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REVIEWS

PROPERTIES AND FORMATION OF STAR CLUSTERS

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Many key problems in astrophysics involve research on the properties of star clusters, for example: stellar evolution and nucleosynthesis, the history of star formation in galaxies, formation dynamics of galaxies and their subsystems, the calibration of the fundamental distance scale in the universe, and the luminosity functions of stars and star clusters. This review is intended to familiarize the reader with modern observational and theoretical data on the formation and evolution of star clusters in our galaxy and others. Unsolved problems in this area are formulated and research on ways to solve them is discussed. In particular, some of the most important current observational and theoretical problems include: (1) a more complete explanation of the physical processes in molecular clouds leading to the formation and evolution of massive star clusters; (2) observation of these objects in different stages of evolution, including protoclusters, at wavelengths where interstellar absorption is minimal; and, (3) comparison of the properties of massive star clusters in different galaxies and of galaxies during the most active star formation phase at different red shifts. The main goal in solving these problems is to explain the variations in the abundance of chemical elements and in the multiple populations of stars in clusters discovered at the end of the twentieth century.

Keywords: *star clusters: formation*

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1. Introduction

A large fraction of the stars in our galaxy were formed in clusters (Lada & Lada, 2003). Star clusters are witnesses to episodes of the most intense star formation in galaxies (Zwart, et al, 2010). Studies of the properties and of the origin and evolutionary paths of star clusters are important for solving some fundamental astrophysical problems. The basic questions of concern to researchers on galactic and extragalactic young and old star clusters include: (1) the structural, dynamic, chemical, and other characteristics (not distorted by observational selection) of star clusters of various ages in our galaxy and others; (2) the physical processes responsible for the formation of clusters with these properties in galaxies of different morphological types and in different galactic subsystems (bulges, disks, stellar halos); (3) how clusters evolve as a function of the surrounding conditions, the percentage of their initial mass that they lose, and the changes in the chemical composition of stars in clusters as they evolve. Many unsolved problems of modern astrophysics are related to these questions, such as: the origin of multiple star populations in globular clusters and the mass function of star clusters and medium-mass black holes[*] in galaxies; the shape of the initial mass function of stars in clusters and in the galactic field; and the fraction of binary stars and low-mass black holes.

In this review article we concentrate mainly on star clusters in our galaxy, since the most complete set of observational data is available for them: thorough color-magnitude diagrams (CMD) that reach the turning point for the main sequence; high resolution spectra for the brightest stars that are members of clusters; and, integrated spectral and photometric characteristics for clusters as a whole in various wavelength ranges. In some cases, we shall compare the properties of clusters in the galaxy with extragalactic clusters.

2. Some history

The history of detailed research on star clusters in our country and overseas goes back more than a hundred years. Advances in this area, as in astrophysics as a whole, are determined by progress in observational technique. The first papers were devoted to cataloging clusters and photometric study of clusters using photographic plates. We recall the work of B. V. Kukarkin, A. S. Sharov, H. Shapley, W.Baade, S. Van den Berg, and P. Hodge. The electronic data bases now available, such as ADS (SAO NASA Astrophysics Data System (http://www.adsabs.harvard.edu/), the SIMBAD Astronomical Database (http://simbad.u-strasbg.fr/simbad/), and others, provide access to almost all of the scientific articles devoted to star clusters. The researchers on stellar dynamics from the school of V. A. Antonov, include the outstanding theoretical stellar astrophysicists V. V. Sobolev and V. A. Ambartsumyan. The achievements of these scientists and their remarkable students and successors are still in active use and cited throughout the world.

Important aspects of research on stellar evolution and nucleosynthesis, the calibration of the fundamental distance scale in the universe, and a number of other problems are being solved with the aid of CMD and spectra

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[*] A black hole with a mass of $100\text{-}10^6$ times that of the sun is considered to be a medium-mass black hole. It is assumed that objects of this kind are found in the active nuclei of low-luminosity galaxies (Merritt, 2013).

of isolated stars and of stars in clusters. In particular, these tasks include: determining the luminosity and color characteristics of the turning point of the main sequence, the peaks of the red giant branch, and other important episodes in the evolution of stars which are used for establishing distances; fitting theoretical models of stellar evolution to observed color-magnitude diagrams; studying the period-luminosity relation for variable stars; and, obtaining astrometric, statistical, and spectral parallaxes for stars in clusters. The books of P. N. Kholopov "Star Clusters" (1981) and B. W. Carney "Stellar Evolution in Globular Clusters" (2001) discuss the evolution of stars in clusters in detail. Carney examines methods for determining the age and metallicity of globular clusters in the galaxy, comparisons of the properties of the star populations of clusters and subsystems in our galaxy (thick and thin disks, bulges, and halos), and the contribution of star formation processes in clusters to the formation of these subsystems. In the book "Star Clusters" (2001) and an article, "Globular cluster systems: formation models and case studies" (1999), E. W. Harris generalizes the available information on the spatially kinematic structure of globular clusters. Yu. N. Efremov has discussed young star clusters, complexes and associations and the astrophysical problems related to them in his articles and his book "Star Formation Sites in Galaxies" (1989). The composition of stars and various aspects of the evolution of star clusters have been studied by many Russian scientists, including members of the Division of Research on the Galaxy and Variable Stars at the Shternberg Astronomical Institute: N. N. Samus', A. S. Rastorguev, Yu. N. Efremov, E. V. Glushkova, V. G. Surdin, and others.

With the building of large earthbound telescopes, high resolution spectroscopy, and the development of extra-atmospheric astronomy, the rate of study of star clusters in and beyond the galaxy has increased significantly. In the visible range, globular clusters and diffuse star clusters that are very faint because of distance and/or shading by dust have been discovered, including: in the central regions of the galaxy and in spiral arms. Young massive clusters have been discovered in our and other galaxies (see the review by Zwart, et al., 2010).

