphery.

6.2. Model of the Evolution of a Galaxy's Disrupted Satellite

To calculate the orbit of a satellite galaxy, we used the *galpy* package [102] written for the Python programming language. The Milky Way Galaxy is represented by a three-component model, which includes a halo (radius 16 kpc), a disk, and an ellipsoidal bulge (size 3 by 0.28 kpc). The total potential includes the components of the potential of the disk, spherical halo, and bulge of the Galaxy. The bulge and disc are described in accordance with the expressions of Miyamoto–Nagai [100]. The spherically symmetric spatial distribution of the dark matter density in the halo is described by the Navarro–Frenk–White potential [99]. The effects of spiral density waves and a supermassive black hole in the center of the galaxy were not considered. We also did not consider dynamic friction. When the mass of the galaxy is below $\sim 10^{10}\,M_\odot$ (Eq. (7) from [103]) the friction effect is insignificant. The galactocentric distance of the Sun was taken equal $r_0 = 8.2$ kpc [104], the orbital velocity of the Sun was taken equal $v_0 = 232.8$ km/s [105].

It is important to note that in fact we would like to consider a 2D model of a flat orbit; however, this is not possible. Any potential satellite orbit, which, as it would seem, should lie in the plane of the Galaxy, due to the large distance of the initial position of the satellite from the GC and from the Galactic plane, strongly oscillates along the Z coordinate.

For the calculations, with results shown in Fig. 3, we selected the orbit of the satellite galaxy with the initial coordinates and spatial velocity components in a rectangular galactocentric coordinate system: $XYZ =$ (13, 7.5, 4.6) kpc, $UVW =$ (0, 250, 0) km/s. In the equatorial coordinate system, the initial position of the satellite is RA = 90°, DEC = 90°. The coordinate axes are oriented as follows: the X axis points toward the center of the Galaxy, the Y axis in the direction of rotation of the galactic disk, and the Z axis to the north pole of the Galaxy. The directions of the spatial velocity components are the same.

To visualize the motion pattern of the satellite, we used a simple cloud model consisting of 1000 points. The points represent gravitationally unbound stars, star clusters, gas clouds, and OB associations flying apart. The orbital motion of the cloud representing a satellite galaxy is modeled by solving the equations of motion for the points and displaying the results as a 3D orbit constructed over a given time interval. The points, which represent the decay products of the satellite galaxy (stars, star clusters, stellar associations, and simply gas clouds) and are initially located outside the galaxy, move through space at different velocities. The directions of the velocities of the scattering points relative to the center of the cloud are uniformly distributed over the sphere; the modulus of the spatial velocity of the scattering is taken equal to 30 km/s.

Figure 3 shows the results of the evolution of the stellar stream up to 10 Gyr for the model with the initial calculation conditions indicated above. On the leftmost panels in Fig. 3, we see that over 1 Gyr the satellite gradually turns into a stream stretched by approximately 30 kpc. The lost products leave the satellite and form a loop-like stream. The length of the stream depends on the integration time. It should be noted that the stream shown in Fig. 3 (left pair of panels) is similar to the stellar stream of the galaxy NGC 5907 [65].

It is easy to notice in Fig. 3 that over the Hubble time of 10 Gyr, the stream is almost completely scattered at the periphery of the Galaxy, becoming part of its halo. It is noticeable that the density of the points representing the decay products is not uniform in space. The condensations show the remainder of the stream split into several parts. One part fills the region near the bulge, while the rest of the stars fill the halo almost completely up to a radius of 40 kpc. There is a visible chaotization of the stream with time caused by the deviation of the potential from spherical symmetry.

In Fig. 4, a variant of the meridional orbit of a satellite incident from the north pole to the GC is considered. There are satellite galaxies that cannot counteract the Galaxy's gravity and fall on it (the incident velocity can reach 400 km/s). An example of such a fall

