THE SEQUENTIAL STAR FORMATION IN GLOBULAR CLUSTERS

M.V. Ryabova[1], Yu.A. Shchekinov[1,2]

[1] Southern Federal University, Rostov-on-Don, Russia, *rgyaf@yandex.ru*
[2] Special Astrophysical Observatory, Nizhnyi Arkhyz, Russia, *yus@phys.rsu.ru*

ABSTRACT. The results of [O/Na] abundance modelling in globular clusters NGC 2808 and NGC 6752 are presented. The evolutionary scenario allowing to reproduce characteristic observed features of [O/Na] distribution function has been suggested. Slow winds from massive rotating stars are assumed as a producer of chemical anomalies. It is shown, that the abundance pattern in globular clusters can be explained within a model with a limited mixing of stellar wind and surrounding interstellar gas. This means in other words that the second generation stars are born in a vicinity of individual massive stars of the first generation from the heterogeneously distributed material ejected by these stars.

Key words: Globular clusters: individual (NGC 2808, NGC 6752), stars: abundances.

1. Introduction

Usually it is considered, that stars of the globular clusters (GCs) are formed simultaneously from chemically homogeneous material. In other words, GCs are considered as “simple stellar population”.

However, there is a growing number of observational facts which challenge this traditional view. Since the eighties we know that GCs show a peculiar pattern in their chemical abundances (Gratton *el al.* 2004 for a review). While they are generally homogeneous insofar Fe-peak elements are considered, they often exhibit large anticorrelations between the abundances of C and N, Na and O, Mg and Al. Moreover, there are direct observational evidences of the presence of more than one stellar population in some GCs.

At present the several hypotheses are suggested for interpretation of chemical anomalies observed in GCs. Most of them are based on the assumption that stars of GCs are originated from material, enriched at previous stages of stellar evolution inside GCs — it is the self-enrichment hypothesis. Arguments for the self-enrichment hypothesis are based on observational O-Na anticorrelation. Indeed, the necessary high temperature ($> 10^7$ K) for CNO-cycle and NeNa-chains is not reached in stars near a turnoff and a subgiants branch for which O-Na anticorrelation is observed. This means, that the Na, O and He abundance anomalies was already present in the material the observed stars have formed from. However, the assumption that Na and O were already present in GCs material before formation of its stars, can be refused, because it means highly efficient mixing of elements of CNO-cycle, on the one hand, and elements of NeNa-chain on the other. It is worth noting that the self-enrichment scenario in modern understanding differs from “classical” self-enrichment scenario, where GCs are assumed to form from pristine gas (Fall & Ress 1989).

At present there is no physically proved self-consistent evolutionary scheme of GCs which would allow to explain the observed abundance pattern. In the present work we are attempting to construct the evolutionary scheme able to reproduce this pattern.

2. Numerical model

For the computing we used a single-zone model based on the standard system of equations describing evolution of the gases mass and the elemental abundances of star forming system (Matteuchi *et al.* 1989, Firmani *et al.* 1992, Shustov *et al.* 1997). In the present work the evolution of GCs is considered within the framework of self-enrichment scenario.

Following Decressin *et al.* (2007), we consider the slow wind from massive rotating stars as a producer of chemical anomalies in GCs.

2.1 Model 1

A detailed description used single-zone model of chemical evolution is given in previous works (Kasjanova & Shchekinov 2005, Ryabova & Shchekinov 2008). In all considered models we assume variations of the initial mass function (IMF) (Kasjanova & Shchekinov 2005).

In the assumption, that all material injected by stars is fully mixed with the interstellar medium, it is not possible to reach the high helium abundance in gas before formation of next stellar generation even if only the massive rotating stars (the main source of helium) are born at the first episode of star formation (SF). At full mixing of the injected material with the gas primordially contained in the protocluster the helium fraction in gas will increase only by $\Delta Y = (\Delta M_{He} - Y \cdot \Delta M)/(\Delta M + (M - M_*)) \sim 2 \cdot 10^{-3}$.

