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Destruction of astronomical systems: theory and observations

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Contents

Abstract. The review is devoted to the analysis of the formation and evolution of streams of astrophysical objects of various natures. The stream components are destructible astronomical objects: comets, asteroids, planets, stars, star clusters, and galaxies. Almost all of these streams are now observed. We discuss the conditions for the destruction of the original objects and for the formation and dissipation of these streams. We construct numerical models of streams generated by comets, asteroids, stars and their clusters, and galaxies in their clusters, and trace the evolution of these streams on the Hubble time scale.

Keywords: kinematics of stellar systems, galaxies, open star clusters, stellar associations, planetary systems, asteroids, comets, planets, exoplanets

1. Introduction

1.1 History of the development of modern ideas about astronomical streams

After the Big Bang, which created the initial hydrogen–helium plasma, the role of the main organizing factor was taken over by gravity, the force that gave rise to the structural elements observable in the Universe (planets, stars, galaxies, and their systems). Gravity concentrates diffuse matter into the principal observable structures: clusters of galaxies and galaxies, clusters of stars and stars, and planetary systems. Observations and theoretical modeling have shown that there are a number of processes leading to the destruction of all these systems created by both gravity and accumulation: photoevaporation of comet nuclei, expansion of HII zones, supernova bursts, dissipative evolution of systems of N gravitating bodies, and collisions of galaxies and their tidal destruction. By virtue of the angular momentum conservation law, scattering and destruction of astronomical objects gives rise to large streams of their decay products: meteoric, asteroidal, planetary, gaseous, and stellar. This review is devoted to the processes of destruction of astronomical systems and an analysis of the evolution of structures resulting from such dissipation: streams of dust, asteroids, comets, and stars of various natures.

Any specific subject in astronomy has deep historical roots, and the problem discussed in this paper is no exception. We briefly consider the origin of modern ideas about the patterns of destruction of astronomical systems and the emergence of streams of astronomical objects of various natures. The appearance of comets, along with bursts of supernovae, has long attracted the attention of researchers looking for links between celestial and terrestrial phenomena. For example, due to Aristotle, comets were expelled from the planetary world for nearly two thousand years, according to the following argument. Aristotle believed that, while the planets concentrate toward the Zodiac, comets fill the entire

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celestial sphere, which relates them to the world of stars. Hippocrates and the Pythagoreans were the first to consider comets to be special planets orbiting the Sun with long periods. In the 16th century, Tycho Brahe [1] regarded comets as part of the Solar System. However, his contemporary Johannes Kepler admitted that some comets are not tied to the Sun, but follow their 'straight' orbits in the stellar world. The recent discovery of comet 2I/Borisov corroborates this idea of Aristotle and Kepler [2]. Newton [3] showed that the motion of comets and planets around the Sun obeys the law of gravity. The periodicity of the appearance of a number of comets in the past was first demonstrated by Halley, directly indicating that they belong to the Solar System.

Immanuel Kant [4] believed that a comet is a solid body evaporated when heated by the Sun at the perihelion of its orbit. Schiaparelli [5], having calculated the orbits of Perseid meteors, found that they coincide with the orbit of comet 109P/Swift–Tuttle. He hence deduced the inevitable evolution of cometary nuclei over time and their transformation into streams of stones and dust of various sizes. This established the modern model of comet nuclei, which are ice blocks several kilometers in size, contaminated with inclusions of dust, sand, and stones. It became clear later that the destruction of other astronomical systems follows the cometary evolution scenario: the formation of streams made of the constituent elements of the destroyed systems.

The study of the physics and evolution of the Solar System has always occupied a particular place in cosmogony, astronomy, physics, philosophy, and occasionally even ideology. Initially, Laplace [6] and Kant [4] linked the formation of the Solar System and other planetary systems to the rapid rotation of the young Sun. This was natural within the scenario that explains the formation of stars by the collapse of rotating gas clouds. The number of possible planetary system formation scenarios has now increased to ten [7]. Nevertheless, Kant's and Laplace's scenario remains the main one for most planetary systems.

The rate of formation of planetary systems was estimated based on the known distribution of multiple stars over the specific angular momentum [8]. During the collapse of a molecular cloud, planetary systems form if the angular momentum of a gaseous protostar is too low for the formation of a close binary system, but too high for its accumulation by a single main-sequence star. The number of single stars with planets expected in this case is approximately 30%. This estimate coincides with the estimates made later by the *Kepler* spacecraft [9].

Detailed numerical simulation of the process of acceleration of asteroids, comets, and small planets by the Sun–Jupiter system allowed studying the pattern of the formation of the Oort cometary cloud and detached interstellar comets and planets [10]. The interstellar ACP (asteroids, comets, planets) component of our Galaxy, given the percentage of planetary systems, can be quite abundant. Some authors believe that, within the Roche lobe of the Sun ($\sim 10^{18}$ cm), the number of interstellar comets of the 2I/Borisov type exceeds the number of solar asteroids [11, 12]. However, the analysis of 11 million orbits of meteors performed in [13] showed that only five of them had hyperbolic orbits relative to the Sun before their encounter with Earth. As regards interstellar meteors, their role as the most representative members of the ACP spears of their stars requires further study to assess their abundance. When searching for such objects, special attention should be paid to potential ACP spears of stars and star clusters close to the Sun. The study of the physics and evolution of star clusters has always been among the main subjects in astronomy. The 'candle' derived from the main sequence of the Hertzsprung–Russell diagram is a reliable tool for determining the age of stellar systems.

The dynamics of a system of N gravitating point masses has been and remains the source of many problems in the dynamics of planetary, stellar, and galactic systems [14]. Over time, it became clear that virtually all stars are born in star clusters, which typically decay after they lose their gaseous component [15]. It was found that the lifetime of star clusters is limited by a number of factors. As noted in [16], field stars, which inevitably penetrate the volume of a star cluster, 'heat' the stars of the cluster. This leads to a gradual 'evaporation' of the stars in the cluster. Another important factor for the destruction of star clusters is the gravitational interaction of the cluster stars with each other [14, 17, 18]. The mechanism of the loss of stars by a cluster is simple: for $M \cong 0.2R^2$ (a relation in CGS units that reflects the observed correlation between the radius and mass of star clusters and galaxies [19]), the binding energy of a star cluster is of the order of the binding energy a single solar-mass close binary, with the semi-major axis $a/R_{\odot} \simeq 10^6 (M_{\odot}/M)^{3/2}$, where M is the mass of the cluster. It follows that, for $M < 5 \times 10^3 M_{\odot}$, the binding energy of the cluster as a whole does not exceed the binding energy of a single close binary system whose components are solar-mass main-sequence stars. The low binding energy of star clusters is conducive to their decay in dense galactic nuclei [20], including in collisions with giant molecular clouds in gas-rich disk galaxies [21]. But the main mechanism for the destruction of more than 90% of young star clusters is still a significant decrease in the gravitational coupling due to the loss of gas [15].

Flammarion was apparently the first to draw attention to the possible existence of a linear chain of stars, a 'celestial road' in the Pleiades [22]. A similarity between the velocities of stars in Taurus and in the Pleiades was noted in [23]. It was clear from the very beginning that reliable information about the velocities of a large number of stars and determination of their distances from the Sun were needed to reliably identify stellar streams in the Galaxy in the vicinity of the Sun [24]. Jeans [25] found that stars in clusters, under the effect of gravitational interaction with the field stars and with each other, should eventually leave the parent cluster, while preserving its spatial velocity. Indeed, the study of the velocity distribution of bright stars revealed the existence of a number of statistically significant groups of stars with almost identical spatial velocities [26]. Their coordinated motion in space was attributed to the general rotation of stars around the center of the Galaxy [27]. The search for stellar streams intensified in the 1960s as the scales of velocities and distances from stars to the Sun were determined more precisely. Thus, in [28], several stellar streams were discovered in the vicinity of the Sun, and were related to dense groups of young clusters and OB associations.

Physicists have the option to conduct key experiments to study the fundamental aspects of the phenomena and objects under study. Astronomers, for obvious reasons, are deprived of such an opportunity. Experiments are performed by nature, and available to astronomers are the results of observations. Their cognitive efficiency, as evidenced by the experience of recent decades, is especially high in observations of close binary astronomical objects: planets, stars, and galaxies. In the course of interaction with each other, the binary companions expose their properties. This, in particular, has allowed turning close binary stars from an object of study into a very productive tool for studying the physics and evolution of stars from their formation to the appearance of final dense stellar objects: degenerate dwarfs, neutron stars, and black holes.

The study of nearby interacting galaxies has long been a tool for studying the structure, physics, and evolution of galaxies — stellar worlds bound by gravity [29–31]. It was realized in the course of that work that the gravitational interaction of nearby galaxies gives rise to tidal tails and spirals, revitalizes the process of star formation in galaxies, and activates gas accretion onto central supermassive black holes (SMBHs) in galactic nuclei [32].

The tidal tails of interacting galaxies have become another example of stellar streams arising in the course of destruction of the peripheral regions of disk galaxies [33, 34]. Gradually, it became clear that part of the linear structures of galaxies is stellar streams — the remnants of low-density galaxies tidally destroyed by massive galaxies [35]. The study of the dense parts and the galactic halo showed the presence of many stellar streams in it, which are traces of the destruction of nearby satellite galaxies [36]. This phenomenon was recognized as common in the world of galaxies. Traces of star clusters have been found in stellar streams.

1.2 Stellar streams

The existence of the Magellanic Stream, an intergalactic stream that includes the Magellanic Clouds, stars, star clusters, and gas, was noted in [37]. The appearance of this stream is an obvious consequence of the partial tidal destruction of our Galaxy's satellites in the course of their close interaction in the past. Later, it was found that the Pleiades and Hyades, together with field stars, are two streams of different ages located in the plane of our Galaxy [38]. The study of the kinematics of stars in the nuclei of massive E-galaxies has demonstrated the presence of stellar streams. At the same time, low-mass E-galaxies turned out to be homogeneous [39]. This was interpreted as the remaining traces of the 'assembly' of massive E-galaxies that absorb nearby low-mass satellites in the course of evolution. The nearby galaxy M 31 also demonstrated the presence of stellar streams in its halo, including satellites, the dwarf galaxies M32 and NGC205 (Ibata [40]). A detailed study of 33 nearby galaxies revealed stellar streams in them [41], confirming the decisive role of galaxy mergers in the formation of their bulges and halos.

An analysis of the chemical composition of stars in several galactic streams confirmed its similarity to the chemical composition of the dwarf galaxies that are the Galaxy satellites [42]. Importantly, the study of the dynamics of stellar streams in the Galaxy led to the conclusion that the shape of its gravitational potential can be reconstructed based on the study of the shape and kinematics of stellar streams [43]. We note that the analysis of the kinematics and differences in the ages of stellar streams turned out to be an effective tool for studying the increase in the mass of the Galaxy in the course of its evolution [44, 45].

Part of the stellar streams usually attributed to the halos of massive galaxies may be the result of the destruction of galaxies by tides or outbursts of star formation in them. As a result, they eventually make up a 'continuous' stellar medium of clusters of galaxies [46]. The detection of such stellar streams is still complicated by their low surface brightness, but their existence as elements of the stellar environment of clusters is currently beyond doubt.

1.3 Summary

To summarize a brief historical introduction to the shaping of modern ideas on the nature and diversity of astronomical streams of different natures, we can conclude that these streams are a special class of astronomical objects along with planets, stars, galaxies, and clusters of galaxies. These objects differ both in the scenarios of their origin and in the physical content of their evolution. Recent observations and a detailed analysis of large volumes of observational data have allowed identifying and studying some details of the observed streams of various natures. It becomes clear that the appearance of stellar streams is an integral part of the evolutionary process of astronomical systems. Streams of different natures are active participants in the creation of some astronomical objects and the destruction of others, and in the evolution of these objects [47–49]. In particular, the disk components of galaxies are essentially the totality of streams of decayed and decaying star clusters of the disk. Elliptical galaxies and bulges, and spheroidal and circumnuclear components of galaxies are mainly a product of the tidal destruction of satellites of massive galaxies.

2. Formation of astronomical streams

We briefly name the main types of astronomical streams known today, their sources, and possible causes of the destruction of astronomical objects that results in the appearance of such streams. All planetary systems are permeated by meteoroid streams, which are products of the destruction of asteroids and comets. Stars that have planetary systems are armed with ACP 'spears,' whose length is determined by the age of these stars and can reach galactic scales [50]. Here and hereafter, spears are understood as young streams of comets, asteroids lost by planetary systems, and young stellar streams lost by star clusters and galaxies. Their spear-like character results from the angular momentum conservation law in the case where the speed acquired by the elements of the spear when escaping from their parent system is much less than the orbital velocity of the parent system. Star clusters have ACPS spears, i.e., also include stars along with ACP objects. The decay of OB associations leads to the appearance of broad ACPS streams, which also include individual accumulations that have survived after the initial loss of gas. The destruction of satellites of massive galaxies leads to the appearance of stellar streams of galactic proportions. The destruction of galaxies during collisions within clusters of galaxies turns these galaxies into broad stellar streams, which ultimately make up the continuous stellar background of clusters of galaxies.

Let us name the main processes of destruction of astronomical objects and systems. The icy nuclei of comets are destroyed by the evaporation of ice and the ejection of dust and rocks by the pressure of water vapor in hot orbits around their stars. Asteroids are destroyed during their mutual collisions. Massive planets that are distant from their stars accelerate the ACP with their gravity. HII zones destroy most of the young star clusters due to the weakening of the gravitational bound of the entire cluster. In addition, the gravitational interaction of stars within star clusters leads to gradual evaporation of the clusters. Outbursts of star formation and supernova bursts in spheroidal galaxies, leading to a rapid loss of gas by these galaxies, can result in their destruction. Collisions of galaxies and tidal interactions between them can be accompanied by their partial or complete decay [51]. The merger of SMBHs in the nuclei during galaxy mergers can also cause partial or complete destruction of these galaxies [19]. Partial or complete destruction of galaxies leads to the appearance in intergalactic space within galaxy clusters of stellar streams with a length of the order of the size of these clusters.

2.1 Streams of asteroids, comets, and planets

We consider a typical scenario of the emergence and evolution of an astrophysical stream that includes asteroids, cometary nuclei, free comets, and stars (Fig. 1). The initial object is a gas and dust cloud, the progenitor of planetary and stellar systems. The collapse of the gas and dust cloud forms planetary systems, stars, and stellar systems. The concentration of dust in protoplanetary disks leads to the formation of asteroids, comet nuclei, and planets. The destruction of the structure of astronomical objects due to the evaporation of icy nuclei of comets and the destruction of star clusters and galaxies gives rise to ACPS streams, which are linear structures, or 'spears,' of comets, stars, and stellar systems. Given enough time, an ACPS spear develops into a ring around the center of the parent system. These processes are underlain by the angular momentum conservation law. With the spherical symmetry of the initial velocity directions of the bodies leaving the destroyed object, a spherically symmetric 'corona' is created, made of the lost bodies. If, on the other hand, the object is a member of a more massive system, then the angular momentum conservation condition gradually forms elongated structures along its orbit (see Fig. 1).

It is well known that single stars, losing matter at the stage of the asymptotic branch of giants or during supernova explosions, are powerful sources of dust. The speed of the dust particles is then of the order of the speed of the gas. For stars of the asymptotic branch, $v = 3–18$ km s^{-1} [52, 53]. Type-SNIb and SNIc supernovae demonstrate the formation and presence of dust in their shells, expanding at a speed of several thousand kilometers per second [54, 55]. Ultrafast dust from supernovae is probably mostly evaporated due to friction with the background gas of the Galaxy, and the dust of the asymptotic-branch stars, patterned on the ACP spears generated by planets, can gradually form dust spears of degenerate dwarfs located along the orbits of parent stars in the Galaxy.

2.2 Stream parameters and their main relations

Interestingly, the ratio of the length of a developed stream to its width is a measure of its age. For streams with a small eccentricity of the initial orbit, the stream width is $\Delta R = (v/w)R$, where v is the velocity dispersion of the members of the stream, w is the orbital velocity of the object that generated the stream, and R is the radius of an annular stream. The length of the stream is $l = vt$, where t is the stream age. The ratio of the stream length to its width is $l/\Delta R = wt/R = 2\pi N$, where N is the number of orbital periods during the lifetime of this stream. Of course, the use of such a simple relation to estimate the ages of observed streams is complicated by a number of obvious factors, the main one being the difficulty of determining the position of its boundaries. These are usually 'set' by the actual density of the background on the image of the stream under study, rather than by the rare elements at the stream boundaries.