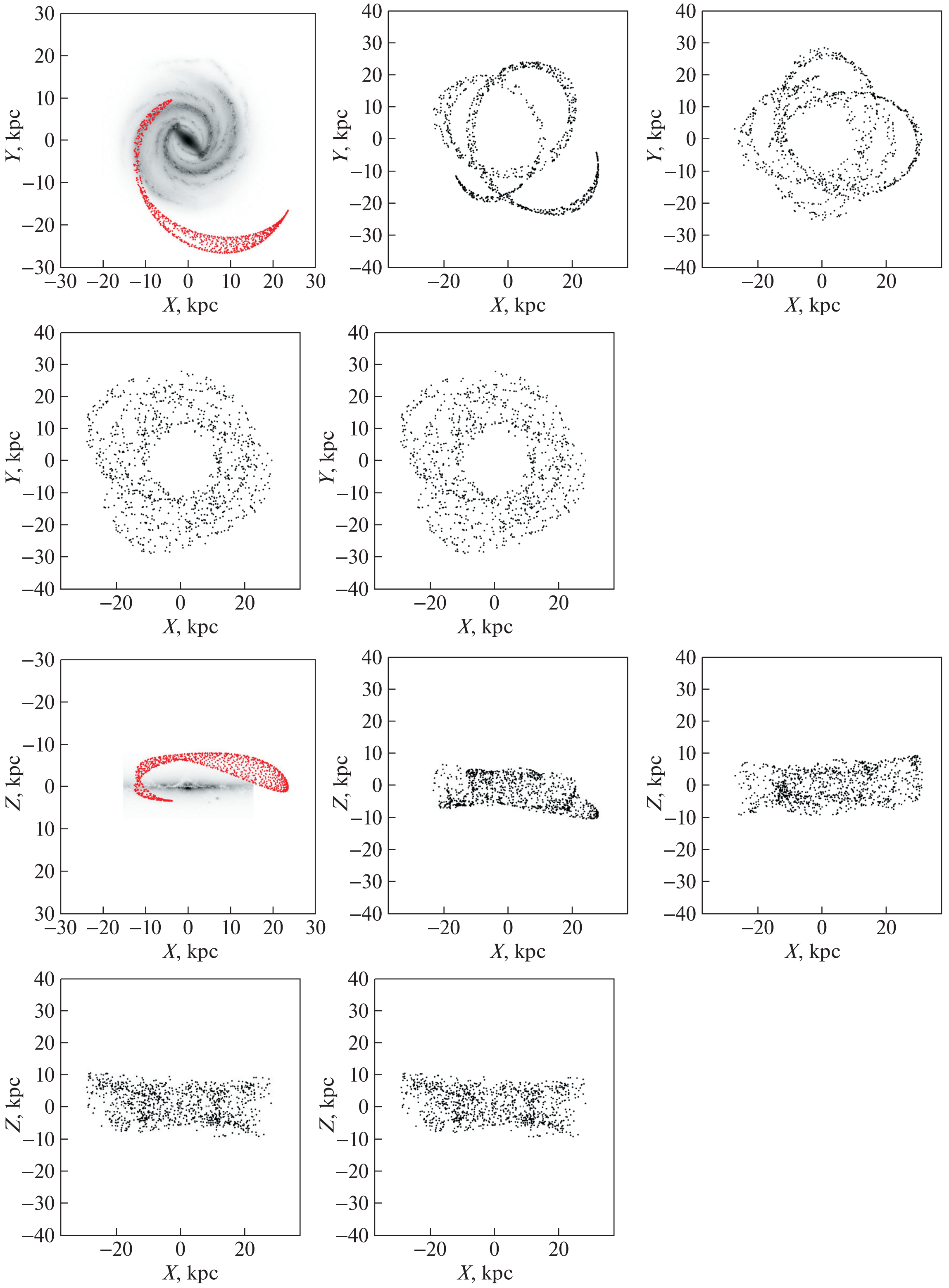

Fig. 3. Calculation results up to the time of 10 Gyr. The pairs of panels (top panel is the *XY* projection; bottom panel is the *XZ* projection) from left to right show the stages of the evolution of the cloud in time for 1, 3, 5, and 10 Gyr. The image of the galaxy courtesy of the *Python* library and *galpy* (https://github.com/henrysky/milkyway_plot). Evolution of a stellar stream generated by a hypothetical satellite passing through the center of the Galaxy. The points represent the stars and star clusters lost by the satellite. The initial values of the spatial velocity components *U*, *V*, and *W* are distributed normally with a maximum of 30 km/s. At the initial time point, the satellite was at a distance of 15 kpc from the GC. Then it moved at a velocity *UVW* = (0, 250, 0) km/s. The distance at the periapsis is 12 kpc from the GC. It can be seen that in the process of destruction, stars and star clusters eventually replenish the stellar population of the halo and bulge of the Galaxy.