In order to avoid full mixing, we will consider that the slow wind material ejected by massive rotating stars is redistributed not over the whole volume of the system, but only over its part where further SF takes place — the area of active SF. Technically realization of such a model is carried out by the control of gaseous mass in this area. Initially this mass coincides with the total mass of the system since the first generation stars are assumed to born through the whole volume of the system. By the moment when the second generation stars are formed this mass should become essentially small, so that its helium abundance would be appreciable. For this purpose in the equation for gaseous mass in active SF area we add the term $-\zeta M_g$ in comparison with the equation for the total mass of the system. The value of ζ is considered distinct from zero over time interval Δt. As a result the gas mass involved in further SF, decreases by factor $e^{\zeta \Delta t}$, which can correspond, e.g., to mass loss forced by energy injection from SNe explosions or stellar wind; ζ and Δt are considered as free parameters. Actually this means, that at $\zeta \Delta t >> 1$ the next generations of stars are born mostly from the material injected by slow wind of massive stars while the gas primordially filled the protocluster leaves the area of active SF. This prescription allows to formalize partial mixing (where the enriched material is mixed with the limited mass of primordial matter) in a single-zone scheme.

Transformation of gas in active area is described by the equation

$$\dot{M}_g' = -\Psi + \int\limits_{M_{min}}^{M_{max}} \Psi(t - \tau_M)\varphi(M, t - \tau_M) M_{\rm ej} dM - \zeta M_g', \tag{1}$$

while for the whole volume the transformation rate of gas is equal to

$$\dot{M}_g = -\Psi + \int\limits_{M_{min}}^{M_{max}} \Psi(t - \tau_M)\varphi(M, t - \tau_M) M_{\rm ej} dM. \tag{2}$$

Here star formation rate is

$$\Psi = f \rho^2 \upsilon,$$

where $\rho = M_g/V$ — the gas density and $\upsilon = M_g' V/M_g$ — the volume of active SF area.

An example of calculation of such a model is presented on Fig. 1. From Fig. 1 one can see, that the suggested model with partial mixing really describes formation of the stellar population with a high helium abundance. However, within the framework of such a model it is not possible to reproduce observed behaviour of [O/Na] function. The distribution shows a failure in the interval of -0.3¡[O/Na]< 0.4. The variation of free parameters of model, such as SF efficiency, the minimal mass of forming stars in the first episode, parameter ζ, changes only the number of stars in the vicinity of peaks. It is caused by the fact that the ejected matter from stars of different mass with various O and Na abundance is mixed in the active area and new stars are born from material with the average abundance of chemical elements. Apparently, it is possible to prove, that observed [O/Na] distribution function evidences of the absence of mixing in the area of active SF.

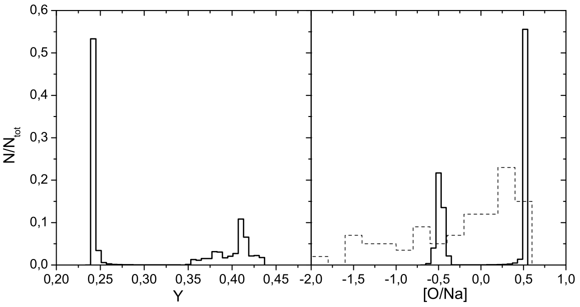

Figure 1: An example of He and [O/Na] distributions in model 1 (solid line). Dash line shows the observed [O/Na] distribution function in NGC 2808.

2.2 Model 2

In order to exclude mixing of chemical elements injected by stars of different masses into the SF area, it is necessary to assume the presence in system of several active areas disconnected with each other. Each such an area should include chemical elements from individual stars or stars in some mass interval.

The description of mixing process within the frameworks of a single-zone models is always schematic, and can be carried out “by hands” only. Technically realization of such a scenario of the partial mixing was carried out as follows. Stars with mass from 20 to $100 M_\odot$ which produce anomalies, have been divided onto groups by mass with an interval ΔM. For each interval of stellar masses which are born in the first episode, the independent set of equations (1) – (2) was solved. The transition time to standard IMF within the frameworks of this model was equal for each group to the life time of a star of the greatest mass (i.e. to minimal time that stars stay on the main sequence for a given group). The obtained abundance distributions for each independent case were summed taking into

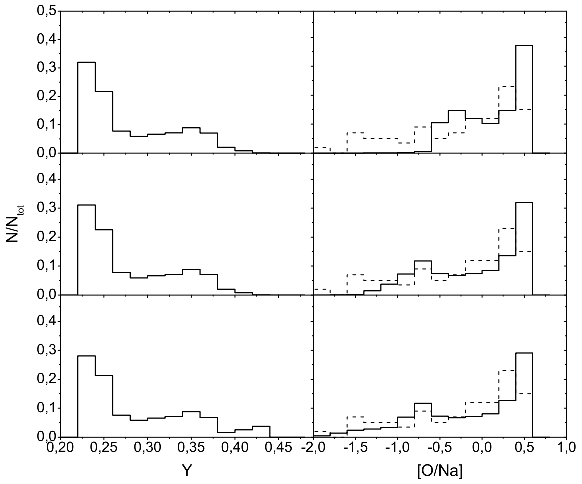

Figure 2: An example of calculations in model 2 (solid line). On right panels dash line shows the observed [O/Na] distribution function in NGC 2808.

account the fraction in the IMF from 20 to $100M_\odot$ occupied by the given group of stars.