For numerical estimates of the parameters of the stellar systems studied in this paper, we must discuss the idea of the initial mass spectrum and the correlation of the mass of astronomical objects with their size R. Modern ideas about the initial mass spectrum of astronomical objects result in the conclusion that it can be written in the form [19, 56–58]

$$\frac{\mathrm{d}N}{\mathrm{d}M} \sim \frac{1}{M^2} \,. \tag{1}$$

The physical content of relation (1) is simple and amounts to the absence of a preferred mass scale. The same mass of matter thus corresponds to each interval of the object's mass logarithm. We note that, for solid objects of the same density, the mass spectrum can be written as a size spectrum,

$$\frac{\mathrm{d}N}{\mathrm{d}R} \sim \frac{1}{R^4} \,. \tag{2}$$

Comparisons of relation (1) with estimates of the initial spectra for various objects (dust, asteroids, stars, star clusters, and galaxies and their clusters) showed good agreement. Deviations of the initial mass spectra derived from observations of various objects can be explained by their formation and evolution being nonconservative.

For quantitative estimates of the characteristics of galaxies, star clusters, and clusters of galaxies, we present the observational relation between their mass M and radius R in a form convenient for estimates [19, 58–60]:

$$M = 0.2R^2[\mathrm{CGS}] \text{ or } \frac{M}{M_\odot} = 10^3 \left(\frac{R}{\mathrm{pc}}\right)^2 . \tag{3}$$

This reflects the observed relation between mass and radius for most star clusters, galaxies, and galaxy clusters with masses $10^5 \leqslant M/M_\odot \leqslant 10^{15}$. A number of galaxies noticeably deviate from the correlation stated in (3), being denser or more rarefied. Such deviations likely result from the

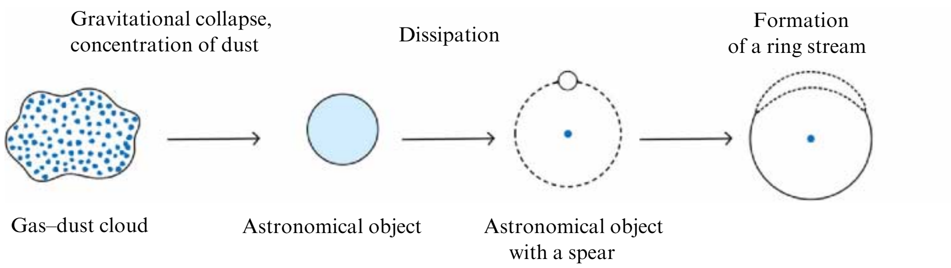

Figure 1. Evolutionary scenario for the formation of stellar and ACP streams. Astronomical objects: asteroid, comet nucleus, planetary system, star cluster, galaxy. Causes of dissipation are the evaporation of comet nuclei, collision of asteroids, destruction of star clusters, tidal destruction of galaxies, outbreak of star formation in a galaxy, and merger of galaxies.

interaction of galaxies with each other during their approaches.

It follows from Eqn (3) that the specific angular momentum of these systems rotating with the Keplerian velocity is $j \sim M^{3/4}$. The rapid growth of j with increasing mass ultimately determines the formation of narrow streams during the decay of cometary nuclei, star clusters in galaxies, and galaxies in their clusters. Equation (3) also implies an estimate of the characteristic Keplerian velocity of star clusters and galaxies,

$$v_{\mathrm{k}} = 200\left(\frac{M}{10^{11} M_{\odot}}\right)^{1/4} \ \mathrm{km\ s}^{-1}\,, \tag{4}$$

and the orbital period of the stars at the boundaries of these objects or the dynamical time scale of these systems,

$$P_{\mathrm{orb}} = 3 \times 10^{8}\left(\frac{M}{10^{11} M_{\odot}}\right)^{1/4} \ \mathrm{years}\,. \tag{5}$$

Equation (4) is known to observers as the Tully–Fisher relation [60].

Thus, the general pattern of the emergence of streams of astronomical objects is as follows. Gravity and collisions form compact systems: comet nuclei, asteroids, and planetary and stellar systems of various classes. The decay of these systems into their constituent elements, due to the angular momentum conservation law, leads to the gradual formation of streams of these elements within the parent systems (see Fig. 1). The analytic estimates in (1)–(5) can serve as a convenient tool for quantifying some parameters of such systems.

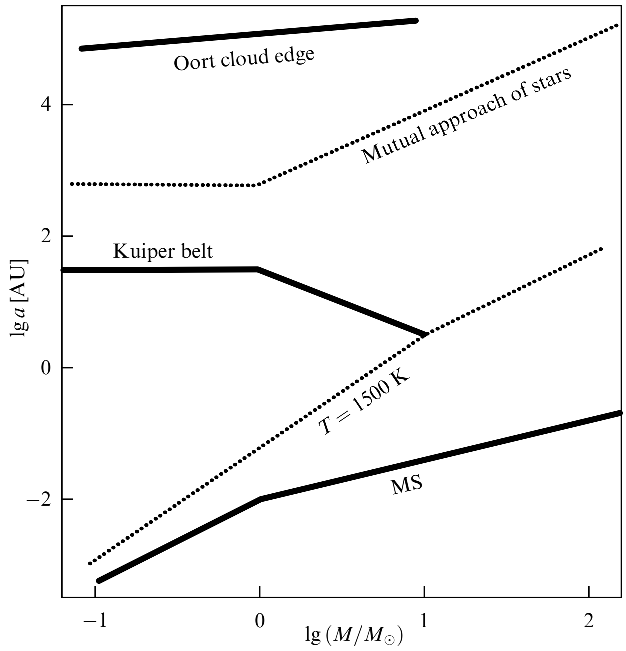

Figure 2. Basic properties of planetary systems as a function of the mass of the central star. Notation a is the distance from the central star of mass M. Shown is the outer boundary of the Oort cloud, mutual approach of stars (boundary of the penetration of field stars into the Oort cloud during the lifetime of the star), Kuiper belt (outer boundary of the planetary part of planetary systems), and inner boundary of the Kuiper belts; $T = 1500$ K is the dust evaporation boundary, MS is the radius of the star.

3. Evolution of comets and asteroids in a planetary system

An asteroid–comet Oort cloud (ACP), approximately $\sim 10^{18}$ cm in size (Fig. 2), is largely formed in a planetary system at the early stages of the formation of distant giant planets. We recall that the ACP Oort cloud is mainly made of stony and icy asteroids, comets, sand, and dust ejected by giant planets into the Hill sphere of the Sun in the early stages of planetary system formation [10, 47, 61]. The presence of dwarf planets in the Oort cloud is also not excluded. We clarify that a comet is typically understood as an icy asteroid in a region close to the Sun, evaporated by solar radiation. The concept of the 'Hill sphere' was introduced by Hill based on the work of Roche. Within the 'Roche lobe,' the gravitational force of an object exceeds that of its satellite in a circular orbit. We use these terms as synonyms in what follows. With the depletion of the ACP material in the inner regions of a planetary system, giant planets change their role from that of the originator of the Oort cloud to its destroyer. They gradually move the ACP objects of the Oort cloud from elliptical orbits to circumsolar hot elliptical orbits or hyperbolic orbits of free ACP objects [47, 61]. As a result, the Oort cloud is depleted over time.

Another possibility of the loss of comets and asteroids by an Oort cloud is related to the planetary systems entering dense (up to 10^{-20} g cm^{-3}), extended ($\sim 10^{21}$ cm), molecular clouds of disk galaxies. With the average gas density in the Galaxy given by 10^{-24} g cm^{-3}, a star spends $\sim 10^{-4}$ of its lifetime inside such a cloud. For the old stars of the galactic disk, this is $\sim 10^{6}$ years. The time to cross giant molecular clouds (GMCs) at the characteristic speed of stars $v \sim 30$ km s^{-1} is about 10^{7} years. Therefore, we can assume that a solar-mass star during its life entering a molecular cloud is a common event.

The objects in a star's Oort cloud $\sim 10^{18}$ cm in size are gravitationally weakly bound to the parent star, and, for the sizes r of these objects

$$r < \frac{\rho v^{2} R^{2}}{GM} \approx 10^{3}\ \mathrm{cm}\,, \tag{6}$$

can be removed from it by the pressure of the oncoming GMC gas. In (6), $\rho \approx 10^{-20}$ g cm^{-3} is the gas density, v is the star velocity across the GMC, $R \approx 10^{18}$ cm is the radius of the Oort cloud, G is the gravity constant, and M is the mass of the star. It is clear that, when a star with an Oort cloud hits a molecular cloud, the outer parts of the Oort cloud lose dust, sand, and pebbles, and the ice evaporates, at least partly. It is easy to imagine that this process results in a star acquiring a dense dust tail extending along its orbit in the GMC, in addition to the ACP spear of this star extending along its orbit in the Galaxy.

Another obvious option of the scattering of ACP Oort cloud objects is due to the regular crossing of the Oort cloud by neighboring stars of the galactic disk. Stars penetrating into the Oort cloud accelerate and expel the ACP objects from it within a cylinder with radius $r \leqslant GM/vw$, where $M \sim M_{\odot}$ is the characteristic mass of stars in the galactic disk, $v \sim 3 \times 10^{6}$ cm s^{-1} is the speed of stars of the galactic disk relative to each other, and $w = \sqrt{GM/R} = 10^{4}$ cm s^{-1} is the parabolic velocity of an ACP object at the edge of the Oort cloud. As a result, the ratio of the area covered by background stars with the above radius r during the lifetime of an old star,

$\sim 10^{10}$ years, to the area of the Oort cloud is

$$\alpha = \frac{GMRNt}{v} \sim 0.3\,, \qquad (7)$$

where $N \sim 10^{-56}$ cm^{-3} is the density of background stars. That is, despite the uncertainty in some parameters involved in (7), a significant part of the Oort cloud ACP objects, formed mainly at the early stages of the formation of a planetary system by giant planets, is lost. Stellar erosion of the Oort clouds constantly replenishes the ACP spears of stars that have planetary systems. It is worth noting that the velocities of the Oort cloud objects at the aphelion are very small, $\sim 10^3$ cm s^{-1}, and hence the radius of the cylinder within which they change noticeably is $r \approx 3 \times 10^{17}$ cm. During the lifetime of the Sun, about 10^3 stars pass within this zone, thus significantly increasing the perihelion distances of the orbits of the Oort cloud objects.

Strömgren [62], having studied the orbits of several circumsolar comets, noted the significant role played by the massive planets, Jupiter and Saturn, in the evolution of the orbits of the Solar System cometary nuclei with time. Oort [63] found that comet nuclei fill the Sun's Roche (Hill) sphere with a radius of $\sim 10^{18}$ cm. The Hill sphere of the Sun with radius $R_{\rm R}$ is the zone of gravitational influence of the Sun in our Galaxy, $R_{\rm R} = 0.4R(M_\odot/M_{\rm G})^{1/3}$, where $M_{\rm G}$ is the mass of the Galaxy and R is the distance from the Sun to the center of the Galaxy. Later, it became clear that, in the process of formation, all planetary systems with massive planets probably fill their Roche lobes with asteroids, comet nuclei, and maybe even low-mass planets [10, 64]. Large and distant planets that satisfy the condition $m/r > M_\odot/a$, as shown by detailed modeling, can accelerate small (ACP) bodies by their gravity to parabolic velocities at the level of their orbits; here, m and r are the mass and radius of a large planet and a is the semi-major axis of its orbit around the Sun.

3.1 Origin of interstellar asteroids, comets, and planets

The acceleration of the ACP bodies of planetary systems by giant planets produces ACP Oort clouds of the Sun and other developed planetary systems (see Fig. 2). Importantly, some of the ACP bodies are ejected from their planetary system into the interstellar space of the Galaxy [10]. We discuss their further evolution below. The observed parameters and the number of Oort cloud members remain rather uncertain due to the weakness of the distant members. The eccentricities of their orbits, which are extremely close to unity, and their infrequent and brief stay near the Sun ensure their long lifetime, often exceeding the Hubble time. As a result, by the end of the nuclear evolution of solar-mass central stars, their Oort clouds and Kuiper belts are inherited by degenerate dwarfs. The presence of the ACP material near some of these is reliably detected by the chemical composition of their atmospheres, which is explained by the accretion of dust and asteroids from the Oort cloud and Kuiper belt surrounding these dwarfs. The rate of accretion of solid matter by degenerate dwarfs that have an Oort cloud can be estimated as 10^7–10^{10} g s^{-1}, which is sufficient for the observed metallicity of their atmospheres [65].

The periodic return of the Oort cloud ACP objects to the inner parts of the planetary system and their approach to giant planets significantly change their orbits. Some of the ACP objects — the nuclei of comets and asteroids — occupy 'hot' orbits close to the Sun. This ensures the gradual evaporation of the comet icy nuclei, the release of dust and sand frozen in the ice, and the appearance of a bright tail that attracts universal attention. The comet nucleus eventually evaporates, producing a stream of dust and sand along the orbit of the comet's former nucleus.

Thus, in the course of their formation, giant Jupiter-class planets create a 'bank' of Solar System asteroids and cometary nuclei in the Oort cloud. During the evolution of the Sun and its planetary system, these planets redirect some of its objects to inner hot orbits. Comet nuclei in hot orbits evaporate quickly, and mutual collisions of asteroids simply destroy them into dust and sand, eventually forming a dust (meteoroid) stream near the Sun. An example of an observed comet currently actively interacting with Jupiter is Comet Hale–Bopp [66]. This concludes the brief summary of the history of the emergence of dust streams in the solar and other planetary systems (see Fig. 2).

We note that the giant planets satisfying the criterion

$$\frac{m}{r} > \frac{M}{a} \qquad (8)$$

are capable of imparting hyperbolic velocities to ACP objects [10], thus replenishing the population of the field of 'free' ACP members of the Galaxy. Such objects have already been found: asteroids 1I/Oumuamua and 2I/Borisov [67] and five out of the 11 million meteors [68] were recognized as interstellar. However, the frequency of the occurrence of interstellar objects and their spatial density remain unclear, because the existing estimates diverge significantly [69]. The obvious rarity of the detection of such objects is a natural consequence of their low spatial density in the Galaxy.

For stony objects that are far from the Sun and therefore do not evaporate, the mass spectrum is close to the reference one in Eqn (1), both for asteroids about 1 km in size [70, 71] and for stones 10 to 10^5 cm in size [72]. When comparing the observed mass spectrum of evaporating icy nuclei of comets with the initial one, we must recall the obvious reduction in the lifetime of nuclei with a decrease in their size. It is natural to take the lifetime of evaporated cometary nuclei proportional to their size. The observed mass spectrum based on Eqn (2) is then given by $\mathrm{d}N/\mathrm{d}R \sim 1/R^3$ or $\mathrm{d}N/\mathrm{d}M \sim M^{-5/3}$. The observed mass spectrum of comets crossing Earth's orbit turns out to be quite close to that estimate: $\mathrm{d}N/\mathrm{d}M \sim M^{-1.9}$ [73]. For comet nuclei greater than 1 km in size, we have $\mathrm{d}N/\mathrm{d}M \sim M^{-1.67}$ [74], which practically coincides with the above theoretical mass spectrum of objects evaporated by the Sun. A study of the mass spectrum of sand and stones with a size of 1 cm released during the evaporation of cometary nuclei showed that it can be written in the form $\mathrm{d}N/\mathrm{d}M \sim M^{-1.8}$ [75]. Thus, most recent information on the observed mass spectrum of comet nuclei demonstrates, after taking their evaporation into account, an almost complete agreement with the predictions based on Eqn (1).

We conclude that, in the presence of massive and sufficiently distant planets, the evolution of planetary systems leads to the formation of Oort clouds within the Roche lobes of the parent stars. The Oort clouds serve as a storage bank for asteroids and comet nuclei for delivery to the inner regions of planetary systems, where icy comet nuclei evaporate and asteroids can collide. These phenomena are the cause of the occurrence of streams of meteor particles in planetary systems. It has now become clear that the multiplicity of stars does not forbid the formation of planetary systems orbiting either a component of the stellar system or the system as a whole. The presence of a stellar companion in this case limits the size of the Kuiper belt and Oort cloud of the companions to their Roche lobes. In a binary system, the size of the Oort cloud of the system as a whole remains limited by the size of the Roche lobe of the system in the field of the galactic gravitational potential.

4. Formation and evolution of a dust spear of comets and asteroids

Evaporation of the icy nucleus of a comet releases its solid component: dust, sand, and stones. This component is abundant: its mass can be several times greater than the mass of ice in cometary nuclei [76]. Over time, it extends along the comet's orbit into a narrow cloud, resembling a spear in outline. Infrared observations aboard the Spitzer spacecraft allowed detecting such symmetric dust spears in 27 out of 34 observed cometary nuclei [76]. They are always located along the orbits of their comets and have been traced to distances up to 10^6 km from the nucleus. It is obvious that the detected dust spears are only the central, densest parts of the dust streams accompanying the comet nucleus on its path around the Sun. Naturally, the evaporation of nuclei and the removal of the dust component are most effective at the perihelia of cometary orbits. The end product of the evolution of a cometary nucleus is the formation of a dust stream along the initial orbit of the cometary nucleus, as was proposed back in 1867 by Schiaparelli [5]. Modern numerical simulations fully confirm this scenario [47].