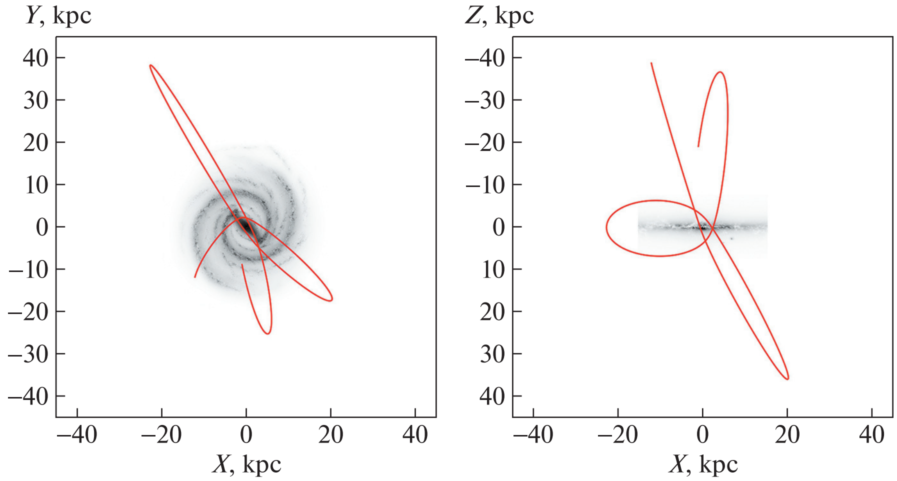

Fig. 4. Radial (i.e., passing through the GC) orbit of the Tucana III satellite of the Milky Way. The projections of the orbit of the Tucana III galaxy over an interval of 2 Gyr in past epochs are shown. The satellite approaches from the North Pole of the Galaxy at a speed of 100 km/s. It can be seen that the orbit passes almost through the GC. The arrows show the direction of motion of the satellite.

of an old (13.5 Ga [106]) dwarf galaxy—the satellite Tucana III—is shown in Fig. 4. Tucana III is associated with a stellar stream that has a length of 4.5 kpc; it has lost 69% of its mass, it moves in a radial orbit, and, as we see in Fig. 4, its decay products could become the population of the bulge [106].

The orbital position indicates that Tucana III, according to the calculations, may have passed through the GC in the past. The orbit, passing almost through the GC, significantly changes the angle relative to the plane of the Galaxy in the meridional direction. It reaches 90 degrees. Approaching the bulge (the distance at the periapsis is 2.5 kpc) or even passing through it, Tucana III turns and moves away in an elongated elliptical orbit (eccentricity is 0.9), then returns again and continues to move in a complex closed orbit (Fig. 4).

Figure 5 shows the result of calculating the motion of a satellite galaxy decaying over 10 Gyr. The satellite moves from the North Pole of the Galaxy meridionally to the Galactic disk. We can see that the decay products fill the region perpendicular to the galactic plane. A significant part of the resulting structure is stretched along the *Z* coordinate. A ring-like structure with a blurred outer boundary is formed in the vertical *ZY* plane.

7. DISCUSSION

Galaxies in dense clusters, as shown above, lead an active life. In addition to the evolution of stellar and gas components, which constitutes the main content of life of isolated galaxies, cluster galaxies can actively interact with their neighbors and intergalactic gas. The latter can both supply the central, massive cD galaxies of the cluster with gas, and rid fast galaxies of the cluster of their gas component due to the pressure of the oncoming gas. Collisions of galaxies not only affect the evolution of the stellar and gas components of colliding galaxies, but also stimulate the accretion activity of their central supermassive black holes [107]. The latter, along with recurrent accumulation and accretion of gas by a supermassive black hole in the nucleus of a massive galaxy, is one of the causes of the appearance of quasars in galactic nuclei. This paper is dedicated to another manifestation of colliding galaxies: their destruction with the appearance of relatively narrow stellar streams, a comprehensive study of which has been recently a subject of many papers.

The destruction of galaxies can be caused by bursts of star formation in them and collisions of gas-rich galaxies (Fig. 1). Low-density satellite galaxies may be destroyed due to their tidal interaction with the central massive galaxy. The condition of gravitational capture of low-mass galaxies in the central dense nuclei of massive galaxies due to their tidal deceleration was estimated within a simple model. The end result of the destruction of galaxies with stellar populations is the appearance of a stellar stream along the orbit of the destroyed galaxy near a more massive companion or its orbit in a galaxy cluster. As a result, a detailed study of the halo of our Galaxy has shown that it is actually the sum of relatively narrow stellar streams: the products of the destruction of the former satellites of the Galaxy [60]. Our modeling confirms this conclusion.