An example of calculations in model 2 with mass spacing $\Delta M = 2M_\odot$ is presented on Fig. 2 (the top panel). It is easy to see, that the model with a limited mixing allows to reproduce the observed distribution function in the range of [O/Na]> -1, limited by the minimal value of [O/Na] available in a used database(Decressin *et al.* 2007). On the middle panel the [O/Na] distribution for [Z]$=-1.75$ is shown. This value of metallicity allows to obtain the stars with low value of [O/Na]. However, it is evident, that in the range of [O/Na]< -1 the number of stars obviously smaller than the observed. Using a more flat IMF corrects this situation: on the bottom panel of Fig. 2 the distribution is presented for the same parameters of model as on the middle panel, but for the slope of the IMF equal to -0.35 .

2.3 Model 3

The results obtained in models 1 and 2 allow to draw a conclusion that the pattern chemical abundances in GCs can be explained by assumption of the limited mixing of metals injected from stars. More specifically this means, that stars of the next generation are born from material, enriched by an individual (i.e. isolated) star. In such a scenario the [O/Na] distribution reflects the contribution of regions, enriched by all set of massive stars with metals ejected into their local interstellar medium. One of the opportunities of realization of such a scenario is the mechanism of stimulated SF. Further development would be the model in which the degree of mixing of the metals ejected even by an individual star turns to be incomplete, i.e. metals can be distributed inhomogeneously in a vicinity of an isolated star. Below we describe model in which such a scenario is realized.

Technically this scenario is carried out as follows: it is supposed, that up to the time $2.6 \cdot 10^6$yr (corresponding to the first SN explosions) the massive rotating stars with masses from 20 to $100M_\odot$ are born. The star formation rate is described by a Schmidt law with a constant $f = 6 \cdot 10^{-10}\mathrm{pc}^3 M_\odot^{-1}\mathrm{yr}^{-1}$. This value of the SF efficiency is by two orders less than the one accepted normally for spiral galaxies (Shustov *et al.* 1997). The necessity of a variation of parameter f in evolution of GCs was shown in (Kasjanova & Shchekinov 2005).

For each interval of time $\Delta t \sim 10^4$ $(0 < t < 2.6 \cdot 10^6\mathrm{yr})$ and the mass interval $\Delta M \sim 0.01M_\odot$ in the whole range $20 < M < 100M_\odot$ the number of the born massive stars $\Delta N = \Psi(t)\varphi(M)\Delta M \Delta t$ is calculated. Further on stars of small masses $(0.1M_\odot < M < 1M_\odot)$ are born from the material ejected by slow wind in the vicinity of each star of the first generation. The chemical abundance of second generation stars is determined not only by the ejected material from massive stars, but also by its mixing with the primordial protocluster gas. Note that here we understand mixing as a dilution of the material injected by massive stars with the surrounding primordial gas. The matter ejected by massive star is mixed inhomogeneously with the primordial gas, which leads to variations of the [O/Na] abundance in the second generation stars born in the vicinity of a parent massive star.

Let M^{SW} is the mass of matter injected by one massive rotating star. This matter is redistributed through over an area of a given mass with the initial chemical composition. Let M_{cloud} is the cloud mass per one star where the injected material is redistributed. The mass transformed into stars of the second generation is equal to $\eta(M^{SW} + M_{cloud})$, where $\eta \leq 1$ is the SF efficiency.

In the model 3 we characterize the degree of mixing $0 \leq \xi \leq 1$ such that matter with the mass $M_{ej} + \xi M_{cloud}$ contains homogeneously distributed products of stellar nucleosynthesis, while the remained cloud mass $(1 - \xi)M_{cloud}$ has the initial abundance. Masses of ith chemical element confined into stars of the second generation in these two regions are determined as $\eta(M_{ej}^{(i)} + \xi Z_i M_{cloud})$ and $\eta(1 - \xi)Z_i M_{cloud}$ correspondingly. The value $\xi = 0$ corresponds to the absence of mixing, while $\xi = 1$ described full mixing of the injected material through over the part of the cloud belonging to the star.

For each individual star the parameter ξ takes a fixed value, however for the whole stellar system we treat this parameter as a random variable. In such an approach we introduce the function $p(\xi)$ which characterizes the probability that in the vicinity of a star the degree of mixing lies in the interval $[\xi, \xi + \Delta\xi]$.