Until recently, globular clusters (GC) were considered to be representatives of simple star populations consisting of stars of with a single age and chemical composition. The discovery of multiple sequences in deep color-magnitude diagrams of globular clusters in the galaxy, as well as of differences in the abundances of chemical elements in the stars in these objects, has led to a revolutionary change in scientific opinion regarding the formation of clusters in the galaxy as a whole (Gratton, et al., 2004). The appearance of new observational data has induced a critical revision of the theory of the formation and evolution of star clusters as a function of epoch and conditions in the surrounding interstellar and intergalactic medium. New hydrodynamic models of turbulent processes in the gas-star medium during cluster formation have been developed. There is an urgent need for new spectral and photometric data in various wavelength ranges from spaceborne and large earthbound telescopes.

3. The various forms of star clusters

3.1. Young massive star clusters. With the launch of the Hubble space telescope and other space missions, as well as the building of large earthbound telescopes, special interest has arisen in the massive clusters rich in stars, young and old, discovered in our and other galaxies, e.g., in the Large and Small Magellanic Clouds (Van den Bergh, 1994), NGC1705 and NGC1569 (Ho & Filippenko, 1996a, b), and M82 (Keto, et al., 2005), and in interacting galaxies such as Antenna (Whitmore & Schweizer, 1995, Johnson, et al., 2015, Schweizer & Seitzer, 2007). A close correlation between the level of star formation in a given part of the galaxy and the number of young star clusters unambiguously indicates that the formation of GC continues to this day, and that the major properties of the most massive young clusters are the same as in the predecessors of the old GC in the galaxy (e.g., Efremov & Elmegreen, 1998, McLaughlin & Fall, 2008). Young objects in this class are referred to the foreign literature as "young massive clusters" and "super star clusters." Very young massive clusters (embedded clusters), with ages on the order of or less than ten million years, embedded in a dense gas-dust shell, like a butterfly in its cocoon, also exist. The properties of young massive clusters (YMC) are studied primarily through observation in infrared and radio wavelengths, where absorption by the dust is minimal. It has been found that the masses of YMC are $10^4 - 10^6\, M_\odot$ and their ages are less than 100 million years. These clusters, made up of hundreds of young massive stars, are an order of magnitude denser, on the average, than diffuse clusters with a central density of $\rho_c > 10^3\, M_\odot$ pc^{-3} (~10^4 stars/pc^3) (Zwart, et al., 2010). With the ALMA (Atacama Large Millimeter/Submillimeter Array) radio telescope, Johnson, et al., 2015, have discovered a dense molecular cloud with a mass greater than $5 \cdot 10^6\, M_\odot$ in an evolutionary stage immediately prior to collapse and cluster formation. The mass and kinetic energy of this object are high. They assume that less than 1 million years are needed for this cloud before gravitational collapse and the star formation process set in. YMC older than 10 million years no longer show signs of ongoing star formation (Bastian, et al., 2013). Understanding the formation and evolution of YMC will require study of both the large-scale processes taking place in galaxies during the period of active star formation and the local phenomena in the interstellar medium leading to the formation of stars with different masses.

3.2. Globular and diffuse star clusters. How do globular clusters (GC) and diffuse clusters (DC) differ? Is there a sharp boundary between them or does the main reason for the differences in their properties lie in the epoch and ambient conditions of their formation? These questions have not yet been definitively answered. Considerable observational and theoretical progress has, however, been made in this area.

GC in our galaxy have ages greater than 8 billion years. This is the main difference between them and DC, the ages of which are less than 300 million years, and from GC in other galaxies, e.g., in the Large and Small Magellanic Clouds (dwarf irregular satellites of the Milky Way). GC in other galaxies can have different ages. The observed difference in the ages and other observational characteristics of GC and DC provide a basis for using the characteristics of clusters for detailed study of the history of star formation in galaxies and modelling the physical conditions at the time of active star cluster formation in galactic subsystems.

Table 1 in the article by Zwart, et al., 2010, summarizes the basic observed parameters of star clusters of different types in the galaxy: age, mass, virial radius, density of the nuclear part, metallicity, characteristic dynamic time (t_{dyn}), and relaxation time (t_{rl}). Besides GC and DC, this table includes data for young massive clusters. The last two characteristics listed in that table (Zwart, et al., 2010) are fundamental for self-gravitating systems and are denoted by (Spitzer, 1987) t_{dyn}, the time needed for a star to cross a cluster, and t_{rl}, the time for a star system to reach thermal equilibrium after two stars collide. The dynamic time is determined by the size and mass of the cluster and is roughly the same for all three kinds of clusters ($t_{dyn} \sim 1$ million years). This characteristic can exceed 1 million years for GC, and be less than 1 million years for DC. The relaxation time is longer when the average dispersion in the velocities of the stars belonging to a cluster is greater and shorter when the local density of matter is higher. The characteristic relaxation times for GC are an order of magnitude longer than for DC and young massive clusters.