We now consider the acceleration of dust grains from a comet nucleus undergoing evaporation. Water evaporation under the action of solar radiation leads to the appearance of a gaseous wind near the comet nucleus, having a speed $\sim 30T^{1/2}$ m s^{-1}, where T[K] is the surface temperature of the nucleus. The gaseous wind interacts with the solar wind. Comparing the momentum fluxes of the cometary wind with the solar one shows that the size of the comet's coma (the influence zone of its wind) is almost 6000 times greater than the size of the ice nucleus [47]. This result is almost independent of the distance between the comet and the Sun, which is confirmed by observations. The wind of the evaporated nucleus accelerates the released dust component to a speed that naturally depends on the size of the dust grains. The existing estimates of this speed vary from a few meters per second [77] to one hundred meters per second [78, 79]. Of importance for us now is that the ratio of the orbital velocity of the comet's nucleus to the velocity of the gas lost during ice evaporation reaches a value of the order of 100. This predetermines the observed width of the dust spear, which is actually defined by the ratio of the velocities [80]. Interestingly, the duration of meteor showers observed on Earth is determined by the width of the dust spear or, ultimately, also by the ratio of these velocities.

The lifetime τ_c of comet nuclei in 'hot' circumsolar orbits can be estimated by assuming that the evaporation of one water molecule requires an energy of about 1 erg, whence $\tau_c \approx 300(a/\mathrm{AU})^2 d/\mathrm{km}$ years, where a is the distance from the comet to the Sun at the perihelion and d is the diameter of the comet's icy nucleus. Obviously, with a nucleus size of several kilometers and distance from the Sun at the perihelion of about 1 AU, the lifetime of the nucleus does not exceed several thousand years. That is, the life of a circumsolar comet in the bright phase is much shorter than the life of its successor, a dust spear that develops over time into a closed dust stream around the Sun.

Several extended asteroid–dust spears of near-solar comets were recently found under the name of 'dust jets' [81, 82]. Due to the evaporation of the icy nuclei of comets, their lifetime in hot orbits is bounded by several ten to several hundred orbital periods [83]. An example of a 'depleted' nucleus is that of the old comet of the Jupiter family, 209P/LINEAR [84]. Radar observations revealed the dust tail of this comet. Another example of meteor accompaniment is demonstrated by Comet 96P/Machholz [85]. It is now clear that all observed meteor showers in the Solar System are the dusty remnants of comets. Asteroids and dust leaving a comet nucleus at a speed $\sim 10^4$ cm s^{-1} [86] fill the orbit of a Jupiter-family comet in several hundred to several thousand years, turning it into a meteor shower. An analysis of the orbits of about 10^7 meteors before their collision with Earth's atmosphere have allowed identifying eight meteor showers with apogees close to the orbit of Jupiter [87]. This confirms the genetic connection of these dust streams with comets and demonstrates the organizing role of Jupiter, which redirects comet nuclei from the Oort cloud to hot orbits (Fig. 3).

4.1 Meteor spears

The current list of circumsolar meteor showers crossing Earth's orbit contains 17 members [84]. They comprise up to half of all near-solar meteoroids, preserving the orbits of recently evaporated cometary nuclei and products of high-velocity collisions of asteroids of comparable sizes. Such asteroids, having no signatures of bright cometary tails, usually remain undetected before the collision. An example of a registered direct collision of asteroids is the 596 Scheide flare ~ 50 km in size [88]. In 2010, a flare occurred, accompanied for several days by a dust tail with an estimated dust mass of $\sim 10^{10}$ g. Such a tail is a product of a partial destruction of asteroids that have undergone a collision. Observed meteor showers are usually inhomogeneous, which may be a consequence of the inhomogeneity of comet and asteroid nuclei [89].

The velocities relative to Earth have been found for 11 streams crossing Earth's orbit and moving around the Sun in almost circular orbits [90]. They are within 12–72 km s^{-1}. These bounds are easy to understand if we take into account that the parabolic speed at the level of Earth's orbit is ~ 42 km s^{-1}, and the circular speed is ~ 30 km s^{-1}. Therefore, the speed of the oncoming stream should be 72 km s^{-1}, and that of the passing one, ~ 12 km s^{-1}, which is indeed observed. The average speed of meteor streams relative to Earth is ~ 47 km s^{-1}, which indicates a nearly random orientation of their circumsolar orbits. Interestingly, the average speed of meteors not organized into streams is only ~ 20 km s^{-1}. This means that the collisional evolution of dust streams and the interaction of dust with the gravitational field of the planets gradually changes their rotation around the Sun to a motion close to the orbital rotation of the planetary system. Indeed, the Sun's zodiacal light exhibits a markedly flattened structure in the orbital plane of the Sun's planetary system.

We see in what follows that all planetary systems of the Galaxy have cometary spears that include dust in their composition. The Sun, in the course of its motion, crosses these spears, occasionally finding itself inside streams of organized motion of interstellar dust. As a result, the problem arises of searching for a connection between interstellar meteors and the stars close to the Sun that generate them. That is, in the field of meteors recorded on

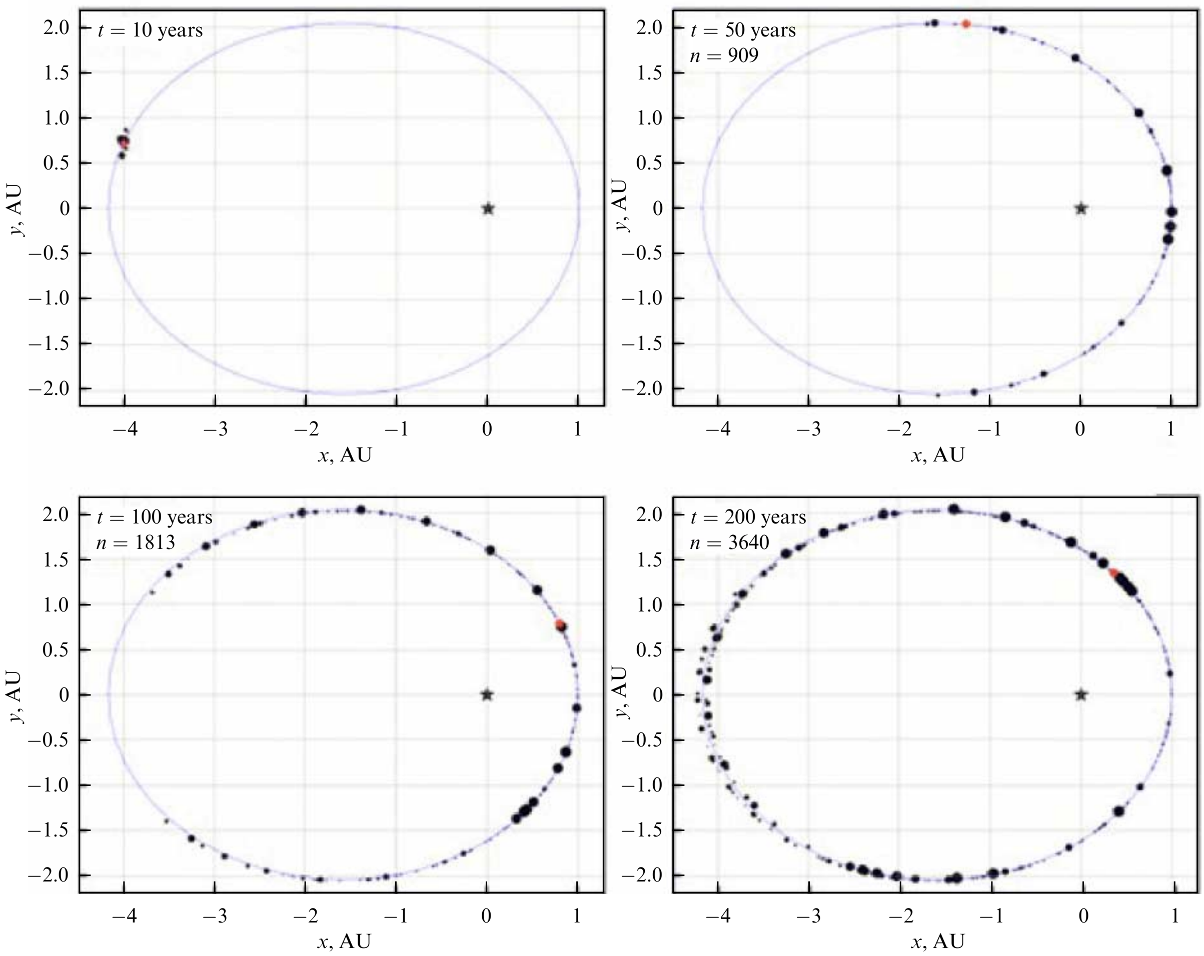

Figure 3. Result of modeling the history of the formation of a comet dust spear around the Sun with a perihelion velocity of 39.9 km s^{-1}. At each integration step, dust evaporates toward the Sun with a speed of the dust particles equal to 126 m s^{-1}. Size of the black dots representing dust clouds is proportional to the number of dust particles ejected at each step. Red dot indicates the comet residual nucleus, which is proportional to $\sim r^{-2}$, where r is the distance from the comet to the Sun. Picture is shown as it develops over time. Integration time and the number of dust grains are labeled in the upper-left corner of each panel.

Earth, we should look for their correlated, statistically significant streams and then attempt to identify the directions of such streams with the vectors of spatial velocities of stars close to the Sun. Proximity to the Sun may in this case condition the high density of the star's cometary spear.

For an asteroid, collisions with other asteroids of a smaller mass play the role of a dust generator in the course of its motion in an orbit around the Sun. The mass spectrum of asteroids is reliably represented by Eqn (1), whence it is clear that circumsolar sand and dust are the main erosive agent for asteroids. This makes the evaporation of the comet's icy nucleus and the collision of large asteroids with sand and dust effective in generating dust spears of comets and asteroids. Collisions of large asteroids of comparable masses are relatively rare events according to Eqn (1), but are not excluded either, and we therefore also consider the instantaneous destruction of an asteroid in a collision. Evaporation of the ice part of cometary nuclei has been the subject of many studies [91, 92]. As a result of the evaporation of the nucleus of a comet, dust and sand appear with the mass spectrum given by Eqn (1).

To study the evolution of the orbits of sand lost by a cometary nucleus on a short time scale, we used the REBOUND program [93], which takes only the gravity of the Sun into account. We studied two scenarios. In the first, sand was removed from the comet's nucleus at a speed of $\sim 10^4$ cm s^{-1} and a rate inversely proportional to the squared distance to the Sun, into the hemisphere facing the Sun (see Fig. 3). In the second scenario, an instantaneous spherically symmetric decay of asteroids was assumed under the effect of their direct collision with each other (Fig. 4). In the course of several hundred years, the products of evaporation of ice nuclei and collisional destruction of asteroids are distributed along the initial elliptical orbits of the parent bodies, forming meteor showers of dust and sand.

Figures 3 and 4 demonstrate the evolution of a comet or asteroid dust spear over time and its transformation into a meteor shower orbiting the Sun. The shape of the streams is determined by the initial orbit of the destroyed object. The difference between the streams generated by comets and asteroids can only be sought in the chemical composition of their matter, because asteroids and cometary nuclei are probably formed at different distances from the Sun and in different epochs of the Solar System's evolution. The destruction of the nuclei of comets and colliding circumsolar asteroids thus results in the formation of relatively narrow streams of dust and sand in the vicinity of the Sun and other stars with planetary systems. The intersection of these streams

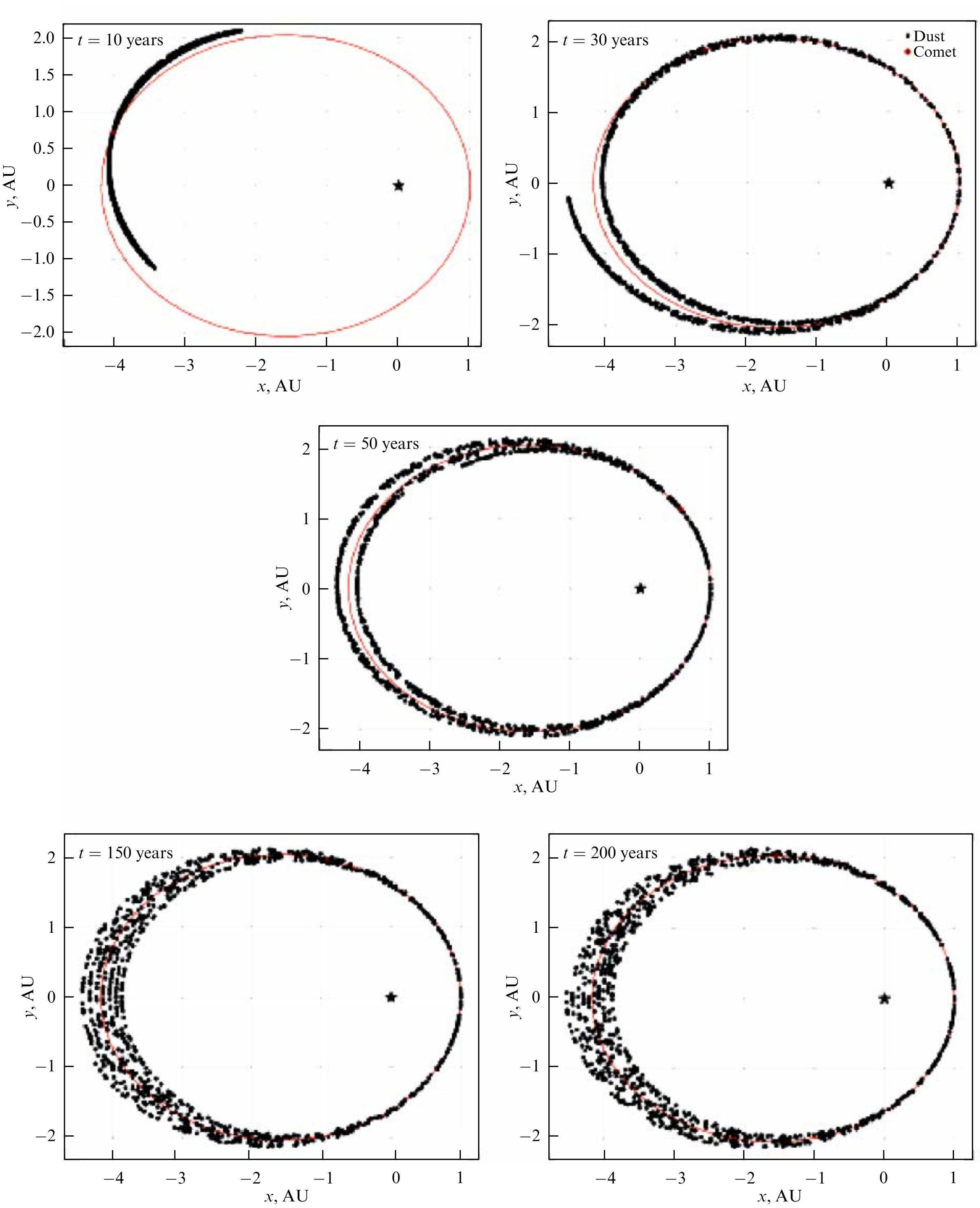

Figure 4. Evolution of a dust stream during an instantaneous decay of the nucleus of a comet or an asteroid at the moment of passing the perihelion as a result of a collision with another asteroid. Debris particles resulting from the collision scatter symmetrically in all directions over the sphere. Departure speed is ~ 2 km s^{-1}. Red dot is the residual nucleus of the comet. Black dots are the positions of dust particles in the stream. In 150 years, dust clouds have time to distribute evenly along the comet's orbit. Initial speed of the comet nucleus is 39.9 km s^{-1}.

with Earth's orbit around the Sun and the entry of dust and sand into Earth's atmosphere are associated with an increase in meteor activity.

A question arises about the future fate of the dust, sand, and cometary parts of these streams. Dust within the zone of influence of the solar wind is under the effect of this wind and solar radiation. The size $R_{\rm w}$ of the solar wind zone of influence is estimated from the condition of the equality of the wind momentum flux and the gas momentum flux of the interstellar medium,

$$R_{\rm w} = \left(\frac{\dot{M}W}{4\pi\rho v^2}\right)^{1/2},$$

where $\dot{M} \approx 10^{12}$ g s^{-1} is the rate of loss of matter via solar wind, W is the wind speed, ρ is the density of the medium, and

v is the speed of the Sun relative to the gaseous medium. Estimates show that, for $v = 3 \times 10^6$ cm s^{-1} and $\dot{M} = 10^{12}$ g s^{-1}, we have $R_w \approx 10^{15} n_H^{-1/2}$ cm, where n_H is the gas density of the medium in units of the number of hydrogen atoms per cubic centimeter. Estimates show that, even in the zone of influence of the solar wind, radiation affects the motion of dust grains more strongly than the solar wind does. Dust particles smaller than $\sim 3 \times 10^{-5}$ cm are immediately removed from the Solar System. The light pressure on them exceeds the solar gravity.