The length of a stream depends on its age and the velocity of its members. The ratio of the width of the stellar stream—the product of the destruction of a galaxy satellite—to the final size of the circular stream is close to the ratio of the characteristic velocity of the stars of the destroyed satellite to the characteristic velocity of the stars of the destroying galaxy. At

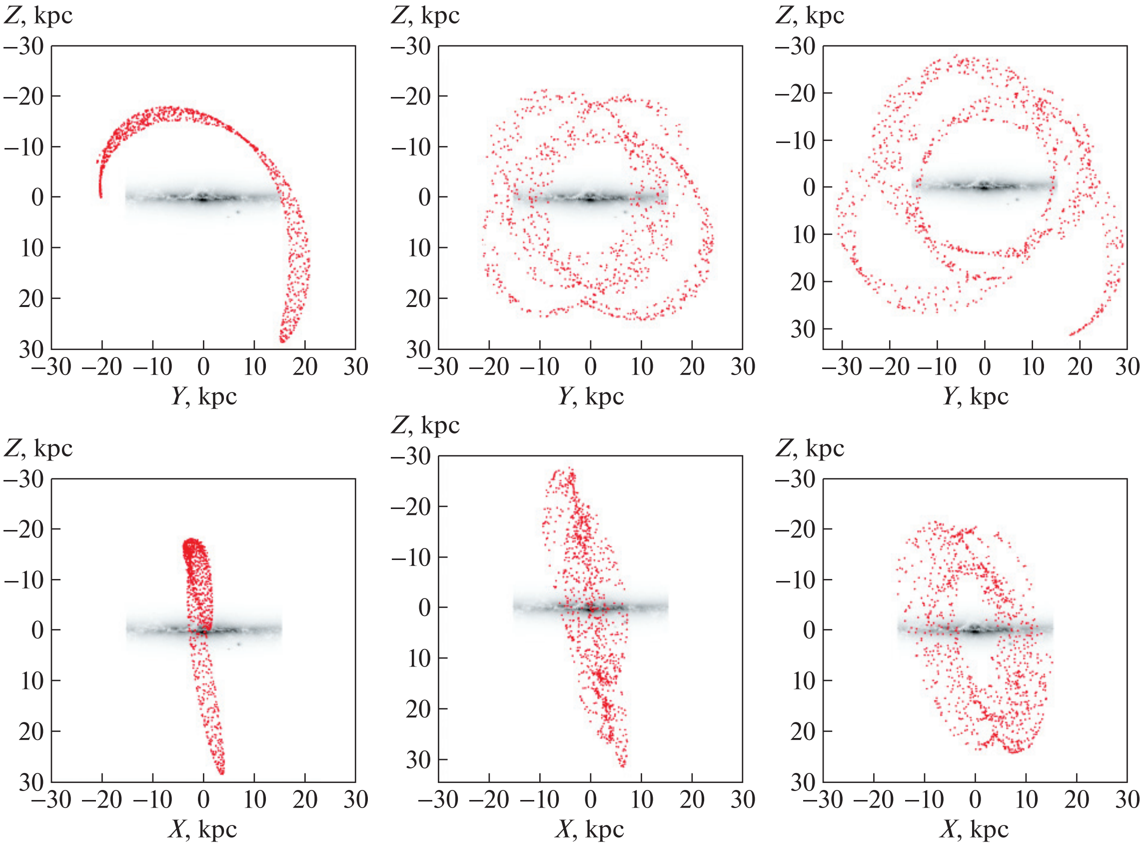

Fig. 5. The result of the disintegration of a satellite penetrating into the Galaxy meridionally ($W = 100$ km/s) along the axis of rotation from the North Pole of the Galaxy. Decay products are shown by dots. The age of the stream is 1, 5, and 10 Gyr.

$M \sim R^2$, the latter ratio is $\sim(m/M)^{1/4}$, where m is the mass of the tidally disrupted galaxy, and M is the mass of the destroying galaxy. The latter ratio can serve as a measure of the mass of a disrupted galaxy turned into a stellar stream. The length of the stream is a measure of its age.