On the average, globular clusters are 2 orders of magnitude more massive than diffuse clusters. YMC in our galaxy occupy an intermediate position with respect to mass between DC and GC. The average virial radius of GC, i.e., the radius at which the total potential energy of the cluster balances the kinetic energy, is an order of magnitude larger than in DC (10 and 1 pc). The ranges of the densities of GC, YMC, and DC overlap substantially. However, GC and YMC have the same tendency to have an elevated average density ($\rho_c > 10^3\, M_\odot\, \text{pc}^{-3}$). At the same time, while GC are distributed in the halo and bulge of the galaxy according to a power law, if we count their number in annuli around the center of galaxies, DC and YMC have utterly different distributions. Young DC are concentrated immediately in the disk and old DC, in the thicker layer of matter above the galactic plane, mainly in the outer disk of the galaxy out to galactic heights of 3 kpc. Note that the observed distribution of DC in the galaxy is distorted by observational selection effects. Because of substantial absorption of light by dust in the galactic plane and the low luminosity of DC compared to GC and YMC, the DC can be observed reliably only within a radius of about 3-4 kpc in the vicinity of the sun. Almost all of the currently known YMC were discovered in the galactic disk within the solar circle. These objects have a tendency to concentrate toward the central regions, the bar, and the spiral arms, where the gas density and the level of turbulence appear to be fairly high, thereby favoring their formation.

GC are mostly much poorer in metals than DC and YMC. Young clusters have been formed from matter in the disk that has become richer in chemical elements over the billions of years the galaxy has evolved. The metallicities of GC are typically 1-3% of that of the sun. On the other hand, the metallicities of DC are an order of magnitude or more higher than that of the sun. It is interesting that old DC with ages exceeding 4 billion years also have metallicities on the order of that of the sun and an elevated abundance of light elements. Here is an example. The origin and properties of the star population of the distance cluster BH176 were little known until recently (Sharina, et al., 2014). It has been found that BH176 is a diffuse cluster in the thick disk of the galaxy. It lies a distance of 15.2±0.2 kpc from the sun and at a height of 1.15 kpc above the galactic plane. This object is rich in metals and light elements and has an age of 7 billion years. Its origin is not clear, but it may be assumed that it arose from a collision of a dwarf satellite or a high-velocity cloud with the galactic disk. Clusters of this kind which are rich in metals and light elements are mainly observed at galactic heights greater than a kiloparsec (Gozha, et al., 2012). There are 16 of them in all (Sharina, et al., 2014, Table A4). Their average characteristics are: $[\text{Mg}/\text{Fe}] = 0.16 \pm 0.1$ dex, $\text{Age} = 5.8 \pm 1.8$ Gyr, and absolute magnitude in the range of $M_V \sim -4.9 \div -1.1$. They appear to move along prolate orbits that are inclined relative to the plane of the disk. The high abundance of iron and light elements may mean that these clusters were formed partially under the influence of type II supernovae or of more powerful star-formation bursts than typical DC. An alternative hypothesis is that they could have been formed in central parts of the galaxy and then, for some reason, moved away from their birth site at a high velocity (Acharova

& Shevtsova, 2016).

4. Modern ideas regarding the formation and evolution of star clusters

4.1. The mass function of star clusters. Elmegreen & Efremov, 1997, have shown that a universal mechanism for the formation of star clusters, both globular and diffuse, operates in nature. These ideas have been developed in later studies by these and other authors (e.g., Elmegreen, 2002, Vesperini, 2001, Kruijssen, 2012, Walker, et al., 2015). Clusters are born in molecular clouds under conditions of turbulence, high gas pressure, and an elevated total virial density of stars, gas, and dark matter. Differences in the masses and structural characteristics of clusters arise as a consequence of differences in gas pressure at the time of formation, as well as because of differences in the physical conditions over the duration of the subsequent evolution. The form of the mass (=luminosity) function of young star clusters in a given galaxy or region of galaxies is always very similar to the mass function of interstellar clouds: $N(M)dM \propto M^{-2}dM$. This power-law distribution holds over the entire range of masses of clusters ($10^2 \div 10^8\, M_\odot$) and is known as the Schechter function (Schechter, 1976, Kruijssen & Cooper, 2012).

Since the 1970's it has been known that the distribution of old GC with respect to stellar magnitude is similar to a gaussian function (Hanes, 1977, Harris & Racine, 1979). Surdin (1979) and Racine (1980) have noted, however, that the high-mass end of the luminosity function of galactic GC can be described successfully by a power-law function. The bright end of the luminosity function changes little during evolution. The drop in the mass function at the low-mass end, observed for systems of old GC with ages on the order of 10 billion years, is the consequence of the breakup of clusters. The peak in the luminosity function of old GC is determined by the properties of the hierarchical structure of molecular clouds in the interstellar gas. This peak does not depend on the luminosity of the parent galaxy and is not determined by the Jeans mass at the time of recombination, as has been assumed previously (Peebles & Dicke, 1968). The mechanisms for breakup of GC in the milky way (Fall & Rees, 1977; Gnedin & Ostriker, 1997) include : (1) collisions with rich, hot and cold, gas in the disk and bulge, (2) dynamic stripping, (3) two-body relaxation, and (4) "evaporation" of low-mass stars. In the outer region of a galaxy, the last two mechanisms are more effective than the others. Thus,, the observed form of the mass function of GC is a function of age alone and is independent of the luminosity of the parent galaxy. According to this scenario, a substantial fraction of the stars in the galactic halo should have developed from destroyed low-mass GC (Surdin, 1995, Murali & Weinberg, 1997). Modern observations of multiple star flows around the galactic GC provide qualitative confirmation of these conclusions (Lisanti, et al., 2015). Work continues today on all the possible modifications of the mechanisms for the destruction of clusters and on numerical modelling of their evolution.

4.2. Physical processes in molecular clouds leading to the formation of star clusters. Young rich clusters contain the most massive stars with luminosities on the order of $L > 100 - 400\, L_\odot$. These galaxies have played a significant role in reionization of the interstellar medium in the early stages of the formation of the hierarchical structure of the universe. The most massive stars that form in molecular clouds are the major objects influencing the formation and evolution of star clusters (Zinnecker & Yorke, 2007, Peretto, et al., 2013, Onishi, 2013). These stars act dynamically and through ionization on the surrounding medium by means of stellar winds and ultraviolet radiation. They enrich the surrounding matter in chemical elements during supernova explosions.