Let us consider the evolution of the components of a stream over time. Dust particles and sand with sizes smaller than $0.1(\mathrm{AU}/R)^2 t/(10^6$ years) cm are decelerated due to the Poynting–Robertson effect and gradually spiral towards the Sun. Here, R is the distance from a dust grain to the Sun and t is the dust grain lifetime. This effect results in the concentration of dust near the Sun, which explains the appearance of the zodiacal light of the Sun and, probably, of all other stars with planetary systems. Indeed, approximately 20% of all stars show signatures of warm zodiacal dust near them [94]. We note that the detectable fraction of stars with zodiacal dust is comparable to the fraction of stars with planetary systems. The dust of the zodiacal wind, approaching the Sun at a distance of about 10^{12} cm, evaporates and is removed from the Solar System with the solar wind. Large objects of the stream can be destroyed as a result of direct collisions in circumsolar space, absorbed or scattered by large planets (see Fig. 2). Such is the fate of circumstellar streams of dust, sand, and rocks produced due to the evaporation of icy nuclei of comets and the collisional destruction of asteroids.

When considering the fate of dust streams, it should be borne in mind that, for young solar-mass stars and for stars of lower mass, the role of wind in the evolution of zodiacal dust can exceed the role of radiation. For example, a study of the dust environment of an M dwarf revealed that the intensity of its stellar wind exceeds that of the solar wind by almost a thousand times [95], which makes such a wind the leading factor in the evolution of the dust environment of young low-mass stars.

Importantly, with the end of the evolution of the central star and its transformation into a degenerate dwarf, the evolution of the star's planetary system does not end. Giant planets with a semi-major axis greater than several astronomical units, the Kuiper belt, and the Oort cloud persist even after the formation of a degenerate remnant of the central star with an initial mass in the range of $0.8M_\odot$–$8M_\odot$ (see Fig. 2). For example, in the region of Pluto's orbit in the Solar System, the formation of new planets will continue due to the accumulation of asteroid-comet matter. Field stars crossing the Oort cloud of a degenerate dwarf enrich the ACP population of its ACP spear. Giant planets that have survived the supergiant stage of their star will continue to transfer ACP objects of the Oort cloud into orbits close to a degenerate dwarf (see Fig. 2). Naturally, some of these objects will fall on the degenerate dwarf, enriching the chemistry of its atmosphere [96, 97]. Indeed, about a quarter of white dwarfs, which is close to the fraction of stars that have planets, exhibit excessive metallicity of their atmospheres. This means that the end of the evolution of the central star does not terminate the evolution of its planetary system [96, 98].

4.2 Results

Summarizing the description of the evolution of circumstellar ACP material, we conclude that its evolution is an important and by now reliably established part of the evolution of all planetary systems (see Fig. 2). The Oort Cloud, created by distant giant planets, serves as a 'bank' of ACP objects, supplying ACP regions to 'hot' orbits in the inner part of planetary systems, again with the help of the giant planets. At the same time, distant giant planets continue to replenish the star's comet spear. The evaporation of icy nuclei of comets and collisional evolution of asteroids support the constant renewal of the dusty component of the zodiacal starlight.

It is possible, for example, that comets are the main suppliers of water to the inner 'hot' terrestrial planets, probably formed from the original dehydrated solid material. Thus, it is not ruled out that the evolution of Oort cloud comets considered in this section, driven by Jupiter, is an important part of the evolution of Earth's water envelope, whose presence is an inalienable part of the process of the emergence and development of life on Earth. Terrestrial planets near solar-mass stars probably arise from dehydrated minerals. The icy shells of dust particles in this 'hot' region are evaporated, and steam is removed from the circumsolar space by the stellar wind inherent in these stars. Such a wind is especially intense at the early stages of the evolution of solar-type stars. The inner terrestrial planets, being potential carriers of life, are watered by distant and cold giant planets, which store water in the form of icy nuclei of comets in the Oort clouds of their stars. The same giant planets, supplying part of the comets to the inner 'hot' zone of the star, constantly enrich the shells of 'hot' planets with water. Dwarf planets either have too low a mass, like Mars, or are too 'hot,' like Mercury, and hence are probably unable to hold the water supplied to their shells by comets, remaining largely dehydrated. Earth turned out to be able to retain water due to its parameters and the parameters of its orbit around the Sun, which eventually turned it into a cradle of life. Thus, it is possible that Jupiter is an active and major participant in the process of the emergence of life on Earth.

5. ACP and streams of stars and star clusters

5.1 ACP spears of stars

The history of the study of star clusters is an essential part of the history of astronomy itself. The Greek astronomer Ptolemy in the *Almagest*, in the 2nd century AD, mentioned the first star clusters as nebulae. The introduction of the telescope into astronomical practice by Galileo allowed Messier [99] and Herschel [100] to compile the first catalogs of star clusters. Interestingly, already at the end of the 19th century, it was clear that star clusters would probably disintegrate with time, turning into stellar streams [101]. The study of star clusters of different ages played a decisive role in the development of modern ideas about the evolution of stars [102, 103]. Chandrasekhar [104] found that star clusters are unstable, and their stars evaporate over time, i.e., leave their parent clusters. The history of the question of the origin and evolution of star clusters as members of associations of young stars several hundred parsecs in size is interesting. The introduction of the concept of gravitational instability of cold gas clouds [105] allowed introducing the concept of OB associations as a result of the collapse of gas clouds about the thickness of the Galaxy in size [106].

Cluster stars, like field stars, have planetary systems which, as we see below, produce interstellar ACP objects, which create a relatively dense ACP environment of the cluster. We therefore consider some features of the evolution of planetary systems of star clusters. At least 30% of cluster stars with masses of the order of the solar mass are born surrounded by protoplanetary disks [107]. The size of these disks is ~ 100 AU and the mass is 10^{-3}–$10^{-2} M_\odot$ [108–110]. The final distribution of the Solar System planets over the semi-major axis of their almost circular orbits is described by a logarithmic law, known as the Titius–Bode law [8, 108–110]:

$$\mathrm{d}N \approx 3\mathrm{d}\,(\log a)\,. \tag{9}$$

This distribution guarantees the stability of planetary orbits with a mass of the order of the Jupiter mass, placing neighboring planets outside their Roche lobes. The power-law nature of the Titius–Bode law implies Eqn (3).

The protoplanetary disk and its ACP objects are located in the gravitational potential well of the central star. Estimates and numerical modeling [10] show that the situation changes with the appearance of massive Jupiter-type giant planets far from their stars. Gravitational interaction of ACP objects with the potential of the Jupiter + Sun system is capable of accelerating ACP objects to hyperbolic velocities of the order of 1 km s^{-1} at infinity [111]. The corresponding condition is given in Eqn (8). In the Solar System, along with Jupiter, the role of an accelerator is claimed by Saturn, Neptune, and Uranus. The ACP objects ejected from their parent planetary systems, due to the comparative smallness of the initial velocity 'push' compared to the orbital velocity of the star in the Galaxy, first form a relatively short ACP stream extending along the star's orbit in the cluster and symmetric with respect to the star; it is called the cometary spear [50]. Some of the ACP objects leaving the parent planetary systems also leave the parent open low-mass star clusters. The escape velocities from these clusters are small, not exceeding several kilometers per second. The stellar part of the streams generated by clusters has long been known. Flammarion, according to Holmes (1894), was the first to pay attention to the linear structure of the stars near the Pleiades, calling it a 'stellar road.' Holmes himself calls such structures 'stellar streams,' thereby introducing the modern term.

The velocities of ACP objects lost by planetary systems (0–3 km s^{-1}) [10] are small compared to the orbital velocities of stars in the Galaxy, ~ 250 km s^{-1}. This determines the width of the ACP streams of stars and clusters in the Galaxy, ~ 50 pc. Interest in interstellar ACP streams is stimulated and supported by the discovery of their two representatives, extrasolar asteroids 1I/Oumuamua and 2I/Borisov [112, 113]. Microlensing allows detecting interstellar planets lost by parent stars [114]. This puts the question of free ACP objects on a solid observational basis. Interestingly, some of the meteorites of terrestrial collections once belonged to other stars. The task is to identify them.

5.2 Sources of replenishment of stellar ACP spears of stars

The ACP spears of stars are replenished due to two main sources. The first, as mentioned above, is the acceleration of ACP objects of stars by giant planets with masses and semi-major axes that satisfy condition (5). The second source is the acceleration of the Oort cloud objects by the field stars of the Galaxy and the stars of their star cluster that penetrate the Oort clouds in the course of evolution. An estimate shows that, during the Sun's lifetime, about 10^4 field stars penetrate into the Sun's Oort cloud, eventually enriching the population of the Sun's ACP spear and, probably, considerably impoverishing the population of the Oort cloud [46]. We note that the number of ACP objects currently inhabiting the Oort cloud remains unknown. A conservative estimate of the number of comets in the Oort cloud is $\sim 10^{12}$ objects [115]. The characteristic velocity of ACP objects at the outer edge of the Oort cloud is several meters per second. Knowing that a star with a planetary system is armed with an ACP spear, we can wonder about searching for them and detecting their meteor showers. The circumstellar part of the ACP spear looks like two oppositely directed jets ~ 30 pc wide. The spear is directed along the orbital motion of the star. Consequently, the Sun, moving in the Galaxy, falls into the spears of neighboring stars. The proximity of a star to the Sun is one of the conditions for the relatively high spatial density of ACP objects of that star. An example of a list of stars that crossed the Oort cloud less than 1 million years ago is given in [50]. It is possible that some of these stars also have ACP spears.

5.3 Interstellar ACP spears

The understanding that planetary systems can extend to interstellar (Oort cloud) scales led to formulating the problem of searching for representatives of the ACP structures of other stars. Such objects were found both among objects with hyperbolic velocities (asteroids 1I/Oumuamua and 2I/Borisov) and among circumsolar objects possibly captured from the interstellar medium by the Sun + Jupiter system [116]. While interstellar dust grains are sought among meteor showers in circumsolar space, the interstellar planets of other galaxies are sought by the microlensing method [114]. The high prevalence of planetary systems losing ACP objects and the interaction of field stars with the ACP Oort clouds of planetary systems [117] make the interstellar ACP component of the Galaxy abundant, and elucidation of its main parameters is a matter for the near future. True, the hope of finding stars that were born in the same cluster and OB association as the Sun [118] seems so far unpromising, because the stellar spear of the Sun's parent cluster, which includes several hundred stars, now occupies the volume of $\sim 10^8$ pc^3, as shown above. In astronomy, OB associations are usually understood as gravitationally unbound groups of young ($\leqslant 10^7$ years) stars with a size of the order of the thickness of the galactic gaseous disk, ~ 100 pc.

Observed star clusters decay over time, losing their components: asteroids, comets, planets, and stars, which form ACPS spears of clusters (Fig. 5). We consider the conditions for the formation and destruction of ACPS spears of star clusters and OB associations. The velocities of 'free' ACP objects leaving the Solar System and accelerated by Jupiter are ~ 1.0 km s^{-1} [10]. Such velocities are sufficient for accelerated ACP objects to escape not only from native planetary systems but also from open star clusters with masses less than $10^3 M_\odot$ if these stars are their constituents (Eqn (3)). As a result, star clusters form their ACP spears over time. The population of ACP spears of clusters is continuously replenished by stars that leave the cluster as a result of the gravitational interaction of stars in the cluster with each other [14]. With time, such a spear turns into an ACPS stream on a galactic scale, which persists for a long time even after the evaporation of the star cluster, with a characteristic lifetime of about 10^8 years [119, 120].

5.4 Decay of star clusters

It has long been clear that most open clusters are destroyed during the initial star formation outburst after the quick loss

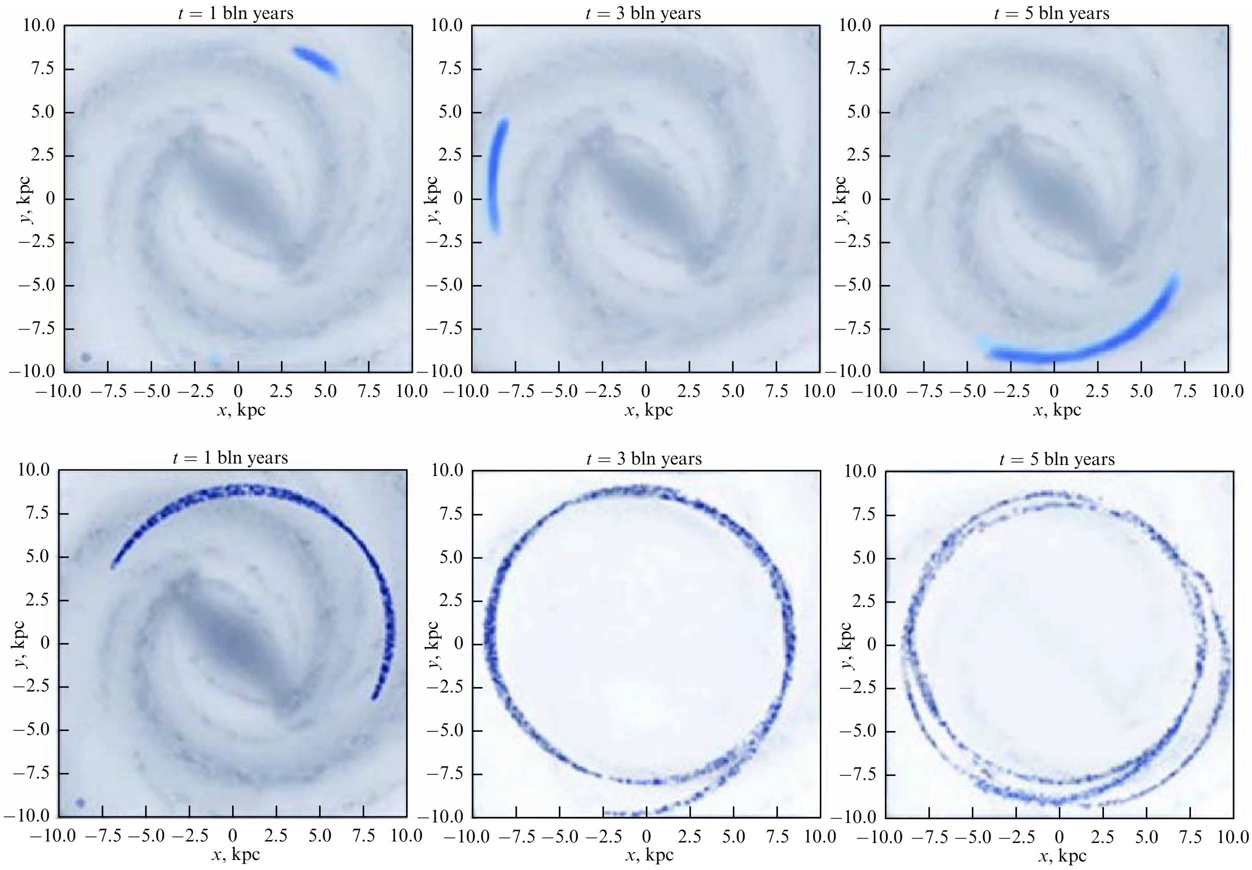

Figure 5. Evolution of a cloud of stellar spears representing cluster stars (light blue stream, top panels) and OB associations (blue dots, bottom panels).

of the gaseous component ionized by the young massive stars of these clusters [15]. This allows reliably drawing a borderline between masses of star clusters, which are stellar systems with a single episode of star formation, and galaxies, with their potential for repeated or quasistationary star formation. The rate of expansion of the ionized gas is ~ 10 km s^{-1}, and the Keplerian velocity of galaxies and star clusters is determined by Eqn (4). Comparing the latter rate with the rate of removal of ionized hydrogen, we find that the gas of stellar objects with a mass less than $\sim 1.6 \times 10^5 M_\odot$ can be removed from them via hydrogen ionization by their massive stars. Consequently, such stellar systems can be called star clusters with a single star formation episode. More massive stellar systems retain their gaseous component during star formation, which allows star formation to be prolonged, depending on ionization and supernovae in the galaxy [121]. This simple estimate of the borderline mass between clusters and galaxies practically coincides with the estimate following from observations [122]. Indeed, the most massive globular clusters ($M \geqslant 10^5 M_\odot$) show the presence of stars belonging to several generations [123].

