ВАК 2024 MODERN ASTRONOMY:
FROM THE EARLY UNIVERSE TO EXOPLANETS AND BLACK HOLES
300 years Russian Academy of Sciences

Stellar populations of extragalactic globular clusters

M. Sharina[1], M. Maricheva[1], I. Acharova[2], and V. Shimansky[1]

[1] Special Astrophysical Observatory of the Russian Academy of Sciences, Nizhny Arkhyz, 369167 Russia

[2] Department of Physics, Southern Federal University, 5 Zorge, Rostov-on-Don, 344090 Russia

Abstract. Globular clusters (GCs) are the oldest (ages up to 13.6 Gyr), but not the most metal-poor ($-2.9 <$ [Fe/H] < 0 dex) objects in the Universe. Studying properties of their stellar populations and comparing them with the properties of structural components of galaxies and stellar streams is necessary to understand the processes of nucleosynthesis and galaxy formation. We analyse integrated-light (IL) spectra of extragalactic GCs in order to determine the properties of their horizontal branch stars, ages and chemical composition. For this purpose, we compare the observed and synthetic spectra of clusters calculated using stellar atmosphere models. In this paper, we address the questions: 1) what signatures of multiple stellar populations can be inferred from the analysis of IL low-resolution spectra of GCs; and 2) what the origin of GCs is and their multiple stellar populations. For the second question, we consider only two sources of multiple stellar populations: asymptotic giant branch and rapidly rotating massive stars, and briefly consider the problems in this scientific area.

Keywords: galaxies: abundances; galaxies: star clusters: general

DOI: 10.26119/VAK2024.088

1 Introduction

Our method of population synthesis of integrated-light (IL) spectra of globular clusters (GCs) has been described in detail by Sharina et al. (2024) (hereafter: S2024; see also references therein). According to this method, synthetic IL spectra of GCs are computed using stellar atmosphere models, selected isochrones of stellar evolution and a stellar mass function. Selection of isochrones with varying helium mass fraction (Y) (e.g. Bertelli et al. 2008) allows us to estimate for GCs not only the chemical composition and age, but also $T_{\rm eff}$ and $\log(g)$ for bluest horizontal branch (HB) stars. The optimum parameters of isochrones used to model IL spectra are determined by comparing the intensities of Balmer and metal lines in the observed and synthetic IL spectra. We have studied the influence of $T_{\rm eff}$ and luminosity of HB stars on the hydrogen lines profiles in IL spectra (S2024). The results of our study serve for more accurate analysis of color-magnitude diagrams of extragalactic GCs and determining distances to them. The comparison of our results for extragalactic and Galactic globular clusters contributes to improving models of stellar evolution and methods of population synthesis.

All methods of population synthesis of IL spectra of GCs are based on the selection of the stellar evolution models capable of characterising the observed data. However, it is known from literature studies of Galactic GCs that most of them contain stars with physical parameters and chemical composition that can not be described by simple stellar populations (e.g. Milone & Marino 2022 and references therein, hereafter: MM2022). In this paper we discuss signatures of multiple stellar populations (MPs) in GCs that can be detected using our method and briefly consider possible sources of MPs and problems with their recognition.

2 Can we detect multiple stellar populations in GCs by analyzing their low-resolution IL spectra?

Many Galactic GCs host two stellar populations that differ in the abundances of light elements (He, C, N, O, Na, Al, and in some cases Mg, Si, and K): the first population with the abundances similar to those of stars in the galactic field at a given metallicity, and the second population with the abundances of elements modified by high-temperature hydrogen burning in the CNO cycle and NeNa and MgAl chains (MM2022). Rare anomalous GCs exhibit variations in the abundance of Fe and s-process elements among cluster stars. They are the most massive GCs in the Galaxy and are thought to be the nuclei of destroyed dwarf galaxies.

The second-parameter problem of the HB morphology is related to the phenomenon of MPs in GCs. The problem is that GCs of the same age and metallicity have different HB morphologies. The colour distribution (i.e., T_{eff} and luminosity) of HB stars varies with age, metallicity, Y and mass-loss efficiency of red giants (e.g. Lee et al. 2000). First population stars are located at the red end of the HB and have lower Y than the stars of the second population enriched in helium and hotter. The scatter in Y for HB stars in a GC, $\Delta Y_{\rm HB}$, correlates with the mass of the cluster, as well as the scatter in element abundances for the cluster stars (MM2022). The higher $\Delta Y_{\rm HB}$, the higher the abundances of N, Na, and Al and the lower C, O, and Mg are observed in the enriched stellar populations. Carbon abundances obtained from the analysis of IL spectra can not serve as an indication of the presence of MPs due to the change in the chemical composition of stellar atmospheres during their evolution (Kraft 1994). As a result, there is a systematic difference between [C/Fe] values determined using IL spectra of GCs and the corresponding C abundances in the red giants of these GCs obtained from the absorption line analysis in high-resolution spectra (Sharina et al. 2020).