Modern observations of giant molecular clouds in our galaxy and its nearest dwarf neighbors, the Large and Small Magellanic Clouds, by means of modern radio and optical telescopes have made it possible to study the processes that preceded the formation of star clusters and the dependence of these phenomena on the surroundings (Subramanian & Subramanian, 2010; Fukui & Kawamura, 2010). These observations show that the layers of molecular gas have a complicated filamentary structure indicative of turbulence in the interstellar medium. Star clusters form at the intersection of dense filaments of gas (Schneider, et al., 2012, Fukui, et al., 2015a, b). Collisions of the interstellar filaments facilitate compression of the gas layers and their descent toward the centers of the fiber structure sites (Elmegreen & Lada, 1977). On the other hand, compression of the gas layers helps speed up the rate of star formation (Fukui, et al., 2015a, b, 2014). Turbulent processes in the interstellar medium are enhanced because of processes related to the birth and evolution of massive stars. In order to support a sufficiently high efficiency of star formation in a given region of the galaxy, the level of accretion of matter must exceed a certain limit. The observations yielded a value of $6\times10^{-4}\,M_{\odot}/\mathrm{yr}^{-1}$ (Fukui, et al., 2015a, b). The dynamic collision time for molecular clouds is tens of thousands of years.

There are weighty theoretical and observational reasons for assuming that even in dense central parts of molecular clouds, massive stars and clusters may appear. The fragmentation of matter prior to the appearance of protostars is a consequence of a rise in the density of the medium beyond a certain threshold (on the order of 10^4 cm^{-3}) owing to turbulence and collisions of clouds, and the subsequent gravitational collapse (Clark, et al., 2008, Smith, et al., 2012, DeSouza & Basu, 2015, Gomez & Vazquez-Semadeni, 2014, Banerjee & Kroupa, 2015). The direct fragmentation of gas during formation of a protocluster has, however, not yet been observed. Only the consequences of this phenomenon have been observed It is assumed that the feedback mechanisms acting during the formation of the first stars and clusters in the early universe are similar in many ways to those acting today. The main difference is that the first stars were much more massive and had low metallicity (type III star population, Pop III). Their temperature is on the order of 30000 K. This energy is sufficient for second ionization of helium (Johnson, et al., 2009) and for complete loss of baryons by the minihalos in which these stars flared up. The further evolution of Pop III stars with masses of $140-260\,M_{\odot}$ lead to supernova explosions and the release of an energy on the order of 10^{53} erg (Heger & Woosley, 2002). The powerful radiation pressure of massive stars, accretion of gas in jets, stellar winds, extended H II regions in the vicinity of massive stars, and supernova explosions are the feedback mechanisms which, first, led to enhanced turbulence and, second, destroyed molecular clouds with masses less than $10^4\,M_{\odot}$ and low-mass clusters (Rosen, et al., 2014, Dale, et al., 2015, Herrera & Boulanger, 2015).

The density, temperature, and kinematic characteristics in giant molecular clouds can be modelled in N-body numerical calculations with magnetohydrodynamic processes taken into account (Inoue & Fukui, 2013, Matsumoto, et al., 2015). According to these models, newly-born stars move in random orbits and in the peripheral regions of a molecular cloud characteristic arched structures develop, which have been observed, for example, with the ALMA (Matsumoto, et al., 2015) and Herschel telescopes (Schneider, et al., 2012). With the ALMA telescope observing CO lines has been possible to detect the youngest supermassive star cluster under development in our galaxy, RCW38 (Fukui, et al., 2015b), which was first discovered by Rodgers, et al., (1960). This is the third object of this kind discovered in the Milky Way, the first two being Westerlund 2 and NGC3603 (Furukawa, et al., 2009, Fukui, et al., 2014). Similar objects have been found in the Magellanic Clouds (Fukui, et al., 2015a). It is interesting that in all three cases, it was found that the bursts of star formation were initiated by a collision of gas clouds. Infrared observations indicate the presence of several thousand young massive stars being born in each of these clusters (Wolk, et al., 2006, Winston, et al., 2011).

4.3. Formation of star clusters in dwarf galaxies. The theoretical basis for studying this problem was discussed by Elmegreen & Efremov (1997), but it is still far from a definitive solution.

It should first be noted that dwarf galaxies in the current epoch (red shift roughly 0) are divided into several types according to morphology, star composition, structural and kinetic characteristics: (1) spheroidal (dSph; prototypes -- Sculptor dSph and Fornax dSph in the Local group); 2) irregular (dIrr; prototypes— large and small Magellanic Clouds); 3) irregular (dSph/dIrr; prototypes the galaxies Cetus and KDG61); 4) elliptical (dE; prototype - M32). dSphs are objects without gas with an old star population (type II). Their surface brightness is a few percent of the brightness of the nighttime sky. The fraction of dark matter in dSphs is considerably higher on the average than in galaxies of other types, such as giant or dwarf (see, for example, p. 14 of Forbes, et al., 2008). Roughly half of the DSphs contain massive star clusters near the optical center. dIrrs are galaxies rich in gas with active star formation over a wide range of luminosities ($-18<M_V<-8$). As a rule, young star clusters are observed in these objects near star formation sites. Besides YMC, stars and clusters of intermediate (roughly 1-6 billion years) and old age are encountered. This appears to indicate an extraordinary richness in gas and a prolonged history of star formation for these galaxies. Today, a few dIrrs without old stars are known, for example, a dwarf of tidal origin next to M81 — Holmberg IX (Makarova, et al., 2002). This object is very bright at the wavelength of HI. It belongs to the x-ray source X-9, which has a higher brightness than the one at the center of M81. dSph/dIrr are objects similar to dSphs with one or two young stars and/or regions of ionized gas.