Obviously, some of the young stars in our Galaxy are now in star clusters. If we assume that about 10% of the stars in open star clusters with masses of $\sim 10^3 M_\odot$ remain gravitationally bound after they lose the gaseous component at the time of their formation [15] and that the average lifetime of such clusters is $\sim 10^8$ years [124], then the total mass of stars in open clusters is about 10^{-3} of the mass of stars in the Galaxy. The characteristic velocities of stars in open star clusters (Eqn (4)) are of the order of 1 km s^{-1}. These velocities almost coincide with those of ACP objects accelerated by giant planets, as was discussed in Section 3. Thus, in a million years, giant planets forming stellar spears of their stars fill the volume of the cluster with ACP material. A continuous ACP medium is thus produced, which is still an invisible component of the cluster. In addition, it is clear that some of the fast ACP objects leaving their stars also leave their cluster, thus forming the cluster's ACP spear. It is clear that, in the course of their motion, the cluster stars continuously accelerate the ACP objects of the cluster's interstellar medium and the ACP objects of the cluster stars to velocities sufficient to leave this cluster. This is the second mechanism of feeding the cluster's ACPS spear. The cluster's ACPS spear is again, like a stellar ACP spear, formed due to the angular momentum conservation law (see Fig. 5).

The spatial speed of a cluster during its rotation around the center of the Galaxy is ~ 240 km s^{-1}, and the speed of the departing ACP objects of the cluster stars and the departing stars of the cluster themselves is about 1 km s^{-1}. This determines the final width of the ACPS spear of the cluster in the Galaxy to be ~ 60 pc. It hence follows that, as a result of the acceleration of ACP objects by giant planets and cluster stars, all star clusters are 'armed' with ACPS spears. Due to the relatively short characteristic lifetime of open clusters, $\sim 10^8$ years, the characteristic spear length of a mature cluster should be ~ 100 pc. The stellar components of these spears have already been found for three star clusters that are 10^8 years old. Among them is the Pleiades cluster. There is no doubt that the stellar spears found in these clusters also contain an ACP component. The final result of the evolution of a star cluster is the complete decay of the stellar component and the transformation of the cluster into an ACPS stream (see Fig. 5). Such streams are an essential part of the stellar component of the disk of our Galaxy and other disk galaxies. We recall that most clusters decay at the moment of formation due to loss of the gaseous component [15]. That is, in this case, the decay of the cluster at its birth leads to the appearance of a stellar spear in it and then to its transformation into an ACPS stream. The ACP component of these streams is formed after the formation of sufficiently distant massive planets of the stellar stream of cluster stars. Therefore, the formation of an ACPS spear of a cluster is a more frequent phenomenon than the formation of gravitationally bound star clusters themselves. Because almost all stars are born in clusters, the disk component of galaxies may eventually be the sum of ACPS spears of decayed star clusters.

Star formation in disk galaxies goes as follows. The gaseous disk of galaxies is inhomogeneous; it includes giant molecular clouds with sizes of the order of the disk thickness, 100–200 pc. The mass of gas clouds grows with time and, upon reaching a critical value, their collapse begins. In spiral galaxies, the collapse is usually triggered by a spiral shock wave caused either by gravitational interaction with nearby galaxies or, possibly, by the interaction of the gaseous disk with the eccentric gravitational potential of the galaxy's dark halo [125]. The collapse of molecular clouds of galaxies that do not have a dark halo begins when they reach the Jeans mass limit. With the beginning of the collapse in giant molecular clouds with a mass of 10^5–$10^6 M_\odot$, the inherent inhomogeneities with the mass spectrum in Eqn (1) divide these clouds into gaseous protoclusters with masses of several hundred thousand solar masses. The collapse of these giant gas clouds creates the observed pattern of OB associations, in which a practically continuous stellar field 100–200 pc in size is the product of the decay of young star clusters under the effect of the loss of gas. Only several percent of all the resulting star clusters in the indicated field of 100–200 pc remain gravitationally bound. The velocity dispersion of stars of OB associations is ~ 10 km s^{-1} (see Eqn (4)). In the absence of gravitational closure of the OB association stars, the tidal force from the Galaxy turns it over time into a stellar stream ~ 200 pc wide and $\sim t/10^6$ years long. That is, in $\sim 10^8$ years, the OB association takes the characteristic shape of a stellar spear with several gravitationally bound star clusters remaining in it (see Fig. 5). The length of the spear increases with time, and the ACPS stream becomes almost annular in the Hubble time. This broad stream consists of narrower ACPS streams that decayed during the evolution of the OB association of star clusters. This is the ultimate structure of the stellar disk of all disk galaxies.

Note that the binarity of star clusters is very low for two obvious reasons. The absence of a close binary, a product of the collapse of a molecular cloud, is a consequence of the fact that the size of the cloud is practically equal to the cluster size (see Eqn (2)). And there is no wide double of gravitationally bound clusters, because the Roche lobes of clusters exceed the size of the clusters themselves by only a few times, and most clusters are destroyed at birth, having lost the gaseous component [15].

5.5 ACP spears of star clusters

In recent years, work has intensified on the search for stellar spears of star clusters; stellar spears, usually called tidal tails, have been found in many nearby clusters [126]. A stellar spear almost 1000 pc long was found near the globular cluster ω Cen [127]. With the observed relative velocities of the spear stars within 10 km s^{-1}, the age of the observed part of the spear is less than $\sim 10^8$ years. The total mass of the ω Cen spear is about 10% of the cluster mass [127]. Stellar streams often include several clusters in close orbits, and this probably indicates that such streams are created by OB associations [128]. Some of the observed streams even contain globular clusters [129, 130]. This means that the source of the stream may be not only the globular cluster itself but also, possibly, a low-mass galaxy destroyed by the tidal effect of the Galaxy, which had included these clusters in its composition. Naturally, the stellar stream component is only a part of the ACPS spear.

Recent work demonstrates the wide distribution of discovered stellar spears of open and globular star clusters. Studying the structure of 389 nearby open clusters in our Galaxy allowed establishing the presence of stellar spears in 71 of them [131]. The authors traditionally call them tidal tails, although their nature is different. This means that open star clusters are much larger than is commonly believed. An extensive study of globular clusters in the neutral regions of the Galaxy [131] has demonstrated the presence of stellar spears of about a dozen globular clusters. It should be recognized that only the inner, densest parts of the most massive star clusters are presently accessible to observational detection. But stellar spears and stellar streams accompany almost all star clusters that lose their stars over time due to internal causes.

Under the gradual formation of stellar spears of long-lived star clusters, low-mass stars are the first to leave clusters. Massive stars escape the cluster later. As a result, there is a mass gradient of stars along the spear. Such a gradient was found using the numerical model of N gravitating point masses. The decay of star clusters and OB associations results in well-defined stellar streams of various lengths in the solar neighborhood [132–134]. Some of the studied streams demonstrate their kinematical similarity with known star clusters [135]. To summarize the presented brief description of the pattern of destruction of open clusters and OB associations with time, we can conclude that such processes first lead to the inevitable appearance of ACPS spears of these objects. The end product of the decay is an ACPS stream of galactic proportions, with the width determined by the ratio of the Keplerian velocities of the destroyed object and the Galaxy.

6. Formation of stellar streams during the destruction of galaxies

The structure of the Universe is such that most of its visible matter is concentrated in galaxies that form galaxy clusters. Galaxies are divided into disk ones, rich in gas and young stars (S), irregular (Irr), almost gas-free elliptical (E), and spheroidal (S0). A detailed study of the properties of galaxies leads to the conclusion that almost all galaxies have spheroidal and disk components, respectively represented by bulges for disk galaxies and compact nuclear star-forming gas disks for E-galaxies. The relative fraction of the bulge mass increases with the mass of the galaxy [136]. The central most massive galaxies in clusters (cD) are ellipsoidal, which emphasizes the role of collisions and mergers of galaxies in the formation of cD and E galaxies, as well as of the bulges of disk galaxies [137, 138]. The high abundance of E-galaxies and bulge disk galaxies is a probable consequence of the high density of galaxies in clusters and collisions between galaxies.

In the first approximation, the gaseous disk of a galaxy can be represented by a disk with radius R and thickness H. Interestingly, H and R can be related by a simple formula within the diffusion model of the expansion of the gaseous disk of a galaxy during its evolution. The expansion time of a gaseous disk is $T_{\rm d} = R^3/(H^2 v_{\rm k}) = T_{\rm H}$, where $T_{\rm H}$ is the Hubble time and $v_{\rm k}$ is the Keplerian velocity at the edge of the disk (see Eqn (4)). This equation implies that

$$\frac{H}{R} = 0.045\left(\frac{M}{10^{11}M_\odot}\right)^{1/8}. \tag{10}$$

In deriving relation (10), we assumed that diffusion occurs due to the turbulence of the gas disk with a scale of the order of its thickness and the velocity of the turbulence elements of the order of the orbital velocity times the ratio of the gas disk thickness to its size. The observed thickness of the thick gaseous disk of our Galaxy at $R > 8$ kpc is about 400 pc, or $H/R \approx 0.05$ [139], which is close to the above estimate. Thus, the initial dimensions of a disk galaxy are probably set by the initial angular momentum of the gas associated with the mass of this galaxy [19]. This estimate is valid for stationary disks of galaxies. The thickness of the gaseous disk, which is controlled by supernova formation in it [140], cannot significantly exceed the above estimate.

Let us consider some features of the evolution of galaxies in their clusters. The sizes of galaxies and their clusters are correlated with their masses, as indicated in Section 2.2 (see Eqn (3)). This allows estimating the average time $T_{\rm coll}$ between collisions of galaxies with each other in a common cluster. We find that $T_{\rm coll} \approx 10^9(M/10^{15}M_\odot)^{1/4}$ years. This means that, during the cluster lifetime, which is close to the Hubble time, an ordinary galaxy undergoes about ten collisions. The comparability of the sizes of galaxies and their clusters makes the collisional evolution of galaxies saturated. This significantly enriches the evolution of galaxies, leading to a number of interesting phenomena and leaving the participants in direct collisions with a number of morphological consequences. It is interesting that direct collisions are not necessary to accelerate the star formation process; tidal influence during their close passage is sufficient.

The approach of galaxies can then lead to the destruction of the smaller-mass galaxy. We consider the conditions necessary for the beginning of tidal destruction of a galaxy of small mass m in the gravitational field of a more massive galaxy with mass M_0. For the massive galaxy, we assume a constant rotation speed independent of the distance to its center R, which fixes the relation of the mass and tidal density to the distance R. By the tidal density, we mean the ratio of the mass $M(R)$ to the cubed distance to the center. We assume that the radius r of the smaller-mass galaxy is equal to Kr_0, where $r_0 \approx 2m^{1/2}$ (see Eqn (3)). A simple estimate shows that the average density of the smaller galaxy becomes equal to the local tidal density of the massive galaxy for

$$K \geqslant \alpha\left(\frac{M_0}{m}\right)^{1/6}, \tag{11}$$

where $\alpha = R/R_0$ and R_0 is the radius of the massive galaxy. It is clear from the last relation that galaxies with a low surface density ($K > 1$) can start being destroyed by tides even before reaching the outer boundary of a massive satellite. For the destruction of ordinary-density galaxies ($K = 1$), a small galaxy must plunge into the larger galaxy by a distance $R = (m/M_0)^{1/6}$. The immersion of low-mass galaxies into the dense nucleus of a massive galaxy is necessary for their destruction, because the average density of galaxies decreases with increasing mass in accordance with Eqn (3). The destruction of the satellite galaxies of massive galaxies creates a 'tangle' of stellar streams and eventually stellar spheroidal bulges of massive galaxies.

The interaction of galaxies with the dense gas of their cluster nuclei leads to the appearance of jellyfish galaxies or gaseous and stellar tails of galaxies. ESO 137-001 of the Norma cluster [141] is an example of a galaxy with a well-developed stellar tail resulting from the pressure of the oncoming intergalactic gas on the gaseous component of the galaxy. The stellar tail of this galaxy is ~ 20 kpc wide and has a length of 60 kpc; the mass of the gas in it is $\sim 10^9 M_\odot$. Low-mass disk galaxies are mostly composed of gas. Tidal destruction of such galaxies leads to the appearance of gas streams at the periphery of massive galaxies. A good example of such a stream was found recently at a distance of about 20 kpc from the center of our Galaxy [142]. A gas stream with dimensions 1000 pc $\times$ 200 pc has a mass of $\sim 10^5 M_\odot$ and expansion velocity of ~ 10 km s^{-1}. These parameters correspond to a gas object destroyed by tides about 10^8 years ago.

Another interesting consequence of the presumably frequent collisions of galaxies in their clusters is the formation of gaseous components of new low-mass galaxies without a dark halo [143]. Indeed, it was previously found that low-mass galaxies typically have no dark component [144]. Therefore, it is possible that galaxy collisions are the cause of the appearance of such galaxies. Other possible consequences of galaxy collisions are their destruction and the formation of new galaxies [145]. Note that the presence of a dark halo is not necessary for all stellar complexes. Its presence is typical of the most massive galaxies, but, for example, star clusters are likely to still be free from the dark component.

The number of known galactic-scale stellar streams rapidly increases with time. As a result, the observed picture of the destruction of dwarf galaxies in the gravitational field of massive galaxies is being substantially enriched. The developed stellar structures of the destroyed satellites of galaxies demonstrate a pattern of stellar streams from the initial stage of their evolution to the appearance of annular stellar streams around the massive galaxies that destroy these dwarfs. A detailed study of the spatial velocities of galactic halo stars in the Sun's neighborhood has shown that about 20% of them are organized into 12 stellar streams, the remnants of the absorbed satellites of the Galaxy [146]. At the same time, retrograde streams are distinguished not only by a low metallicity but also by their large age compared to other stars in the galactic halo.

As shown above, galaxies lead an active life in dense clusters. In addition to the evolution of the stellar and gaseous components that constitute the main life-long occupation of isolated galaxies, cluster galaxies can actively interact with their satellites, neighbors, and intergalactic gas (Fig. 6). The gas can both supply central, massive cD galaxies of the cluster with gas and deprive fast galaxies of the cluster of their gaseous component due to the incoming gas pressure. Galaxy collisions not only influence the evolution of the stellar and gaseous components of colliding galaxies but also stimulate the accretion activity of their central SMBHs.

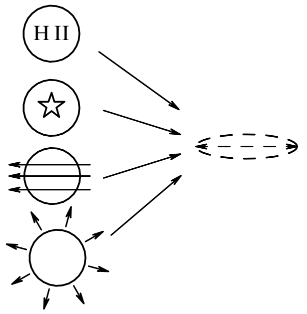

Figure 6. Options for the destruction of galaxies transforming them into stellar streams.

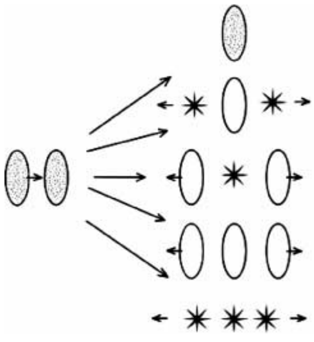

Figure 7. Scenarios of collisions of disk galaxies.

The interaction of galaxies in dense clusters often leads to their decay and transformation into gravitationally unbound streams of stars. The causes of the destruction of galaxies can be outbursts of star formation in them, collisions of gas-rich galaxies (Figs 6 and 7), and tidal decay during their tidal interaction with the central massive galaxy. The end result of the destruction of galaxies with stellar populations is the appearance of a stellar stream extending along the orbit of the destroyed galaxy around the more massive satellite or its orbit in a cluster of galaxies. A detailed study of the halo of our Galaxy showed that it is in fact the sum of relatively narrow stellar streams, the products of the destruction of satellites of the Galaxy [147]. Our simulation confirms this conclusion.

The stream length is determined by its age and the speed of its constituents. The ratio of the width of the stellar stream (the product of the destruction of a galaxy satellite) to the final size of the annular stream is close to the ratio of the characteristic speed of stars of the destroyed satellite to the characteristic speed of stars of the destroyer galaxy. For $M \sim R^2$ (see Eqn (3)), that ratio is $\sim (m/M)^{1/4}$, where m is the mass of the tidally destroyed galaxy and M is the mass of the destroyer galaxy. The last ratio can serve as a measure of the mass of a galaxy destroyed and turned into a stellar stream. The stream length, as usual, is a measure of its age.