Let us consider the conditions and characteristic time for the dissipation of stellar streams in galaxies. Let the stellar stream be formed as a result of the decay of a galaxy with the velocity dispersion σ. The mass of a large spherically symmetric galaxy containing this stream is M, and its radius is R. The dispersion of the velocities of perturbing objects with mass m will be $v = \sqrt{\frac{GM}{R}}$. The radius of the perturbation zone of the velocities of the stars in the stream at $\sim\sigma$ will be $r = \frac{Gm}{v\sigma}$. The time required for the velocity of the elements of the stream to change by a value on the order of σ or, in other words, considering (2), the time of destruction of the stellar stream τ_d will be

$$\tau_d = \tau_{\rm ff}\left(\frac{\sigma}{v}\right)^2 \frac{M}{m}. \qquad (9)$$

At $M = 0.2R^2$ [17], $\tau_{\rm ff} = 10^5(M_{11})^{1/4}$ years and $\frac{\sigma}{v} \cong \left(\frac{m}{M}\right)^{1/4}$. Relation (9) allows us to understand the role of various gravitational factors in the expansion of stellar streams that occur from the destruction of galaxies. The main factor is the ratio of the mass of the galaxy to the mass of the perturbing elements. For the stars, the ratio $M/m \cong 10^7$–10^{11}, which allows stellar streams in galaxies to "survive" the Hubble time. Stellar streams from the decay of low-mass galaxies in galaxy clusters at $\frac{\sigma}{v} \approx 10^{-2}$ can be destroyed during the Hubble time by the galaxies of this cluster, eventually forming a continuous stellar medium of the cluster's extragalactic stars.

These estimates allow us to assess some parameters of the observed "classical" stellar stream near the galaxy NGC 5907 [56]. The observed ratio of the stream width to the distance from the center of this galaxy ~1/7 makes it possible to estimate the ratio of the mass of the destroyed galaxy to the mass of NGC 5907 as ~1/2500. Since the mass of NGC 5907 is $\sim 10^{11}\,M_\odot$ [56], the mass of the destroyed satellite is $\sim 10^7\,M_\odot$.

Galaxies of such masses at $v \cong 250(M_{11})^{1/4}$ km/s have a velocity dispersion of approximately 35 km/s. At the observed length of the NGC 5907 stream of ~40 kpc [56], its age is estimated at ~10^9 years. The model we obtained (Fig. 4) with this age is close to the observed pattern of the NGC 5907 stream.

To successfully distinguish the stars of the stream from disrupted galaxies against the stellar background of the accretor galaxy, low background brightness is required. This condition makes it obvious why the known stellar streams of galaxies lie, as a rule, in the peripheral regions of galaxies with a low surface brightness of the stellar background. Searching for stellar streams in zones of high surface brightness requires extensive analysis of the kinematics and chemistry of the background stars in order to isolate the stars of the stream. Another circumstance facilitating the search is a burst of star formation in the galaxy at the time it passes the pericenter of its orbit. It is likely that such bursts took place in the Leo I galaxy, as evidenced by the analysis of available observational data [108]. Galaxies disintegrating in the course of collisions and bursts of star formation eventually replenish the field of intergalactic stars of a galaxy cluster. Observations indeed show a noticeable increase in the proportion of such stars in a cluster of galaxies over time. While at $z = 0$, this fraction is ~40%, at $z = 0.5$ it does not exceed ~20% [109].

It has long been clear that the thick stellar disk of the Galaxy and its stellar bulge are represented by two stellar families. Those are extremely old first stars of the Galaxy and stars of the tidally disrupted low-mass satellites of the Galaxy. Separating these components is a complicated task, which can be solved by a joint analysis of the kinematics of stars and their chemical composition. The noticeable bimodality of [O/Fe] at [Fe/H] ≤ –0.5 is well known [110]. This bimodality is ensured by the presence of these families. Stars with a large [O/Fe] ratio are probably extremely old stars of the Galaxy, while stars with a low [O/Fe] ratio are stars of low-mass galaxies that were absorbed by our Galaxy in the past. The relatively low oxygen abundance of these stars in this case can be explained by the low gravitational potential of such galaxies and the high intensity of galactic winds of these galaxies generated by intense star formation with outbursts of massive supernovae.

The merger of galaxies leads not only to the appearance of stellar streams, but also to the formation of galaxies with unusual properties. For example, there have been found galaxies with gas rotating in the direction opposite to the rotation of the stars of these galaxies [111, 112]. This can be explained by the mergers of galaxies, or the accretion of intergalactic gas with the opposite angular momentum vector. In addition, dwarf galaxies with an inverse radial gradient of metal abundance are known [113], which can again be understood as a result of the merger of two galaxies or as a consequence of the accretion of intergalactic gas onto the central regions of massive galaxies.