From our analysis of low-resolution IL spectra (S2024), we can judge the presence of MPs in the studied GCs using the obtained Mg, Ca, and Na abundances and T_{eff} of bluest HB stars, according to the parameters of the employed isochrones. Mg is the α-process element mainly produced by explosive C-burning in massive stars and in core-collapse supernovae (CCSNe). Na can be produced by C-burning in the interior of massive stars. Ca is mainly produced in CCSNe and SNe Ia. Low [Mg/Fe] and high [Na/Fe] and [Ca/Fe] obtained from IL spectra are considered as evidence of the predominance of the second stellar population, which is expressed in Mg-Al, Mg-Na and Na-O anti-correlations among cluster stars, as well as the presence of stars with extreme Mg depletion (MM2022, Larsen et al. 2022, S2024).

Six of the eight very metal-poor GCs studied by S2024, have -0.4 $\leq$ [Mg/Fe] $\leq$ 0.05 dex and 0.2 $\leq$ [Ca/Fe] $\leq$ 0.6: [VFH2013] PA-N147-1, Hodge III, [CS82] C39, Bol 2, Ext 8, and [GPH2009] KK 197-2. All of them have extended blue HBs with the maximum T_{eff} in the range 8000–12600 K. This can be judged from the isochrone data used in the spectrum modelling and by comparison them with the observed color-magnitude diagrams (S2024). Unfortunately, the available wavelength range did not include Na lines. As a result, we conclude that these six very metal-poor GCs contain MPs.

3 On the sources of multiple populations in metal-poor GCs

One of the studied GCs, Ext 8, exhibits the lower metallicity ([Fe/H] ~ -2.8 dex) among all known GCs (Larsen et al. 2022, S2024). This value is below the inferred "metallicity floor", i.e. the minimum metallicity estimated in a sample of about two thousand GCs from 28 galaxies (Beasley et al. 2019). The chemical composition of Ext 8 is unique among all known objects in the Universe (Larsen et al. 2022, S2024). It is characterised, in particular, by a very low Mg abundance ([Mg/Fe] $\sim -0.4 \div -0.3$ dex). Note, that the distribution of GCs by colour and metallicity is bimodal in many massive galaxies with the metallicity peaks near [Fe/H] = -1.6 dex and [Fe/H] = -0.6 dex (e.g., Beasley et al. 2019; Acharova et al. 2022 and references therein), while GCs with [Fe/H] < -2 dex are very rare. The same metallicity distribution is demonstrated by circumgalactic clouds (CGCs) at various redshifts (Acharova et al. 2022). CGCs are structures containing gas of different densities and ionization degrees. Based on the statistical analysis of the distribution of elemental abundances in GCs and CGCs and the comparison of the calculations based on it with the models of supernovae yields, it has been concluded that GCs could form in CGCs (Acharova et al. 2022). The metallicity of ultra-faint dwarf galaxies (UFDs) (Simon 2019) is similar to that of very-low-metallicity GCs. UFDs have predominantly old stellar populations and are observed in the vicinity of our own and some nearby galaxies. Due to their low mass and low stellar density, their detection at large distances from us is difficult. GCs were not found in or near UFDs. The models of pair-instability supernovae yields were used to explain the observed elemental abundances in UFDs (Sanati et al. 2023).

Because the processes of the chemical evolution mentioned in Sec. 2 cannot occur in low-mass stars, and MPs are observed even among low-mass stars in Galactic GCs, it is suggested, that stars in GCs originated from the gas enriched by massive stars of the first generation (MM2022). These could be fast-rotating massive stars (FRMSs) with the masses from 12 to 50 $M_\odot$ (Carretta et al. 2010) (hereafter: C2010). Stellar wind from these objects enriched the interstellar medium of young gravitationally bound GCs. However, after a few million years, these stars exploded as SNe. The explosion of numerous SNe inevitably blew gas out of GCs together with the wind from FRMSs. In order for the products of stellar evolution to remain in GCs, the ratio of the gravitational potential to the number of massive stars in GCs should be similar to that in dwarf galaxies where the contribution of supernova enrichment is observed. The fact that variations in Fe and s-process elements are present in anomalous GCs suggests that such massive GCs existed. In general, the most massive GCS in our Galaxy are the old and low-metallicity GCs (C2010). Otherwise, GCs should be located at the centers of galaxies so that SNe outflows can return back to GCs (Shapiro et al. 2010).