We consider here the conditions and characteristic time for the dissipation of galactic stellar streams that arose in the decay of low-mass satellites. Let a stellar stream be formed as a result of the decay of a galaxy with a velocity dispersion σ in it. The mass of the larger spherically symmetric galaxy, including this stream, is M, and its radius, R. The velocity dispersion of perturbing objects with mass m is $v = \sqrt{GM/R}$. The radius of the zone of significant perturbation of the velocities of the stream stars by a quantity of the order of σ is $r = Gm/(v\sigma)$. Then, the time required to change the speed of the stream elements by an amount of the order of σ or, in other words, the stellar stream destruction time $\tau_{\rm ff}$, is (see (2))

$$\tau_{\rm ff} = \tau_{\rm d} \left(\frac{\sigma}{v} \right)^2 \frac{M}{m} \,, \tag{12}$$

where $\tau_{\rm d} = R^{3/2}/\sqrt{GM}$ is the dynamical time of the galaxy. For $M = 0.2R^2$, we have $\tau_{\rm ff} = 10^8 (M/10^{11} M_\odot)^{1/4}$ years and $\sigma/v \cong (m_0/M)^{1/4}$, where m_0 is the mass of the galaxy disintegrated into a stellar stream. Relation (12) allows appreciating the role of various factors of a gravitational nature in the expansion of stellar streams arising from the destruction of galaxies. The leading one is the ratio of the mass of a galaxy to the mass of the perturbing elements. For stars, the ratio is $M/m \cong 10^7$–10^{11}, which allows stellar streams in galaxies to 'outlive' the Hubble time. Stellar streams from the decay of low-mass galaxies in dense galaxy clusters can be destroyed in the Hubble time by galaxies of the same cluster, eventually forming the observable continuous stellar medium of the cluster.

To successfully identify stars in the stream originating in destroyed galaxies in the stellar background of an accretor galaxy, a low background brightness is required. This condition makes it obvious that the known stellar streams of galaxies are typically located in the peripheral regions of galaxies with a low surface brightness of the stellar background. The search for stellar streams in areas of high surface brightness requires extensive analysis of the kinematics and chemistry of background stars in order to identify the stream stars.

Other possibilities for the destruction of galaxies and the appearance of stellar streams are associated with global outbursts in star formation in galaxies, leading to their decay after the removal of gas by massive supernovae (see Fig. 6). One of the causes of such an outburst may be the mutual approach of galaxies in the course of their motion in the cluster. It is likely that such outbursts occurred in the Leo I galaxy, as evidenced by the analysis of the existing observational data [148]. The galaxies destroyed in the course of collisions and outbursts of star formation in them eventually replenish the field of intergalactic stars of galaxy clusters. The observations do show a marked increase in the fraction of such stars in a cluster of galaxies over time. This fraction is $\sim 40\%$ at $z = 0$, but does not exceed $\sim 20\%$ at $z = 0.5$ [149].

The thick stellar disk and the stellar bulge of the Galaxy are represented by two stellar families: the extremely old first stars of the Galaxy and the stars of the tidally destroyed low-mass satellites of the Galaxy. The separation of these components is a complex problem whose solution can be facilitated by a joint analysis of the kinematics of stars and their chemical composition. The noticeable bimodality of [O/Fe] at $[\mathrm{Fe/H}] \leqslant -0.5$ is well known [150]. This bimodality is a manifestation of the presence of these families. Stars with a high [O/Fe] ratio are probably extremely old stars in the Galaxy, and stars with a low [O/Fe] ratio are stars of low-mass galaxies that were swallowed up by our Galaxy in the past. The relatively low abundance of oxygen in these stars can be explained by the high intensity of the galactic winds of these galaxies, generated by intense star formation with bursts of massive supernovae and the low gravitational potential of such galaxies.

Approaches and collisions of galaxies in the course of their motion in clusters create conditions for enhanced star formation in their gaseous disks. E- and S-galaxies, blown through by the galactic wind, are unable to accumulate gas in their peripheral regions. The wind in them is heated and supported by the bursts of SNIa supernovae. However, estimates show that the energy of such supernovae is not enough to prevent the cooling of gas in the dense nuclei of these galaxies, which leads to its accumulation over time. As a result, the star formation activity in the nuclei of spheroidal galaxies can be an effective mechanism for both the recurrent activity of circumnuclear gaseous disks of such galaxies [151–153] and the accretion activity of SMBHs in their nuclei [154]. Indeed, the proportion of galaxies with active star formation is markedly increased in the dense nuclei of galaxy clusters. The most massive galaxies with accreting SMBHs, quasars and active galactic nuclei, are also concentrated there.

6.1 Retrograde stream motion in the Galaxy

Clear evidence of the active absorption by our Galaxy in past epochs of some of its satellites is provided by the existence of an extensive population of stars with retrograde spatial rotation (i.e., reverse relative to the galactic disk rotation) of the main mass of the disk and the bulge of the Galaxy. The first to consider such stars were Parenago [155] and Vorontsov-Velyaminov [156]. Modern studies have shown that the retrograde stellar population of the galactic halo is the product of absorption by the Galaxy of its low-mass satellites. In addition to its kinematics, this population is distinguished by a low abundance of heavy elements [157, 158]. This 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 metallicity $[Fe/H] < -1.0$ revealed several isolated groups of stars with similar orbital parameters. As it turned out, these groups are stellar streams produced in the decay of satellite galaxies absorbed by our Galaxy in the past. They clearly demonstrate the features of assembling the stellar bulge and the halo of our Galaxy. Halo stars with $[Fe/H] < -2.5$ are the sum of two almost equal populations: those with prograde and those with retrograde motion around the galactic center [159]. Most of these stars previously belonged to satellites with random orbital directions absorbed by the Galaxy during its formation. A detailed analysis of 23 stellar streams of the Galaxy allowed finding the dwarf galaxies that are progenitors of some of these streams. Eight of the observed streams turned out to be associated with massive globular clusters, probably former constituents 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 [160] showed that, at $[Fe/H] \geqslant -1.0$, most of them have a common galactic direction of rotation and a relatively low (less than ~ 0.3) eccentricity of orbits, and their orbit planes are close to the plane of the Galaxy. This means that these stars originated in the disk of the Galaxy. Satellites with $[Fe/H] < -1.0$ often have high-eccentricity and even retrograde orbits around the galactic center. Their orbit planes deviate significantly from the plane of the Galaxy. We add that the pericenters of the orbits of the studied satellites are in the range of 0.5–30 kpc, and the apocenters are in the range of 2–100 kpc [160]. Evidence of the active role of mergers in the evolution of the Galaxy is also provided by the presence of stars with velocities close to or even greater than the escape velocity of ~ 445 km s^{-1} [161]. All this is evidence of the past activity of the Galaxy in the absorption of its satellite low-mass galaxies.

6.2 Consequences of collisions of galaxies

Let us consider the observed consequences of the collision and merger of galaxies. Figures 6 and 7 show scenarios of these processes. Some galaxies are members of their dense clusters. At the same time, the example of our well-studied Galaxy shows that massive galaxies are immersed in a cloud of their satellites, whose number reaches many dozens [162]. In the process of cluster evolution, high-speed collisions clear galaxies of gas (see Fig. 6), which may be one of the causes of the appearance of S0 galaxies [163].

Collisions with low relative velocities and gravitational deceleration lead to the merger of galaxies, and this leads to several observable consequences, such as the retrograde rotation of some of the stars of galaxies [164, 165] and the appearance of double galactic nuclei [166]. A detailed analysis of the chemical composition of stars allowed establishing that stars with retrograde rotation in the Galaxy have an order of magnitude lower metallicity than other stars [167]. In addition, the merger of galaxies explains the presence of binary stars outside the central nuclei in a significant number of observed galaxies [166, 168]. The accretion activity of some quasars is provided by mergers of dense nuclei of colliding galaxies [169].

7. Causes of the destruction of galaxies and their satellites

7.1 Destruction of the stellar component of a galaxy

The wide distribution of relatively narrow stellar streams found near galaxies raises the question of the conditions for their formation [147]. A possible scenario for the appearance of such streams is associated with the destruction of one of the interacting galaxies (see Fig. 6). Observations have shown [170] that up to 20% of starlight from clusters of galaxies belongs to the continuous stellar background of these clusters and cannot be directly associated with individual galaxies. During their evolution in clusters, a significant proportion of galaxies decay for various reasons, thus forming a continuous stellar background of the cluster.

An example of a gaseous component of a galaxy destroyed in a collision [171] is the Leo Ring Cloud. Here, the giant gaseous ring (with a radius of about 10^5 pc) of neutral hydrogen is devoid of stars and has an almost solar metallicity. The mass of neutral hydrogen in this ring is $\sim 2 \times 10^9 M_{\odot}$, and the expansion rate is ~ 100 km s^{-1}, which corresponds to the age of $\sim 10^9$ years. The cause of the formation of such a ring may be an outburst of star formation in a precursor disk galaxy or a collision of two galaxies at hyperbolic velocities (see Fig. 7). These processes could significantly reduce the mass of the galaxy by 'liberating' its gaseous component.

The role of galaxy collisions in the formation of stellar halos of massive galaxies has been quantified using our Galaxy as an example [172]. The study of degenerate dwarfs close to the Sun has shown that about 15% of them are relatively young (their ages are several billion years) but have high spatial velocities corresponding to the stars of the galactic halo. Because the formation of 'native' halo stars was completed about 10 to 12 billion years ago, young degenerate halo stars are probably the decay products of young dwarf satellites of the Galaxy, absorbed in the course of its evolution.

7.2 Role of intergalactic gas in the evolution of galaxies

The observed cluster galaxies are immersed in a relatively dense intergalactic gas with the density $n_{\rm H} = 10^{-3}$–10^{-2} cm^{-3} [173]. The interaction of this gas with the gaseous component of moving galaxies can lead to the appearance of stellar tails in them (see Fig. 7). These are the so-called 'jellyfish' galaxies [174–176]. The stellar tails of jellyfish galaxies are bimodal. Some of these tails owe their appearance to the loss by the galaxy of its dense peripheral gas due to the pressure of intergalactic gas advancing at a speed of up to 1000 km s^{-1}, followed by star formation in the lost gas [177]. The other part may be the product of star formation in the dense intergalactic gas streaming around a moving galaxy with density $n_{\rm H}$. The condition for the cooling of the gas during the motion of a disk galaxy with a velocity of the order of the parabolic one at its edge is given by

$$n_{\rm H} > \frac{0.005}{k^2}\left(\frac{M}{10^{11}M_\odot}\right)^{1/4}{\rm cm}^{-3}\,, \qquad (13)$$

where k is the coefficient in relation (3) for the mass and radius of a galaxy [19],

$$\frac{R}{\rm pc} = k10^4\left(\frac{M_{11}}{M_\odot}\right)^{1/2}. \qquad (14)$$

It follows from relation (13) that cooling of the intergalactic gas and star formation in it are possible in low-mass galaxies with $k \simeq 2$–3 (low surface brightness), moving in the dense nuclei of their clusters, which is indeed observed.

The loss of gas by a disk galaxy leads to a decrease in its density and surface brightness. Observations show that the sizes of low surface brightness galaxies are increased by several times relative to normal sizes [178]. The low surface density of such galaxies makes it easier for them to lose gas due to the pressure of the incoming gas of the environment [179, 180]. In this case, the galaxy not only may lose the gas but also can be entirely destroyed in the dense nuclei of galaxy clusters. As a result of the destruction of such galaxies, stellar streams can form. Dense star clusters can then be located inside stellar streams. Therefore, the observed stellar streams of the nature under consideration can be of interest as signatures in the search for new star clusters belonging to other galaxies.

The answer to the question about the nature of stellar streams in galaxies and their neighborhoods is not new. The synchronous spatial motion of stars was already attributed to the decay of star clusters about 100 years ago [181–183]. Recently, in connection with significant progress 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 thorough attention. Particular attention is devoted to the so-called Magellanic Stream, a gas-star structure connecting the Magellanic Clouds and our Galaxy. It covers about 200 degrees of the southern sky [184] and includes star clusters along with gas and stars. Numerical simulation suggests the scenario of the formation of this structure during the last encounter of the Magellanic Clouds with our Galaxy [185, 186]. It is possible that the approaches of the Magellanic Clouds to the Galaxy in the past occurred repeatedly, which complicates the observed picture and, naturally, the attempted interpretations with the help of models. The study of the Magellanic Stream and other stellar streams allows us to observe the pattern of tidal phenomena in the world of galaxies 'from the inside' and, in particular, to evaluate the role of the dark component of the Galaxy in its morphology.

Examples of decaying globular clusters observed as extended structures resembling 'stellar spears' (Palomar 5 and Palomar 15) several ten parsecs in size [187, 188] give an idea of the consequences of tidal disruption of relatively weakly bound stellar systems. In addition, these clusters may be the nuclei of tidally destroyed dwarf galaxies, which continuously replenish the stellar population of the galactic halo. Currently, more than 40 stellar streams are known in the Galaxy [189]. The study of the galactic halo with $[{\rm Fe/H}] < -2.0$ allows identifying kinematically distinguished stellar streams among them [190]. An analysis of the [O/Fe] and [Fe/H] values of halo stars led to the discovery of groups of low-metallicity stars distinguished by their chemical composition, which in the past belonged to nearby low-mass galaxies. They are continuously absorbed by our Galaxy in the course of its evolution in the Local Cluster [191]. The well-known bimodality of the distribution of low-metallicity stars in terms of the [O/Fe] ratio [192] is a possible consequence of the mixing of the oldest stars in the Galaxy with stars of the satellite galaxies absorbed by it.

To date, the most complete study of stellar streams in our Galaxy has been carried out by Ibata et al. [193] based on the Gaia DR2 and Gaia EDR3 catalogs. Streams associated with 11 globular clusters have been found, including ω Cen. The length of the observed part of the streams in the sky ranges from several to 100 degrees of the celestial sphere. Some of the stellar streams are likely to have belonged to dwarf galaxies destroyed by the tidal forces of our Galaxy. This is evidenced by the low abundance of iron, which does not exceed 10% of the solar abundance. The authors of [193] conclude that the halo of our Galaxy, woven from threads of stellar streams, resembles a 'ball of wool.' This conclusion can also be applied to the stellar component of stellar halos and other stellar disks of galaxies, as well as to the stellar medium of the field of galaxy clusters.

The study of the nearest massive neighbor of the Galaxy, the Andromeda Nebula [194], is indicative. Within 150 kpc of the Andromeda Nebula, several arched star formations are visible, including six globular clusters. These arcs are probable products of the tidal decay of Andromeda's satellites, resulting in the formation of stellar streams in the halo with a length of up to 120 kpc in the observed part alone. A comparison of the structures of the halo of our Galaxy and the Andromeda Nebula is indicative of the significant role played by the destruction of satellites of massive galaxies in the morphology of their stellar halos. A detailed study of the periphery of neighboring galaxies has shown that stellar streams of different shapes and different observed brightnesses are very diverse, as was demonstrated, for example, in [195–199].

Recent studies allow expanding the observed information on the effect of the pressure of the oncoming intergalactic gas on the morphology and evolution of galaxies. Its effect increases with the mass of the clusters, reflecting the role of the velocity and density of the gas. The intergalactic gas has been found to suppress star formation in galaxies by removing gas from them on a short time scale of $\sim 10^7$ years. The role of the star formation suppression effect increases as the redshift increases. Observations show that the oncoming gas of the cluster mixes with the gas of peripheral disk galaxies, and this leads to the appearance of dense gaseous tails of galaxies. It is interesting that star formation is observed in the densest gas tails of this kind. We note that the pressure of the oncoming intergalactic gas can also play an important role in the evolution of galaxy clusters. The rapid loss of gas by low-mass galaxies at high velocities due to the pressure of dense intergalactic gas leads to the decay of the stellar component of such galaxies with their transformation into a stellar stream.

7.3 Causes of destruction of galaxies and their satellites

We now discuss the possible causes of the destruction of cluster galaxies, which ultimately lead to the appearance of stellar streams of gravitationally unbound stars. These causes include the interaction of galaxies with the dense gaseous medium of galaxy clusters, collisions of galaxies, and outbursts of star formation in them, leading to the loss of a massive gaseous component (see Fig. 6). An observed example of the interaction of disk galaxies with the gaseous environment of their clusters are the so-called jellyfish galaxies, mentioned in Section 7.2. They are characterized by an umbrella morphology and active star formation at the edges. The length of the gas–star tails of such galaxies reaches 100 kpc, which, at the velocity of galaxies equal to 300 km s^{-1}, corresponds to their formation time of 3×10^8 years. Estimates show (see Eqn (13)) that this time is sufficient for the heated gas to cool and for stars to form in the streaming gas of the dense nucleus of the parent galaxy cluster (see Eqn (1)). An active increase in the observational base of jellyfish galaxies [200] and three-dimensional gasdynamic models of the interaction of inhomogeneous gas disks of galaxies with a dense gas of the environment [201, 202] have allowed visualizing the picture of this phenomenon. A list of 11 galaxies of this type is given in [203].