Among unusual galaxies, along with galaxies of low surface brightness, it is worth noting very compact dwarfs with a mass $10^6 \leq M/M_\odot \leq 10^8$ and sizes less than ~200 pc [114] falling out of the mass–radius relation for ordinary galaxies [17]. It is possible that these galaxies are the nuclei of more massive S or E galaxies disrupted by tidal interactions with massive galaxies in their dense clusters. The discovery of these peculiar galaxies once again emphasizes the role of the interaction of galaxies with each other and intergalactic gas during their evolution. The study of the shape of stellar streams forming after the destruction of satellites of massive galaxies will, in time, make it possible to approach the estimation of the rotation velocities of the dark halo of the latter [115].

CONCLUSIONS

In general, summarizing the results of this research and a number of studies we performed earlier, we can conclude that the formation of gravitationally unrelated stellar streams completes the picture of the evolution of compact astronomical objects: comets, planetary systems, and various stellar ensembles (star clusters and galaxies). Accumulating collisions of dust particles, asteroids, and comets, as well as gravity (stellar ensembles) concentrate the scattered matter of the Universe in the form of gas and dust into compact objects. The processes of evaporation of cometary nuclei, as well as the gravitational interaction of planets with their stars in planetary systems and stars among themselves in star systems, lead to the destruction of some of these relatively compact systems. In such cases, streams are formed from the objects that comprise these systems. Given sufficiently high velocities of these objects and sufficient time, the streams, extending along the orbits of the parent systems, close in rings (in the shape of tori), which approximately match the orbits of their parent systems. The ratio of the thickness of the tori to the radii of the rings depends on the ratio of the characteristic velocities of the members inside the disrupted systems to the spatial velocities of the systems themselves. For a long time, observational studies of streams were impeded by the difficulty of identifying their members, which, as a rule, are objects of low surface brightness. Modern methods of observing such objects make it possible not only to identify, but also to study them.

The systems we studied have similar origin; they all appear as a result of the "evaporation" of their parent systems and the action of tidal forces on the decay products:

(1) Stellar streams is a product of galactic interaction include free asteroids, comets and exoplanets.

(2) Exoplanetary systems producing streams of free asteroids, comets, and planets around their stars on account of massive planets.

(3) Disintegration of star clusters under the influence of (a) loss of the gas component in the initial system, (b) star formation, and (c) dynamic evaporation of these systems due to pair interactions of stars.

(4) Disintegration of OB associations (with initial dimensions on the order of the thickness of the gas disk) of the Galaxy due to their loss of gas and galactic tidal forces.

(5) Disintegration of low-density galaxies—satellites of massive galaxies—due to the loss of gas as a result of bursts of star formation or the tidal influence of the central galaxy.

(6) Disintegration of galaxies—members of galaxy clusters—due to the interaction with other galaxies: mergers or collisions of galaxies with transformation of them into stellar streams on the scale of clusters.

Thus, the disintegration of galactic, stellar, and planetary systems forming from gas under the influence of gravity turns them over time into stellar and planetary meteor showers, which permeate intergalactic, intragalactic, and circumstellar space, respectively. Stellar streams in galaxies are the decay products of clusters, OB associations, and satellite galaxies. They transform the stellar component of galaxies and their halos into a family of stellar filaments and rings. The morphology of the intergalactic stellar component of galaxy clusters is the same. It is known that approximately half of the stars in intergalactic space in galaxy clusters are products of galactic decay. They form a star field. The general field of galaxies of their clusters is also formed by the planets lost first by their stars, and then by galaxies. The existence of such planets can be reliably shown by microlensing [116].

The numerical modeling allows, on the one hand, understanding the reasons for the great variety of observed stellar streams located both near and inside galaxies. They are observed in well-studied nearby galaxies [117]. The variety of their shapes is determined by the differences in the initial conditions for the destruction of satellites of galaxies. On the other hand, the chaotization of stellar streams (arising from the destruction of satellite galaxies) in the central parts of massive galaxies can lead to the appearance of galactic spheroidal bulges. The latter, in all likelihood, can almost entirely consist of the stars of absorbed and decayed satellite galaxies. Observations clearly demonstrate an increase in the fraction of the mass of bulge stars with an increase in the mass of galaxies. The masses of the bulge and the stellar disk usually become equal when the mass of the galaxy is $\sim 6 \times 10^{10} M_\odot$ [118]. This may mean that while the disk component is mainly a product of the collapse of the initial gaseous protogalaxy, the bulge is the result of the accumulation of stars of nearby low-mass satellites with a low initial angular momentum.

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