UDC 524.7-17 *Astrofiz. Issled. (Izv. SAO)*, 1993, **35**, 43-59

THE EVOLUTIONARY SYNTHESIS OF INTEGRATED GALACTIC SPECTRA

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Received January 15, 1992

ABSTRACT. *Methods of evolutionary synthesis of integrated spectra of stellar clusters and galaxies are described. The model parameters are the initial chemical composition of stars, the slope of the initial mass function, the rate of star formation and the age of a system. The database for the evolutionary synthesis is a library of stellar spectra and evolutionary tracks of stars. The color (B-V) and equivalent widths of some absorption hydrogen lines, and metal lines and bands of the model spectra are the numerical characteristics of the model.*

Comparison of the model spectra with those of actual stellar clusters provides satisfactory results.

Further calculations of integrated spectra of galaxies by the method of evolutionary synthesis with modification of all the parameters of the model are discussed.

Описана методика эволюционного моделирования интегральных спектров звездных скоплений и галактик. Параметры модели - начальный химический состав звезд, наклон начальной функции масс, интенсивность звездообразования и возраст системы. Базой данных для эволюционного моделирования являются библиотека звездных спектров и набор эволюционных треков звезд. В качестве численных характеристик модели взяты (B-V) цвет и эквивалентные ширины некоторых абсорбционных линий водорода и линий и полос металлов.

Сравнение модельных спектров со спектрами реальных звездных скоплений *дает удовлетворительные результаты.*

Обсуждаются дальнейшие расчеты интегральных спектров галактик методом эволюционного моделирования с варьированием всех параметров модели.

I. INTRODUCTION

Most galaxies are so distant that they are not resolved into individual stars, and we are able to measure only their integrated parameters. Therefore from the very initial stage of development of extragalactic astronomy it confronted the problem of determination of mean characteristics (averaged age, metallicity, mass distribution) of stellar population from the integrated spectra of a galaxy (or some part of it, e.g. the nucleus).

Historically a method of the so-called population synthesis appeared first. A library of stellar spectra of various spectral classes was compiled, then these spectra were summed with weights corresponding to a portion of stars of each type in the stellar population of a galaxy. In such a way the integrated spectrum of a galaxy was obtained. So an inverse problem was solved: unknown contributions in the radiation of various-type stars were determined from the measured integrated spectrum of a galaxy. This is a linear set of equations, and its solution would be of no difficulty, if it were not for a series of unpleasant circumstances. First, as any other inverse problem, this one is unstable as the right-member errors, and the observed spectra of galaxies always have errors. Second, arbitrary rule is always present in forming a library of stellar spectra: it is unknown if composition of a chosen library corresponds to the true composition of the galaxy in question, and if only one type of stars is lacking in the library, the whole solution has no sense. Third, in such tasks it is needed that the basis should always be orthogonal, in other words, the spectra of stars of different types should radically differ from one another. Meanwhile it is quite unphysical: it is known that spectral classification of stars is practically continuous, i.e. different types of spectra pass smoothly into one another.

All these difficulties with the population models nonplussed repeatedly the researchers dealing with their development. The resulting negative contributions of some types of stars were an ordinary effect. One had to introduce "astrophysical constraints" on solutions: first, simply the nonnegativity of contributions, then monotony and continuity of the Main Sequence and the giant branch, then the fit of the found distribution of stars on the Hertzsprung-Russell diagram to the stellar luminosity functions known from observations of our Galaxy. Finally, the "astrophysical constraints" transformed into parameters and became so complicated that in the paper of Turnrose (1976), for instance, the population synthesis transformed practically into evolutionary.

A method of evolutionary synthesis of integrated characteristics of galaxies was first developed by Tinsley (1968, 1972). The evolutionary synthesis is based on the theory of stellar evolution. This synthesis is more "theoretical" than population one, hence its merits and demerits. The merits are that the model is undoubtedly physical and has a relatively small number of parameters (there are 4 main parameters). The demerits consist in complication of solving the inverse problem, which is nonlinear, and, of course, the fact that all restrictions and imperfections of the initial theory - our ideas of the evolution of stars and galaxies on the whole - reduce automatically the applicability of results of evolutionary synthesis of integrated galactic spectra. And, nevertheless, in the present paper we have decidedly given preference to the evolutionary synthesis rather than population.