The loss of peripheral regions of the gaseous disk of moving galaxies under the action of the gas of the environment explains the appearance of rings of young stars near such galaxies, which are probably not gravitationally bound to them [175]. In addition, it is easy to imagine that fast motion in a dense gaseous medium can lead to a complete loss of gas by a galaxy (see Fig. 6). We find a condition for this to occur. In the framework of a single-zone homogeneous model of a galaxy with mass M and radius R, the condition for gas loss with an average density $\rho_g = 3M_g/4\pi R^3$ due to the pressure of the incoming gas of the environment (with density ρ_0) is given by

$$\frac{v}{v_k} \geqslant \left(\frac{\rho_g}{\rho_0}\right)^{1/2}, \qquad (15)$$

where v is the spatial velocity of the galaxy and $v_k = (GM/R)^{1/2}$ is the Keplerian velocity at the edge of the galaxy. It follows from the expression for v_k that, under condition (15), fast galaxies with a low surface gas density can indeed lose their gas in a dense gaseous medium of galaxy cluster nuclei. It becomes clear that elliptical or lenticular (S0) galaxies in dense clusters can lose gas not only under the action of type-SNIa supernovae but also due to the ram pressure of the intergalactic gas. The rapid removal of gas from galaxies in the dense nuclei of their clusters leads to a number of interesting consequences, shown in Fig. 7. If the mass of the gas of the galaxy was less than the mass of the stars, then a gasless galaxy would turn into an E or S0 galaxy without star formation and with wind supported by SNIa supernovae. Observations support the possibility of the formation of at least some E galaxies in the course of collisions of their predecessors [204].

If the mass of the stars of a moving galaxy was less than the mass of the gas in it, then the rapid loss of gas by such a galaxy would lead to the decay of its stellar component, eventually turning into a stellar stream along the galactic orbit within the cluster. Indeed, the mass of gas in low-mass disk galaxies ($M < 10^{10} M_\odot$) is often comparable to that of their stars [205]. This process is also possible for satellites of massive galaxies, whose gas loss is initiated by their powerful galactic wind. Such a wind can also be caused by the collision of galaxies, which increases the rate of star formation in them and the power of the galactic wind by a factor of several ten [205]. Collisions leading to an increase in the rate of star formation simultaneously lead to a sharp increase in the rate of supernova bursts associated with the end of the evolution of massive ($M \geqslant 8 M_\odot$) stars. This can also lead to the loss of the gaseous components of colliding galaxies and the subsequent destruction of their stellar components [138], with their transformation into stellar streams.

It was found in [206] that close satellites of the Galaxy typically belong to E-galaxies, while distant satellites are irregular and disk galaxies with gas and star formation. It is natural to assume that close satellites repeatedly crossed the dense gaseous disk of our Galaxy in the past and lost their gaseous components, turning into E galaxies. Distant satellites whose orbits lie far from the dense gaseous disk of the Galaxy preserve the ability to keep their gaseous disks, in which star formation is supported. A study of the mass spectrum of satellites of massive galaxies has shown that it can be represented by the function $dN/dM \sim M^{-5/4}$ [207]. The reduced slope of the satellite mass function compared to the classical one, equal to -2 (see Eqn (1)), may indicate the predominant destruction of low-mass satellites in the course of interactions with central galaxies and their absorption by massive galaxies. Thus, galaxy collisions involving the intergalactic gas of galaxy clusters play an important role in determining the proportion of E galaxies (devoid of gas and star formation) [208].

Collisions of galaxies in dense clusters are, by virtue of empirical relation (3), a common occurrence. Approaches and collisions of galaxies significantly affect their morphology. Tidal tails were the first reliable indicators of the gravitational interaction of nearby galaxies. It is possible that the appearance of spirals of some disk galaxies is a consequence of the interaction of their disk with the dark halo of these galaxies, whose gravitational field has a dipole component. This component can either be the original one, inherited from the time of the formation of a massive galaxy, or be excited in the course of evolution by collisions with neighboring galaxies. The global result of the destruction of galaxies in the process of their interaction is the enrichment of the intergalactic medium of galaxy clusters with stars and ACPS material. Observations show that up to a quarter of the light and the corresponding fraction of the mass of galaxy clusters belong to intergalactic stars and gas, which relatively uniformly fill the volume of their clusters [209]. The large proportion of intergalactic stars in clusters is a measure of the active role played by galaxy collisions in their destruction.

A collision of galaxies can lead to star formation in their common gas with the decay of the newly formed stellar system (see Fig. 7). Examples of such collisions are the Taffy system

(UGC 1294/5) and Arp 194 [209], which demonstrate gas structures with star formation between two stellar disks. The destruction of galaxies during their collisional evolution in clusters is a common phenomenon in the world of galaxies, which continuously replenishes the extragalactic environment of clusters with stars.

The star formation rate controlled by hydrogen ionization was estimated in [121] as

$$\frac{\mathrm{d}\rho_{\mathrm{g}}}{\mathrm{d}t} = -5 \times 10^7 \rho_{\mathrm{g}}^2 ,$$

where ρ_{g} [g cm^{-3}] is the gas density. Given the observed correlation $M \cong 0.2R^2$ (see Eqn (3)), where M and R are the mass and radius of a galaxy, we find that, for $M \leqslant 10^7 M_{\odot}$, the characteristic star formation time is less than the Keplerian time. As a result, in the course of the initial outburst of star formation, a spherically symmetric galaxy of such a mass can disintegrate, having lost most of its mass in the form of gas and turning into a stellar stream. Observations confirm the role of the mutual approach of galaxies in the activation of star formation in them [210]. The decay of a significant part of low-mass galaxies also helps us to understand the causes of the gradual decrease in the slope of the mass function of galaxies with age [19].

Thus, a very probable mechanism for the decay of young gas-rich galaxies, following the example of the decay of star clusters [8], is the initial outburst of star formation in them. The conditions for this phenomenon, as indicated in Section 6, are the compactness and spherical symmetry of a young galaxy. The latter condition allows assuming an efficient transfer of the kinetic energy of supernova shells to the energy of motion of the gaseous component of the galaxy. The characteristic kinetic energy of the shell of a massive supernova is $\sim 10^{50}$ erg. The gravitational energy of the gas component of the galaxy, given $M = 0.2R^2$ (see Eqn (3)), is $\sim 10^{59} M_{11}^{3/2}$ erg (here, $M_{11} = M/10^{11} M_{\odot}$). Under the condition that the Salpeter initial stellar mass function ($\mathrm{d}N/\mathrm{d}M \sim M^{-2.35}$) is applicable, we have $\sim 100 M_{\odot}$ of less massive stars with $M > 1 M_{\odot}$ per massive supernova (with a mass greater than $10 M_{\odot}$). It hence follows that, when the mass of young stars is greater than $M_{11}^{3/2}$, the energy of supernovae (starburst products) is sufficient to rid such a galaxy of the gaseous component with a mass of the order of the galaxy mass. For an outburst of star formation to occur, the Keplerian time of the galaxy ($\sim 3 \times 10^7 M_{11}^{1/4}$ years) must be shorter than the lifetime of massive stars ($\sim 10^7$ years). That is, for galaxies with a mass less than $\sim 10^9 M_{\odot}$, the transformation into stars of just ~ 0.1 of the entire mass of its gaseous component is sufficient to rid it of the gaseous component and hence destroy its stellar component. Observations show that galaxies with a gas mass greater than that of stars are common among galaxies with a total mass less than $\sim 10^{10} M_{\odot}$ [211]. The effectiveness of this mechanism depends on the degree of symmetry; ordinary disk galaxies 'dump' the excess supernova energy with the help of polar wind. The stellar component of galaxies destroyed in this way transforms over time into a stellar stream and replenishes the field of intergalactic cluster stars.

An outburst of star formation in low-mass satellites of massive galaxies can be caused by tides. If the orbit of a satellite is sufficiently elliptical, an outburst can occur with an increase in the star formation rate in the perihelion part of its orbit. This may explain the relatively short, $\sim 5 \times 10^8$ years, outburst of star formation in the faint ($M_{\mathrm{V}} = -7^m$) dwarf galaxy Eridanus II, a satellite of our Galaxy [212]. Another example is the galaxy BOSS–EUVLG1 [213] with a mass of $\sim 10^{10} M_{\odot}$ and a star formation rate of $\sim 10^3 M_{\odot}$ year^{-1}. The observed rate of gas loss by this galaxy is $\sim 50 M_{\odot}$ year^{-1}. This suffices for a significant decrease in its mass in a time comparable to its dynamical time, which not only can significantly expand the galaxy, turning it into a galaxy of low surface brightness, but also may completely destroy it, turning it into a stellar stream over time. It is interesting that star formation outbursts can also be caused by the immersion of galaxies into the dense gaseous environment of the nuclei of their clusters, as is demonstrated by an analysis of galaxies of 40 observed galaxy clusters [214].

The main conclusion of the above analysis is that, regardless of the mechanism of the decay of stellar systems (expansion of HII zones as the cause of the sweeping out of gas, an outburst of star formation with explosions of massive supernovae, or collisions of gas-rich galaxies (see Figs 6 and 7)), a dense gravitationally unbound cloud of stars eventually appears. The further evolution of this cloud is determined by its environment. The decay of a single galaxy in a galaxy cluster leads to the transformation of its stellar component into a stellar stream along the orbit of this galaxy in the cluster. The time of destruction of such a stream in a cluster due to a collision with galaxies can be estimated as follows. We assume that a stationary cluster of galaxies with mass M and radius R consists of identical galaxies, each with mass m and radius r. Dispersion of the velocities of the stars of the decayed galaxy is $v = \sqrt{Gm/r}$, and the velocity of stream stars and cluster galaxies is $V = \sqrt{GM/R}$. We assume that the condition for the decay of a stellar stream is a change in the velocities of its components in the course of its evolution by the value of the initial dispersion of stars under the influence of approaching the cluster galaxies. A simple analytic calculation leads to the following estimate of the lifetime of a stellar stream resulting from the destroyed galaxy:

$$\tau = \frac{R}{r} \frac{R^{3/2}}{G^{1/2} M^{1/2}} = \frac{R}{r} \tau_{\mathrm{d}} \approx \tau_{\mathrm{d}} \left(\frac{M}{m} \right)^{1/2} , \tag{16}$$

where G is the gravitational constant and $\tau_{\mathrm{d}} = R/v$ is the characteristic dynamical time of the galaxy cluster. With $M = 0.2R^2$ and $m = 0.2r^2$ (see Eqn (3)), this estimate becomes $\tau = 4 \times 10^{10} (M_{15}^{3/4}/m_{11}^{1/2})$ years. Obviously, for the characteristic masses of galaxies of $10^7 M_{\odot}$–$10^{11} M_{\odot}$ and clusters of $10^{13} M_{\odot}$–$10^{15} M_{\odot}$, this time exceeds the Hubble time. As a result, we come to the conclusion that free stellar streams from destroyed galaxies can persist in the cluster for the Hubble time. The stellar environment of clusters of galaxies in their cluster, which constitutes up to half its mass, is mainly represented by stellar streams, whose degree of development is determined by age. The observational identification of these streams is typically complicated by their low brightness [215].

We consider here some consequences of the collision of galaxies. One such consequence is galaxy mergers (see Fig. 7). When analyzing the conditions for the merger of galaxies and for the existence of satellites of massive galaxies, it is necessary to take the conditions of dynamical friction of their motion in a gravitating medium into account. 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 nucleus of a nearby satellite absorbed by our Galaxy.

The magnitude of the drag force acting on a body moving in a gravitating medium was first found by Chandrasekhar [216]. It can be estimated within a simple model. Let a point-like body of mass m move with a speed v in a field of point-like gravitating bodies whose average density is ρ. The motion of the bodies of the medium within a cylinder of radius $r = Gm/v^2$ is then gravitationally perturbed by the moving object. As a result, these bodies concentrate in the tail of that object. A gravitating force F decelerating the body thus occurs. It is given by $F \approx G\rho m r \approx (G^2 m^2/v^2)\rho$. Deceleration of a mass-m satellite due to dynamical friction in a mass-M galaxy is

$$\tau = \frac{v^3}{G^2 \rho m} \approx \tau_{\mathrm{d}} \frac{M}{m}\,, \tag{17}$$

where $\tau_{\mathrm{d}} = R^{3/2}/(M^{1/2} G^{1/2})$ is the dynamical time. Relation (17), derived by Chandrasekhar in 1943 [216], also includes a logarithmic factor of the order of 10, which takes the rearrangement of the field bodies outside the 'zone of influence' of the moving mass m into account. Substituting the parameter values characteristic of galaxies in relation (17), we obtain

$$\tau = 3 \times 10^7 \left(\frac{M}{10^{11} M_{\odot}}\right)^{1/4} \frac{M}{m} \text{ years}\,. \tag{18}$$

The average density of galaxies increases as R^{-2} in approaching the galactic nucleus at a constant galaxy rotation rate. Therefore, for $\alpha = R/R_0$, Eqn (18) can be written as

$$\tau = 3 \times 10^7 \alpha^2 \left(\frac{M}{10^{11} M_{\odot}}\right)^{1/4} \frac{M}{m} \text{ years}\,. \tag{19}$$

This condition allows understanding the general pattern of the deceleration of satellites of galaxies in the parent galaxy. It is clear that effective deceleration requires a large mass of the decelerating satellite and its proximity to the dense nucleus of the galaxy. The deceleration and merger of galaxies can result in observable galaxies whose nucleus rotates in the opposite direction to the rotation of the galaxy itself.

We note that the absorption of satellite galaxies leads to the expansion of absorbing galaxies, because the kinetic energy of satellites is decreased due to an increase in the internal energy of these galaxies. The result of this process is the appearance of low surface brightness galaxies [217]. Some of them consist of old red stars, and some also include young stars [218]. When studying distant ($z > 1$) young galaxy clusters, it was found that the proportion of low surface brightness galaxies in them is one third that in present-day clusters [219]. This is consistent with the collisional mechanism of their formation. Collisions of disk galaxies with hyperbolic velocities are another possibility for the formation of low surface brightness galaxies [138, 220]. The total gaseous component can then become a young galaxy of low surface brightness, and the stellar components can become red galaxies of this type (see Fig. 7).

An analysis of Eqn (18) leads to the conclusion that the characteristic deceleration time strongly depends on the velocity of the decelerated galaxy relative to the one causing deceleration. In massive galaxies with $M \geqslant 10^{10} M_{\odot}$, most of the mass belongs to the dark halo [221]. As already mentioned, the study of stellar streams in the Galaxy has allowed establishing that some of them move in the direction opposite to the rotation of the stellar component of the Galaxy [222, 223]. This, first, indicates the extragalactic nature of some of the stellar streams and, second, allows us to hope for a detailed analysis of the kinematics of the galactic stellar streams as a future method for estimating the rotation rate of its dark halo.

The merger of galaxies containing SMBHs in their nuclei can lead to the destruction and loss of their stellar components [111]. The final product of such a process may be a binary, or even a single, SMBH, if the final binary SMBH turns out to be close enough for their components to merge in Hubble time. Galaxies with binary SMBHs in their nuclei are known [224]. The stars of galaxies lost in the course of dynamical deceleration of the binary SMBH components acquire high velocities, up to 10^4 km s^{-1} [225], which for extremely close SMBH components can reach $\sim 10^5$ km s^{-1} [111]. Obviously, the merging galaxies acquire stellar spears in the process of relaxation, which over time develop into stellar streams in their clusters of galaxies. Interestingly, some of the stars accelerated by close binary SMBHs to such high velocities leave not only their galaxies but also the galaxy clusters, because the parabolic velocities of the clusters do not exceed several thousand kilometers per second even for the most massive clusters of galaxies (see Eqn (3)). Because the characteristic escape velocities of neighboring clusters are also of the order of several thousand kilometers per second, the space between them must be filled with ultrafast stars accelerated by close binary SMBHs of merging galaxies.

The merger of galaxies leads to a number of interesting consequences. The continuous process of tidal destruction of galactic satellites described above results in a noticeable enrichment of the stellar components of the disk and bulge of massive galaxies. This process was especially effective at the early stages of the evolution of galaxies [224–226]. Indeed, an obvious correlation has emerged between the masses of the bulges of massive galaxies and the number and masses of their satellites [227]. The merger of galaxies of comparable masses may result in the formation of galaxies with two stellar disks rotating in opposite directions [228, 229]. Another consequence of the merger of galaxies is the formation of ultracompact spheroidal dwarf galaxies with sizes noticeably smaller than the usual ones (see Eqn (3)). They are actually compact nuclei of satellite galaxies, destroyed by the tides of massive galaxies. As a result of galaxy mergers, galaxies with a reverse metallicity gradient may appear [230]. Absorption of nearby irregular galaxies by E galaxies may support the recurrent process of star formation in their nuclei [231] along with the accumulation of gas lost by old stars. The study of the Magellanic Stream has shown that it contains not only stars but also a gaseous component with a mass comparable to that of the stars [232].