Asymptotic giant branch (AGB) stars with the masses from 4 to 8 $M_\odot$ can be responsible for the observed MPs in GCs (C2010, MM2022). Their enriched shells are ejected as planetary nebulae and serve as the material for next generations of stars. Let us estimate the initial mass of the primordial population, needed to provide the material for the second generation stars in GCs. We assume, following Larsen et al. (2020), who studied Ext 8, that the total mass of a metal-poor GC is $10^6 M_\odot$, that the observed Mg abundance can be reproduced with two populations having lower and higher Mg abundances than this value, and each population makes up half of the stars. Although the last point is only a hypothesis based on measurements of absorption line intensities in the spectrum, it cannot be ruled out. It should be noted that variations of Mg abundances are more significant in low-metallicity GCs (MM2022). The normalising condition of the Salpeter (1955) IMF is the following: $\int_{0.1}^{50} 0.1716 \cdot m \cdot m^{-2.35} dm = 1$ (see, e.g., Larsen et al. 2022, more on the fact that the Salpeter IMF can be successfully applied to analysing the IL spectra of GCs). Let us calculate the mass fraction returned into the interstellar medium of Ext 8 from AGB stars: $\int_4^8 0.1716 \cdot (\mathrm{m} - \mathrm{m_w}) \cdot \mathrm{m}^{-2.35} \mathrm{dm} = 0.06$, where $\mathrm{m_w} = 0.08 \cdot \mathrm{m} + 0.47$ is the mass of the stellar residue of the white dwarf for $\mathrm{m} \leq 9\mathrm{M}_\odot$ (Weidemann 2000). Calculated in the same way the mass fraction returned to Ext 8 from FRMs stars with the masses from 12 to 50 $M_\odot$ gives 8 % and does not depend on the mass of the cluster. If one supposes that only AGB stars form the mass returned into the interstellar medium and that it has moved to the stars of the second generation with time, then $0.5 \cdot 10^6 M_\odot$ is 6 % of the initial mass of the cluster. Note, that the value 6 % does not depend on the mass of the cluster. In this case, the initial mass has been equal to $\sim 10^7 M_\odot$ and this GC contains ∼8 % of the initial stellar mass. This result is consistent with the data on the mass loss for many GCs in our Galaxy (C2010). The mass $\sim 10^7 M_\odot$ is comparable to the mass of a dwarf galaxy.

The actual situation with determining sources of MPs is much more complicated (e.g. Winter & Clarke 2023). In order to precisely calculate the mass budget of MPs in GCs and its evolution with time, it is necessary to take into account binary stars, sub-stellar companions, and stellar-mass black holes (e.g. Gieles & Gnedin 2023). Space observations have revealed signatures of different dynamical evolution of first and second generation stars (Scalco et al. 2024). It is of interest that the fraction of second generation stars varies from cluster to cluster and correlates with the present-day stellar density and cluster mass (Lagioia et al. 2024).

4 Summary

In Sec. 2, we considered the signatures of MPs that can be detected in our analysis (S2024) of low-resolution IL spectra of extragalactic GCs: low Mg abundance, high Ca and Na abundances, and high Y value set by the isochrone of stellar evolution used to model the IL spectrum. The temperature $T_{\rm eff} > 8000$ K of bluest HB stars argue in favour of the presence of MPs in old low-metallicity GCs.

We discussed the relationship between the initial and present-day masses of GCs with sources of MPs: AGB and FRMSs. (Sec. 3). By calculation of the mass fraction returned from massive stars into interstellar medium, we have shown that the initial mass of the cluster was approximately 8 times larger than the present-day one. This result is consistent with the data on the mass loss for many GCs in our Galaxy (e.g. C2010).

Funding

The work was partially supported by the Ministry of Science and Higher Education of the Russian Federation grant 075-15-2022-262 (13.MNPMU.21.0003).

References

Acharova I., Sharina M., and Kazakov E., 2022, Monthly Notices of the Royal Astronomical Society, 511, p. 800
Beasley M., Leaman R., Gallart C., et al., 2019, Monthly Notices of the Royal Astronomical Society, 487, p. 1986
Bertelli G., Girardi L., Marigo P., and Nasi E., 2008, Astronomy and Astrophysics, 484, p. 815
Carretta E., Bragaglia A., Gratton R., et al., 2010, Astronomy and Astrophysics, 516, p. 55
Gieles M. and Gnedin O., 2023, Monthly Notices of the Royal Astronomical Society, 522, p. 5340
Kraft R., 1994, Publications of the Astronomical Society of the Pacific, 106, p. 553
Lagioia E., Milone A., Legnardi M., et al., 2024, Astrophysical Journal, Submitted, arXiv:2406.16824
Larsen S., Eitner P., Magg E., et al., 2022, Astronomy and Astrophysics, 660, p. 88
Larsen S., Romanowsky A., Brodie J., and Wasserman A., 2020, Science, 370, p. 970
Lee H., Yoon S., and Lee Y., 2000, Astrophysical Journal, 120, p. 998
Milone A. and Marino A., 2022, Universe, 8, p. 359
Salpeter E., 1955, Astrophysical Journal, 121, p. 161
Sanati M., Jeanquartier F., Revaz Y., and Jablonka P., 2023, Astronomy and Astrophysics, 669, p. 94
Scalco M., Gerasimov R., Bedin L., et al., 2024, Astronomische Nachrichten, 345, p. 40018
Shapiro K., Genzel R., and Forster S., 2010, Monthly Notices of the Royal Astronomical Society (Letters), 403, p. 36
Sharina M., Maricheva M., Kniazev A., et al., 2024, Monthly Notices of the Royal Astronomical Society, 528, p. 7165
Sharina M., Shimansky V., and Shimanskaya N., 2020, Astrophysical Bulletin, 75, p. 247
Simon J., 2019, Annual Review of Astronomy and Astrophysics, 57, p. 375
Weidemann V., 2000, Astronomy and Astrophysics, 363, p. 647
Winter A. and Clarke C., 2023, Monthly Notices of the Royal Astronomical Society, 521, p. 1646