Elliptical dwarfs are rare. Structurally and in terms of the properties of the star population, dEs are similar to low-mass bulges. According to Kormendy & Bender (2012), there is only one object of this type in our Local group. It is a neighbor of the Andromeda nebula M32. There is a small GC at the center of this galaxy.

dEs occupy a special place in the multidimensional relationship “luminosity - surface brightness/density - size - velocity dispersion” among the fundamental parameters of galaxies. Only a comprehensive examination of all these parameters will provide a correct classification of a galaxy of this type (Kormendy & Bender, 2012). They assume that the origin of dEs is firmly related to the surroundings. It is not by chance that most of them are found near centers of rich galactic clusters. As a result of tidal interactions with more massive neighbors, the outer parts of dEs appear to be detached. Only dense bulges without gas remain (Bekki, et al., 2001, Graham, 2002).

We return to our discussion of the formation of GC in dwarf galaxies. Elmegreen & Efremov (1997) noted that, despite the low mass and average density of the material, dwarf galaxies should produce globular clusters that are just as massive as giant galaxies, and even more compact. In dwarf galaxies there are plenty of reasons for reaching a high pressure and the threshold gas density as a triggering mechanism for cluster formation: supernova explosions which cause a rapid outflow of gas and, thereby, a high virial total density of matter (gas, stars, and dark matter). Critical densities of gas that are 10-100 times higher than in the case of normal galaxies are typical of dwarf galaxies. On the average, dwarfs have a much lower metallicity than normal galaxies. This means that cold parts of molecular clouds lie much closer to their dense centers. In addition, the line density of the dust-free gas is higher owing to the formation of molecular hydrogen on dust particles. Thus, the pressure in the star formation regions of dwarf galaxies is higher than in normal galaxies. This leads to the formation of massive compact clusters (Elmegreen & Efremov, 1997). We note also that GC in dwarf galaxies have far fewer reasons to be destroyed because of the absence of massive disk structures. Therefore, the high rate at which GC are encountered in dwarf galaxies can be explained.

Searches for GC in dwarf galaxies beyond the confines of the Local group have been made by Sharina, et al. (2005) and Georgiev, et al. (2009). The earlier conclusions about a high rate of encountering GC in dSphs and about the percent fraction of dwarf galaxies with and without clusters were confirmed.

Kruijssen & Cooper (2012) have tested whether the masses of old GC in dwarf galaxies actually correspond to the values based on the assumption that they were formed as YMC in nearby galaxies with active star formation. In particular, they were interested in the agreement between the masses of the most massive GC in dwarf galaxies and the Schechter function at the time they were formed. Model calculations showed that the expected agreement occurs in 90% of the cases for GC with masses of $10^7 - 10^9 M_{\odot}$. The remaining 10% of the most massive GC in dwarf galaxies are nuclear clusters which gained mass during mergers with other clusters and stars in galaxies. Their estimate for the percentage of metal-poor GC in the Milky Way which were previously nuclei of dwarf galaxies is 1/3.

Objects exist in nature with properties (masses, sizes, relaxation times, stellar velocity dispersions, mass to luminosity ratios) that are intermediate between those for massive GC and dwarf galaxies. These are the so-called ultra-compact dwarf (UCD) galaxies (Hilker, et al., 1999), which are compact star systems consisting of stars that are old and of intermediate age with masses greater than $2 \cdot 10^6 \div 10^8 M_{\odot}$, sizes of 3-50 pc, and stellar velocity dispersions below 100 km/s, which is roughly an order of magnitude greater than in globular clusters. Figure 1 is an image of a UCD found by Chilingarian & Mamon (2008) at a distance of ~9 kpc from the giant elliptical galaxy M59 (NGC4621) near the center of the Virgo galaxy. In this image of a region of the sky from the Sloan Digital Sky Survey, SDSS,[*] M59 and two dwarf galaxies of early morphological types with nuclear globular clusters can also be seen: IC809 and IC3486 (Seth, et al., 2008).

Some UCS contain supermassive black holes and they have significant rotation (Seth, et al., 2014, and Mieske, et al., 2012, with references to articles on the properties and possible origin of UCD). The metallicities of the UCD were found to vary widely: $-1.7 < [\mathrm{Fe/H}] < 0$ dex. The metallicity per unit luminosity for the UCD was higher than

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[*] http://www.sdss3.org

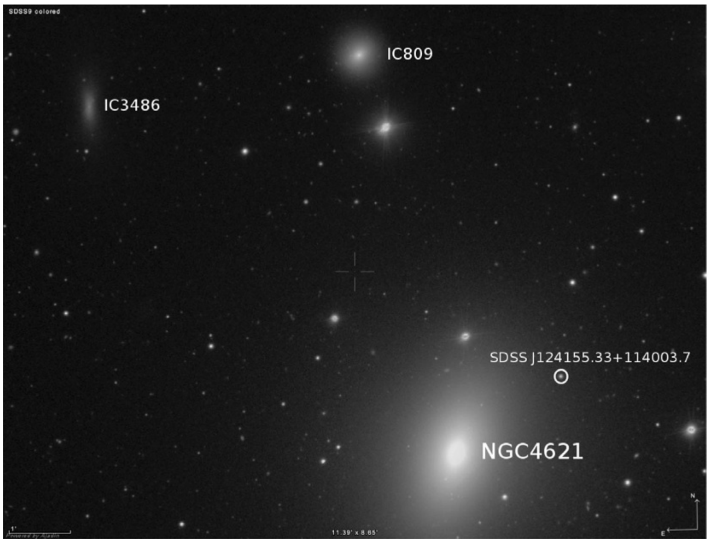

Fig. 1. An SDSS image of the region of the sky in the neighborhood of the giant elliptical galaxy in the Virgo Messier 59 (NGC4621) cluster. The circle indicates the ultra-compact dwarf galaxy found by Chilingarian and Mamon (2008) at a distance of ~9 kpc from M59. Two dwarf galaxies of early morphological types with nuclear globular clusters, IC809 and IC3486 (Seth, et al., 2008), are also noted.

for giant elliptical galaxies (Chattopadhyay, et al., 2012) and is similar to that for M32, which argues for the origin of UCD as nuclear parts of galaxies with different masses (dwarf and normal).