On Fig. 3a the resulting [O/Na] distribution is presented for the following parameters of the model:

[Z]=-1.5, $M_{cloud} = 200M_{\odot}$ and $p(\xi) \sim 1/(\xi + C)$, $C = 0.001$. The dash line corresponds to the observed distribution function for NGC 2808. It is readily seen, that the modelled distribution is in a good agreement with observation for [O/Na]> -1. However, as well as in the model 2 the interval [O/Na]< -1 contains no stars.

The value of initial metallicity [Z]=-1.75 allows to obtain stars with low [O/Na] (Fig. 3b). For the normal slope of the IMF the number of such stars remains still smaller than found in observations. However, for a more flat IMF (the slope equal to -0.35) the similarity of the modelled distribution and the observed one is obvious (Fig. 3c). On Fig. 3d the observed [O/Na] distribution function in NGC 6752 is shown by dash line. Despite the fact that this cluster and NGC 2808 have similar metallicity, they present distinct shapes for their [O/Na] distribution function. In order to reproduce the behaviour of the [O/Na] distribution function for NGC 6752 we have assumed the following parameters of the model: [Z]=-1.75, $M_{cloud} = 40M_{\odot}$ and $p(\xi) \sim 1/(\xi + C)$, $C = 0.003$, and in addition we assumed that stars do not form from the remaining mass of the cloud with the chemical composition. The result is presented on Fig. 3d by solid line. It is easy to see that the obtained distribution looks similar to the observed one not only qualitative, but also quantitatively.

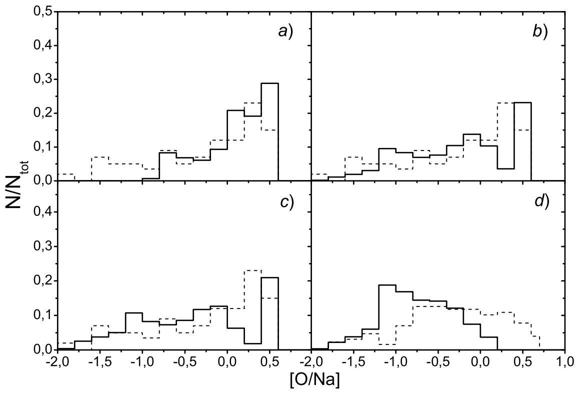

Figure 3: Examples of calculation of model 3 for probability density law $p(\xi) \sim 1/(\xi + C)$ (solid line). Dash line shows the observed [O/Na] distribution function in NGC 2808 (a,b,c) and NGC 6752 (d). Parameters of model:) [Z]=-1.5, $M_{cloud} = 100M_{\odot}$, $C = 0.001$; b) [Z]=-1.75, $M_{cloud} = 100M_{\odot}$, $C = 0.001$; c) the same as on the Fig. 3b, but the slope of the IMF equals to -1.35; d) [Z]=-1.75, $M_{cloud} = 40M_{\odot}$, $C = 0.003$.

3 Conclusions

The results of modelling of chemical evolution of GCs within the frameworks of a single-zone models allow to draw the following conclusions:

1) The excess of helium abundance in GCs NGC 2808 and NGC 6752 can be reached assuming that the first generation stars remove out of the protocluster an essential part ($\sim 90\%$) of its baryon mass.

2) The [O/Na] distribution functions in GCs NGC 2808 and NGC 6752 reflect incomplete mixing of the stellar wind and the surrounding interstellar gas. In other words, the [O/Na] function indicates that the next stellar generation is born in the vicinity of an individual parental star. It can be understood as a stimulation of SF by stellar wind.

Acknowledgements. This work was supported by the Federal Education Agency (project code RNP 2.1.1.3483).

References

Gratton R. *et al.*: 2004, *Astron. Astrophys.*, **369**, 87.

Fall M., Rees M.: 1985, *Astrophys. J.*, **298**, 18.

Matteucci F., Greggio L.: 1989, *Astron. Astrophys.*, **154**, 279.

Firmani C., Tutukov A. V.: 1992, *Astron. Astrophys.*, **264**, 37.

Shustov B. M., Wiebe D. S., Tutukov A. V.: 1997, *Astron. Astrophys.*, **317**, 397.

Decressin T. *et al.*: 2007, *Astron. Astrophys.*, **464**, 1029.

Kasjanova M. V., Shchekinov Yu. A.: 2005, *Astron. Rept.*, **82**, 11.

Ryabova M. V., Shchekinov Yu. A.: 2008, *Astron. Rept.*, **85**, 398.