The interaction of galaxies is multifaceted. Along with gas and stars, galaxies have a scattered solid component. The recent discovery of extrasolar asteroids leaves no doubt about the existence of a wide mass spectrum of the solid-body interstellar component of the Galaxy (see Eqn (1)). It is clear that fine dust is quickly decelerated by gas, joining the general field of stellar dust. But coarse-grained dust and sand can preserve the original orbit of the objects that gave rise to them, and when entering Earth's atmosphere they can in principle point to its source. One way to identify interstellar dust is by the speed of its collision with Earth. The dust of the Solar System has a speed of 12–72 km s^{-1} relative to Earth, but the speed of the stars of the spherical component of the Galaxy reaches 650 km s^{-1} [233]. It is interesting that space observations of air showers caused by cosmic rays can eventually be effectively used to search for high-velocity interstellar dust. These observations cover large areas of Earth's surface, hundreds of times larger than the areas controlled by terrestrial observations of meteors. And, most importantly, the first possible indication of a probable intrusion of an interstellar high-velocity component of interstellar dust into Earth's atmosphere already exists [234]. This method of searching for and detecting interstellar dust grains now seems promising for detecting interstellar and, possibly, even intergalactic dust. Currently, it is clear that some of the comets, asteroids, and planets of our Galaxy are extragalactic.

Probably the closest example of a galaxy destroyed by the tidal influence of our Galaxy is the stream that includes the Magellanic Clouds. Linden-Bell [235] found that many satellites of our Galaxy are located along a great circle that includes the Magellanic Clouds. This circle is noticeably inclined to the plane of the Galaxy. A detailed study of the geometry of this circle suggests that its members are products of the tidal decay in the past of a massive, $\sim 10^{11} M_{\odot}$, satellite of our Galaxy [236]. The shape of the circle, which in this case is a stream of members of a galaxy that decayed several billion years ago, coincides with the shape of its orbit. It is possible that a detailed study of the orbits and positions in the sky of the satellites of our Galaxy will in the future allow finding other organized streams, the products of the dynamical evolution of the galactic environment and a vestige of the making of our Galaxy in the past.

Stellar streams — products of the decay of stellar galaxies and satellites of galaxies in the stellar medium — have a long lifetime: according to Eqn (19), their components retain the initial velocity dispersion, filling the initial orbit of the decayed object in a galaxy. The main cause of the 'loss' of stellar streams by observers is the increase in their length over time. This noticeably lowers the surface brightness of the stellar stream, first complicating its identification and eventually practically forbidding it. Therefore, despite the large number of stellar streams discovered so far, they are a small part of all streams in our Galaxy. The remaining streams form a homogeneous medium of the disk and halo of the Galaxy. At the same time, the stellar halo of the Galaxy includes two populations of stars: remnants of the initial spheroidal stages of the evolution of the stellar component of the Galaxy and stars of satellite galaxies absorbed by the Galaxy in the course of its evolution. The study of the chemical composition and kinematics of halo stars will eventually allow distinguishing among the stars of these halo populations .

The observable detection of astronomical streams defined in this review is hindered, as usual, by obvious observational selection effects. The main one is the low surface brightness of these objects, which makes it difficult to distinguish them from the background of other stellar and gaseous objects. The search for stellar copies of star clusters is complicated by the need for a detailed study of the spatial velocities of a large number of stars surrounding these clusters in order to search for stars with velocities, distances, and ages close to those of the corresponding clusters. Such complex work on the identification of astronomical streams has become productive only in recent years with the development of all-wave highly sensitive receiving equipment and modern methods for processing observations. A detailed analysis of the halos of nearby massive galaxies has allowed establishing the presence of planar systems of satellites in them, including dwarf galaxies [237]. These systems may be products of tidal decays of massive satellites of these galaxies. Equation (3) demonstrates that the density of galaxies noticeably decreases as the mass increases. Therefore, the tidal destruction of massive satellites of galaxies leads to the creation of planar stellar systems, which currently mark the orbital plane of the destroyed massive satellite galaxy. The causes of the destruction of satellites is their low density and immersion in the central dense regions of the Galaxy.

Figure 8 shows the results of the evolution of a stellar stream formed by the tides of a destroyed galaxy for up to 10 Gyr in the model whose initial stages of calculations are outlined in [46]. We can see in the figure that, in 1 billion years, the satellite turns into a stellar stream with a length of ~ 30 kpc. The lost stars, as we see in Fig. 8, escape the satellite and form a loop-like stream over time. The length of the stream depends on its age. Note that the stellar stream obtained in Fig. 8 (leftmost panels) is similar to that shown for the stellar stream of the galaxy NGC 5907 [189].

It is easy to see from Fig. 8 that, during the Hubble time of 10 billion years, the stream is almost completely dissipated at the periphery of the Galaxy, becoming part of its halo. The density of points representing decay products is seen to be nonuniform in space. The denser regions show the remnants of a stream that has decayed into several pieces. One piece fills the region near the bulge, and the remaining stars fill the halo almost completely, up to distances of 40 kpc along the radius. The chaotization of the stream with time is clearly visible, caused by the deviation of the galactic potential from spherical symmetry.

In Fig. 9, we consider a variant of the meridional orbit of a satellite falling from the north pole toward the galactic center. Satellite galaxies are observed that cannot withstand the attraction of the Galaxy and fall on it (the falling speed can reach 400 km s^{-1}). An example of such a fall of an old (13.5 Gyr [106]) dwarf galaxy, the satellite Tucana III, is shown in Fig. 9. Tucana III is associated with a stellar stream, has a length of 4.5 kpc, has lost 69% of its mass, and moves in a radial orbit, and, as we see in Fig. 9, its decay products could become the bulge population.

The position of the orbit shows that the Tucana III galaxy, according to calculations, could have passed near the center of the Galaxy in the past. The orbit in this case has a complex shape due to the gravitational potential of the Galaxy. Approaching the bulge (the distance at the periapsis is 2.5 kpc) or even passing through it, Tucana III makes a U-turn and moves away along an elongated (eccentricity 0.9) elliptical orbit. It then returns and continues to move along an intricate closed orbit (Fig. 9).

A detailed study of the Fornax cluster of galaxies made it possible to detect 13 stellar structures in it, which are stellar streams with the radial velocity dispersion ranging from 20 to 100 km s^{-1} [238]. Most of them owe their appearance to dwarf galaxies that are being or have been tidally destroyed. The study of the kinematics of stars in our Galaxy with a low abundance ($[Fe/H] \leqslant -0.8$) of metals has allowed identifying eight stellar streams associated with known globular clusters [239]. Several dozen such streams not associated

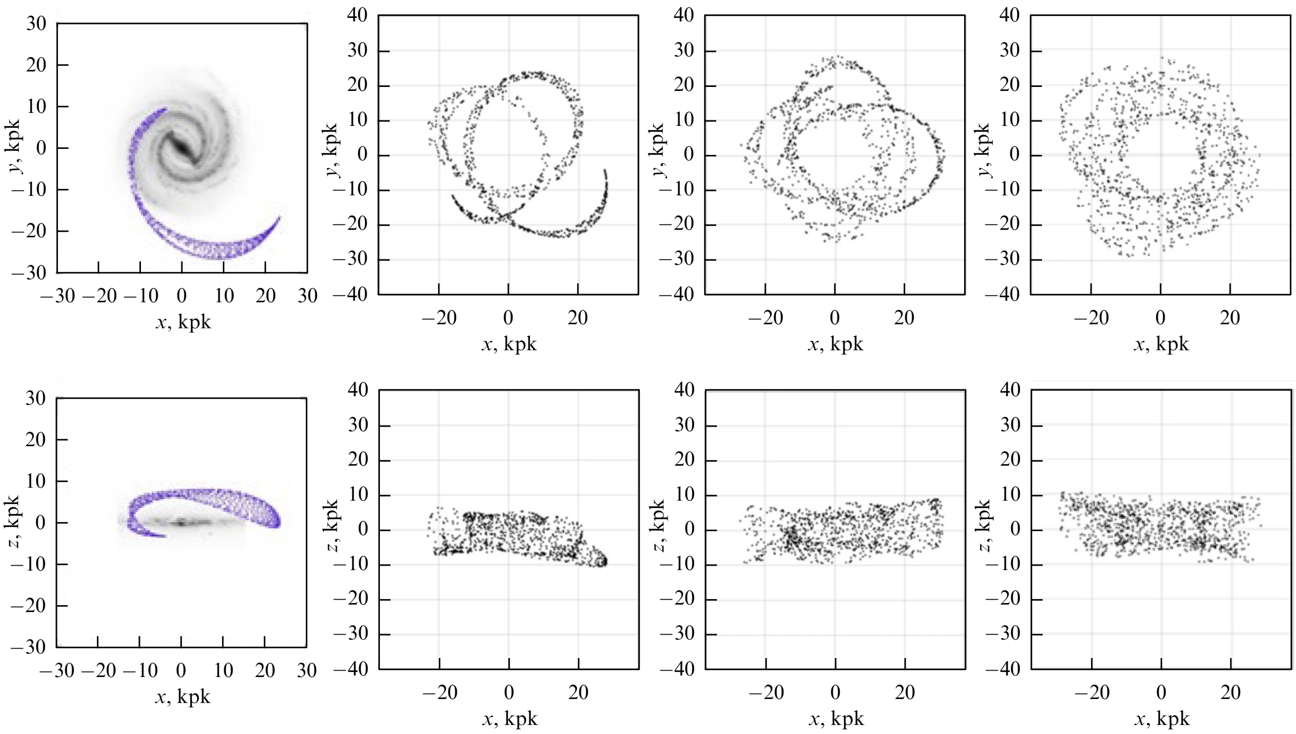

Figure 8. Model of the evolution of a galaxy destroyed in 10 billion years. Pairs of panels (upper *xy* projection, lower *xz* projection), from left to right, show the evolution of the cloud in 1, 3, 5, and 10 billion years. Galaxy image is provided by the *Python* and *galpy* library, URL = https://github.com/henrysky/milkyway_plot.

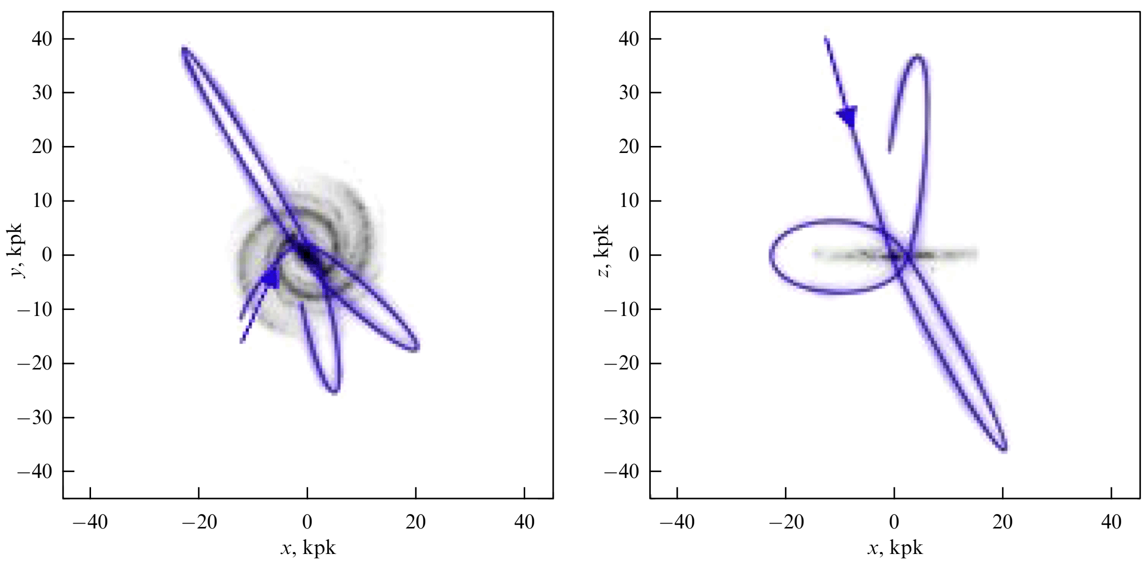

Figure 9. Radial (passing through the galactic center) orbit of the Milky Way satellite Tucana III [106]. Projections of the Tucana III orbit for 2 billion years are shown. Satellite approaches from the north pole of the Galaxy at a speed of 100 km s^{-1}. Orbit is seen to pass practically through the galactic center. Arrows show the direction of the satellite's motion.

with clusters probably relate to decayed star clusters and satellites of the Galaxy. We note that mergers with galactic satellites can affect the accretion activity of SMBHs located in the nuclei of almost all galaxies. Low-mass, gas-rich satellites can markedly increase the star formation rate in the nucleus, causing an outburst of star formation. The perturbation and kinematics of the stellar field near the black hole may also increase the rate of tidal destruction of stars in the nucleus by the central black hole. We see that the manifestations of the interaction of galaxies with their satellites and neighboring galaxies are diverse, and the observed stellar streams are mere signatures of the close interaction of galaxies in the past and deserve a separate detailed study.

Figures 8 and 9 illustrate the model decay of galaxies and the evolution of their shapes according to a standard scheme. The stellar spear is elongated with time, first turning into an annular stream and then, under the influence of the complex potential of the Galaxy, expanding significantly. The result of such a process with many satellites of the Galaxy coming from different directions is the formation of a spheroidal bulge.

Similar absorption processes of nearby satellites also occur in other massive galaxies, which acquire their bulges over time. Let us recall that the stellar disks of galaxies are the sum of streams from destroyed OB associations and star clusters of the disk because all stars are born there.

8. Conclusions

In general, to summarize this review and a number of previous studies, we can conclude that the formation of gravitationally unbound streams of stars completes the picture of the evolution of compact astronomical objects: comets, planetary systems, and stellar ensembles of various types (star clusters and galaxies). Accumulating collisions of dust grains, asteroids, and comets, in concert with gravity (stellar ensembles), concentrate the initial scattered matter of the Universe in the form of gas and dust into compact objects. The processes of evaporation of cometary nuclei and gravitational interaction of planets with their stars in planetary systems and stars among themselves in stellar systems lead to the destruction of some of these relatively compact systems. In such cases, streams are formed made of the objects that make up these systems. With sufficiently high velocities of these objects and sufficient time, the streams, expanding along the orbits of the parent systems, close into rings (in the form of tori) that approximately coincide with the orbits of their parent systems. The ratio of the thickness of the tori to the radii of the rings that form these tori is determined by the ratio of the characteristic velocities of the constituents inside the destroyed systems to the spatial velocities of the systems themselves. The observational study of streams has long been hampered by the difficulty in identifying their constituents, which are normally objects of low surface density. Modern methods for observing such objects allow not only identifying but also studying them. Observational studies and theoretical modeling of the formation and evolution of stellar streams in massive galaxies will eventually turn them into a tool for studying the density profile of the dark halo of these galaxies [240] and the law governing its rotation.

Ultimately, the formation and evolution of the considered streams is the main part of the general evolutionary process of matter in the Universe, responsible for the destruction of systems formed by gravity. The result of such destruction is the formation of meteor showers and the zodiacal light of stars during the destruction of the nuclei of comets and asteroids. The destruction of star clusters of disk galaxies determines the stream structure of galactic stellar disks. The destruction of satellites of massive galaxies and their close neighbors eventually leads to the formation of galactic bulges. Outbursts of star formation and collisions of galaxies with each other lead to the appearance of stellar streams on the scale of galaxy clusters and a well-populated continuous stellar component of these clusters. Thus, gravity, with the help of the processes of dissipation of the thermal energy of gas, creates gravitationally bound systems: planetary systems, star clusters, galaxies, and galaxy clusters. A number of processes described in this review, such as the evaporation of comet nuclei, close passages of planets and stars, and collisions of galaxies, lead to the destruction of the above systems and their transformation into streams of asteroids, comets, planets, and stars. The destruction of streams in the course of their evolution leads to the emergence of a continuous environment of dust in planetary systems, free planets, and stars in stellar systems. A detailed study of the process of decay of astronomical systems is a logical conclusion of the process of studying their evolution in the Universe.

The systems we study are connected by similarities in their origin and evolution; they are all formed as a result of the evaporation of parent systems and the action of tidal forces on the decay products. We list the studied systems.

1. Comets, producing meteor showers in their planetary systems.

2. Planetary systems, due to massive planets producing streams of free asteroids, comets, and planets around their stars.

3. Decay of star clusters under the effect of their loss of the gas component of the original system and star formation, and during the dynamical evaporation of these systems due to pairwise interactions of stars.

4. Decay of OB associations (with the initial size of the order of the thickness of the gaseous disk) of the Galaxy due to their loss of gas and galactic tidal forces.

5. Decay of low-density galaxies that are satellites of massive galaxies due to their loss of gas under the action of ram pressure and due to outbursts of star formation or tidal influence of the central galaxy.

6. Decay of galaxies belonging to a cluster of galaxies due to interaction with other galaxies by mergers or collisions of galaxies with each other, transforming them into stellar streams on the scale of the cluster.

Thus, the decay of galactic, stellar, and planetary systems formed from gas under the influence of gravity turns them over time into stellar and planetary meteor showers, which permeate intergalactic, intragalactic, and circumstellar space. 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 same morphology is characteristic of the intergalactic stellar component of clusters of galaxies.

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