4.4. The rate at which globular clusters are encountered in galaxies. In 1981, Harris and Van den Bergh (Harris & Van den Bergh (1981) and Harris (2001)) introduced the term "specific frequency" or number of globular clusters per unit of galactic luminosity, which is still in use: $S_N = N_{cl} \cdot 10^{0.4(M_V+15)}$, where M_V is the integral absolute magnitude of the galaxy and N_{cl} is the total number of GC. Research on globular cluster systems in galaxies has long been a separate branch of astrophysics that employs modern spectral and photometric observations with spaceborne and the largest earthbound telescopes in various wavelength bands and deals with the following questions: the luminosity function of GC, the spatial distribution and kinematics of GC, the distributions of GC with respect to age, metallicity, and light element abundance, and the origin and evolution paths of GC.

4.5. Possible ways of forming old globular clusters. There are several scenarios for the formation of GC with ages comparable to that of the universe. Here we list the major scenarios:

(1) Globular clusters can be the central regions of low-mass galaxies that have lost their outer parts during

interactions with more massive neighbors. Catalogs of dwarf galaxies in the rich clusters of galaxies in the Virgo and Fornax constellations that are nearest to us, as well as photometric studies of these clusters with the Hubble telescope, reveal a large number of dwarf galaxies with a predominantly old star population and central bright star clusters (Binggeli, et al., 1985, Ferguson, 1989, Karachentseva & Sharina, 1989, Sharina, 1989, Cote, et al., 2006). Spectrophotometric studies have made it possible to study the structural and kinematic characteristics of nuclear clusters (Geha, et al., 2002; Lotz, et al., 2004, Puzia & Sharina, 2008, Sharina, et al., 2010). It turns out that, in terms of their properties, a large fraction of the nuclear clusters are very similar to old GC in our galaxy. Theoretical models have been developed to explain the origin of nuclear GC in dwarf galaxies. For example, according to Bekki, et al. (2006a, b), these objects could be formed in multiple dissipative mergers of gas and stellar regions of the central disks of galaxies owing to gravitational instability. (2) Globular clusters may be the successors of massive star clusters formed in gas-rich galaxies at $z > 3$ destroyed by tidal interactions, which then fall into the outer parts of neighboring galaxies during mergers and interactions of these galaxies (Kruijssen, 2014). Scenarios with large mergers of galaxies (Ashman & Zepf, 1992, Toomre & Toomre, 1972; Toomre, 1977, Schweizer, 1987, Li & Gnedin, 2014, Muratov & Gnedin, 2010) predict the formation of GC populations that are rich and poor in metals owing to mergers of gas-rich spirals and gas-poor elliptical galaxies. Galactic mergers are an inevitable part of the generally accepted hierarchical scenario for the evolution of the universe and show up in detailed numerical cosmological calculations (e.g., Ibata, et al., 2014). (3) Globular clusters could be formed in galaxies from low-metallicity gas at high densities in early epochs owing to multiphase dissipative collapse (*in-situ* scenarios; Forbes, et al., 1997).

Based on the age and metallicity of globular clusters in the galaxy determined from HST studies of the deep CMD (Van den Berg, et al., 2013, Leaman, et al., 2013, Marin-Franch, et al., 2009), clusters continued to form up to red shifts $z \sim 2$. The age-metallicity relation for these is strictly maintained. GC beyond the solar circle (a galactocentric radius of 8 kpc) have 0.4-0.5 dex higher metallicity at the same age than GC within it. For nearby galaxies, aside from the very faintest dwarfs, there is a reliable dependence of the mass of a system of globular clusters on the mass of the parent galaxy (Spitler & Forbes, 2009; Harris, et al., 2013; Hudson, et al., 2014). Observational data indicate that mergers of gas-rich massive galaxies have played an important role up to red shifts of approximately 2, and this is confirmed by cosmological hydrodynamic calculations (Li & Gnedin, 2015). These calculations have made it possible to reconstruct an initial luminosity function for the star clusters, as well as its evolution and detachment at the bright end. The maximum mass of a globular cluster in a galaxy and the fraction of the mass of a galaxy confined in globular clusters are directly proportional to the mass of the parent galaxy, the star formation rate (SFR), and the density of the surroundings at the time the clusters are formed (and, accordingly, the density of the surroundings at the present time) (Adamo, et al., 2015, Kruijssen, et al., 2012, Whitmore, et al., 2014, Fall & Chandar, 2012, Chandar, et al., 2015).

There are numerous versions of the scenarios enumerated above. According to Gnedin, et al., (2014), massive central clusters and black holes in the galaxies could be formed by mergers of sets of clusters falling into the nucleus as a result of dynamic friction and tidal interactions with the outer parts of gas-star disks, star haloes, and gaseous coronas. It is clear that to a great extent, these scenarios are not in mutual conflict, but supplement one another. There are, however, some observational fact that are hard to explain by any one model or even a combination of several scenarios, e.g., the existence of multiple star populations discovered in galactic GC and in clusters in the Magellanic clouds (Milone, et al. 2015).

4.6. Multiple star populations in globular clusters. Research on variations in the abundance of chemical elements and on multiple star populations in globular clusters has a rich history (Freeman & Norris, 1981, Lee, et al., 1999, Gratton, et al., 2004, Caretta, et al., 2009, Gratton, et al., 2012, Dotter, et al., 2015; Milone, et al., 2013, 2015). Variations in the amounts of light elements (O-Na, Mg-Al) are related to their production in the CNO-cycle in massive stars (Prantzos, et al., 2007). So-called "anomalous" second generation stars have reduced oxygen abundances and elevated abundances of sodium. In some clusters, also referred to as anomalous, these stars are a majority (roughly 2/3). The following anomalous clusters are known: Omega Centauri, NGC1851, M22 (NGC6656), M54 (NGC6715), M2 (NGC7089), Terzan 5, NGC5824, NGC5286, M19 (NGC 6273) (Marino, et al., 2015, 2014a). The variations in C+N+O for stars in anomalous clusters correlate with the abundance of s-process elements and [Fe/H] (Marino, et al., 2012a, b; 2014a, b). Two populations of stars exist in these clusters: s-element/Fe rich and s-element/Fe-poor. In every anomalous cluster, each of these populations has its own form of O-Na, Mg-Al, C-N anticorrelations (Marino, et al., 2011). It has been found that the C+N+O variations can be responsible for the observed splitting of the branches in the CMD.

Multiple star populations (multiple turning points in the main sequence, binary red clumps, binary main sequences) are observed in old globular clusters in our galaxy, but also in clusters of young and intermediate age (1-2 billion years) in the Magellanic Clouds (Milone, et al., 2009, Girardi, et al., 2009, Milone, et al., 2013, 2015). From the standpoint of the theory of stellar evolution, multiple turning points can be a consequence of: (1) the presence of star populations with different ages in the clusters (Goudfrooij, et al., 2015); (2) differences in the rotation rates of the stars (Bastian & de Mink, 2009); and (3) interacting binary stars (Li, et al., 2014b). Li, et al., (2014a) and Bastian & Nederhoter (2015) have refuted the hypothesis of a prolonged history of star formation in star clusters of intermediate age in the Magellanic Clouds. They showed that the multiple turning points in the main sequence and the binary main sequences for these objects are not accompanied by a multiplicity of other sequences in the CMD (e.g., in the red giant or subgiant branches). This means that other mechanisms are responsible for the observed effects in this case.

Figure 2 shows color-magnitude diagrams for two globular clusters with multiple star populations: NGC6838 and NGC6218 (Carretta, et al., 2010), derived from stellar photometry data of Piotto, et al. (2002). Khamidullina, et al. (2013) have carried out a population synthesis of the total radiation from the stars in the clusters using long-slit, medium resolution spectra, the stellar mass functions of Cabrier (2005), and synthetic spectra for models of the stellar atmospheres. The agreement between the theoretical isochrones and the parameters determined by Khamidullina, et al. (2013) (age, [Fe/H] and Y) for the observed CMD can be seen in the left panels of the figures. The isochrones of Bertelli, et al. (2009) with the parameters determined by van den Berg, et al. (2013) are plotted to the right on the observed CMD. On one hand, this example illustrates the well known "age-metallicity" degeneracy and, on the other, the complexity of analyzing the CMD of clusters. Methods employing various theoretical assumptions can

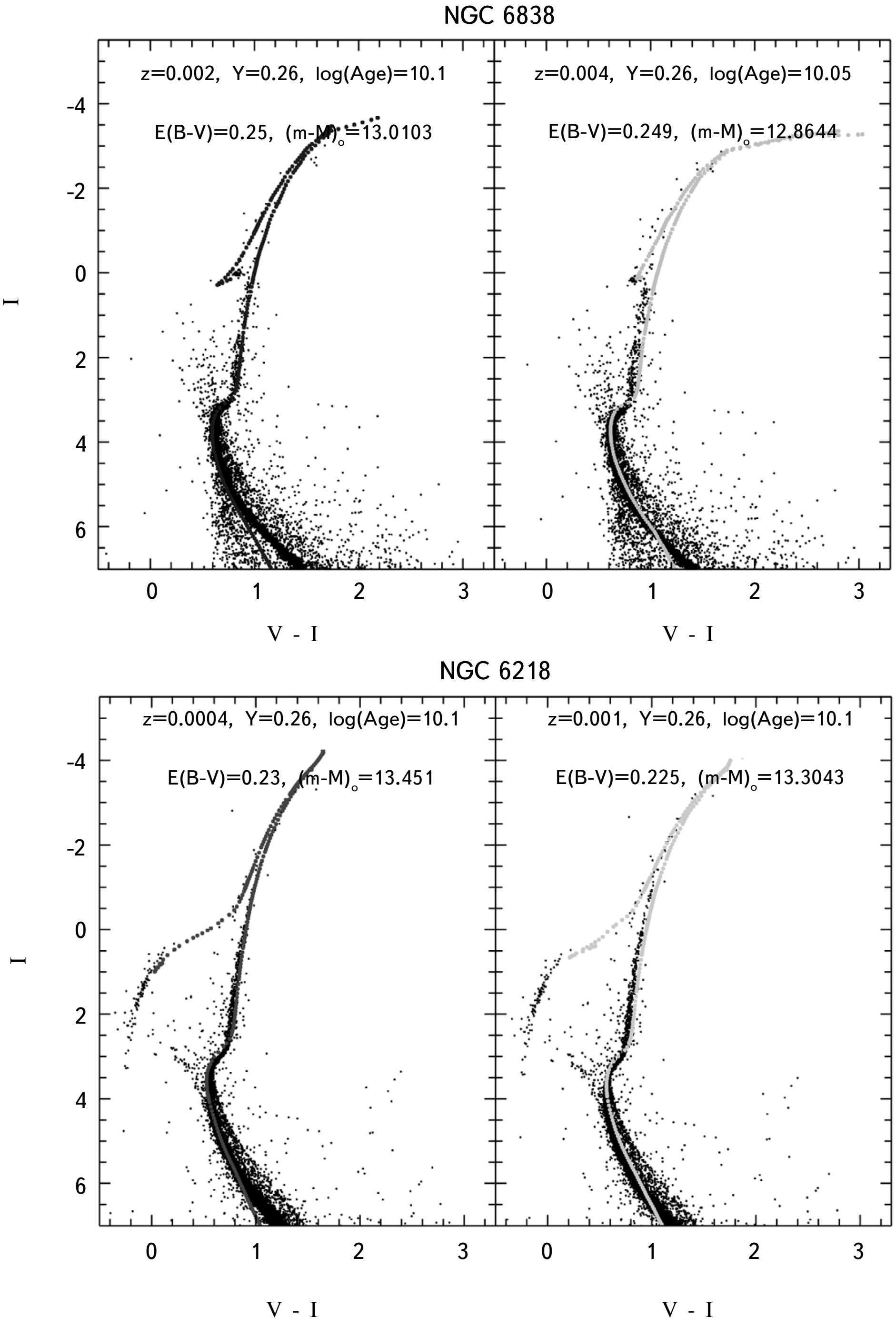

Fig. 2. Comparison of the position of the clusters NGC6838 and NGC6218 on a color-magnitude diagram (CMD) based on photometric data of Piotto, et al., 2002, with isochrones from Bertelli, et al., 2009. The parameters of the isochrones (age, [Fe/H], and Y) on the graphs at the left and right were determined in different ways. Shown on the left are the results of a population synthesis of combined spectra of the stars in the clusters (Khamidullina, et al., 2013). Isochrones with parameters determined by Van den Berg, et al, 2013, from an analysis of the CMD themselves are shown on the right.

yield different estimates of age and metallicity. Published results on multiple star populations in one or another object are based on very careful photometry and analysis.

The reasons for the observed chemical anomalies for stars in globular clusters have not yet been studied definitively (Bastian, et al., 2015). There are several proposed star-sources for enrichment in chemical elements that can lead to the observed anticorrelations: (1) massive stars in the asymptotic branch ($Mass \sim 5 \div 9 M_{\odot}$) (D'Ercole, et al., 2010); (2) rapidly rotating massive stars ($Mass > 20 M_{\odot}$) (Decressin, et al., 2007); (3) interacting massive binary stars ($Mass \sim 10 \div 20 M_{\odot}$); and (4) very massive stars ($Mass > 10^4 M_{\odot}$) (Denissenkov & Hartwick, 2014). The AGB-scenario essentially involves matter that has been ejected during the evolution of first generation AGB (asymptotic giant branch) stars that cannot leave a massive cluster. This matter cools and sinks toward the center of the cluster. Stars of a second generation are formed from this material and products of the evolution of the other stars in the cluster. The FRMS scenario uses material remaining in the cluster after production of the first generation stars and ejection of rapidly rotating massive stars that are rich in helium and sodium and lean in oxygen to produce a second generation of stars. Interacting binaries have been examined as a source of enrichment of the matter in star clusters in so-called "early disk accretion" (EDA, Bastian, et al., 2013). In the EDA scenario, low-mass stars up to the main sequence with protoplanetary disks accumulate matter which remains after evolution of the massive interacting binaries in the disks. Bastian, et al. (2015) have developed a model for self-enrichment of clusters by products of the evolution of all five types of stars. [Na/Fe], [O/Fe] and the helium content were modelled as functions of stellar mass. The models were compared with observed elemental abundances for stars in the clusters NGC104, NGC288, NGC2808, NGC6121,NGC6397, NGC6752, NGC7078, and NGC7099. It was concluded that no single self-enrichment source of the ones that were considered nor a combination of these can explain the observed data.

It has been proposed that the variation in the Fe abundance in anomalous clusters may occur because these objects have been much more massive in the past. For example, the Omega Centauri cluster is considered to be the nucleus of a dwarf galaxy that was destroyed by tidal interactions (Bekki & Norris, 2006). It is assumed that ordinary GC, which consist of stars with the same metallicity and a constant [(C+N+O)/Fe] ratio, were formed by self enrichment during hydrogen burn reactions with participation by stars from the asymptotic branch (D'Ercole, et al., 2010), or by rapidly rotating massive stars (Decressin, et al., 2007). Variations in the abundance of chemical elements have been observed in stars in these GC, as in anomalous clusters (Bastian, et al., 2013). The stars in the galactic field with a pattern of chemical abundances similar to that in the anomalous stars are carbon-enhanced, extremely metal-poor, s-process AGB stars (CEMP), in which a neutron source in the form of the carbon isotope ^{13}C predominates.

5. Concluding remarks

This article has discussed theoretical and observational data on the properties and the origin and evolution of star clusters that can shed light on the problem of multiple star populations in globular clusters. Some questions have been left out of this review or discussed all too briefly, for example: the dependence of the properties of GC systems on the properties of parent galaxies, the development of and improvements in methods for determining the age and chemical composition of star clusters, the spatially kinematic structure of the galactic system of globular clusters, GC outside of galaxies, star flow in the halo of our and other galaxies, searches for traces of destroyed star clusters, and black holes in globular clusters. These questions will be the subject of a separate article.

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