II. THEORY OF EVOLUTIONARY SYNTHESIS

At the evolutionary synthesis the integrated spectrum of a galaxy is obtained by summation of the spectra of its component stars, the integration is being done over the stellar masses and ages:

$$L_\lambda = \int_0^T \int_{\mathfrak{M}_{min}}^{\mathfrak{M}_{max}} L_\lambda(\mathfrak{M},\tau)\ N(\mathfrak{M},\tau) d\mathfrak{M} d\tau, \text{ where} \qquad (1)$$

L_λ - galaxy luminosity at the wavelength λ,
$L_\lambda(\mathfrak{M},\tau)$ - luminosity at the wavelength λ of a star of mass $\mathfrak{M}$ and age τ,
$N(\mathfrak{M},\tau)$ - number of stars of mass $\mathfrak{M}$ and age τ in the galaxy,
T - age of the galaxy (i.e. age of its oldest stars), it is a parameter of the model,
$\mathfrak{M}_{min}$ and $\mathfrak{M}_{max}$ - limits of stellar masses; usually assumed to be $\mathfrak{M}_{min}=0.1\mathfrak{M}_\odot$ (objects of a smaller mass are unable to maintain thermonuclear burning), and $\mathfrak{M}_{max}=40\text{-}60\ \mathfrak{M}_\odot$.

From which sources can the value of $L_\lambda(\mathfrak{M},\tau)$ be derived? The stellar evolutionary theory allows to calculate, under the condition of given initial chemical abundance, the evolutionary track of a star of mass $\mathfrak{M}$ in the diagram (L_{bol}, T_{eff}). The initial stellar chemical composition - the helium abundance Y and the metallicity Z - is a parameter of our model. Thus, from the theory we have dependences $L_{bol}(\mathfrak{M},\tau)$ and $T_{eff}(\mathfrak{M},\tau)$. Further for each star of mass $\mathfrak{M}$ and age τ we select a spectrum according to T_{eff} and luminosity class, either theoretical, from the model stellar atmospheres or from the library of the observed stellar spectra, and normalize it so, that the integral over the wavelengths would coincide with the corresponding $L_{bol}(\mathfrak{M},\tau)$. This normalized spectrum is exactly $L_\lambda(\mathfrak{M},\tau)$ in the integral (1). In order not to introduce a variable limit of integration with respect to the age, we assume that after its death ($\tau>\tau_{\mathfrak{m}}$) the star has a zero luminosity.

The number of stars of mass $\mathfrak{M}$ and age τ is set as follows: assuming that the stellar mass distribution of new-born stars remains unchanged in the course of evolution of the galaxy, in $N(\mathfrak{M},\tau)$ one can separate the variables:

$N(\mathfrak{M},\tau)=\varphi(\mathfrak{M})\ f(T-\tau)$, where

$\varphi(\mathfrak{M})$ is the initial mass function (IMF)
$f(t)$ is the star formation rate (SFR) in the galaxy.

In the very early paper of Salpeter (1955) it was found that in the neighbourhood of the Sun in rather wide stellar mass interval the IMF - stellar mass distribution in the new-born generation - is well approximated by the power law $\varphi(\mathfrak{M})\sim\mathfrak{M}^{-\alpha}$, where $\alpha=2.35$. Attempts have been made repeatedly ever since to specify the IMF in the solar neighbourhood and to examine it for galactic clusters in our Galaxy and for Magellanic Clouds. In principle no essential departures from the Salpeter's law have been found, therefore in our model of integrated spectra we utilize the power law for the IMF: $\varphi(\mathfrak{M})=\mathfrak{M}^{-\alpha}$, where α is the parameter of the model.

The function f(t), the characteristic of the general star formation rate in the galaxy at the moment t, must be (on rather large time scales) a monotonous nonincreasing time function, since from the general point of view it is evident that gas in any galaxy decreases being transformed into stars, and material for star formation is getting more and more scarce. (Any catastrophic accretion event, such as merging by other galaxy, is suffered by the galaxy on time scales of about 10^8 years, which is much less than its lifetime). Therefore it is convenient to set f(t) by a family of exponents: $f(t)\sim\exp(-\beta t)$, where β is the parameter of the model and may change from 0 to $+\infty$.

The approximation of the SFR by exponent has physical grounds too: the known Schmidt's law (Schmidt, 1959) for the dependence of the star formation rate on the gas density in the current interpretation will look like

$$d\mathfrak{M}_*/dt \sim \rho_{gas}.$$

If we write by analogy $-d\mathfrak{M}_g/dt \sim \mathfrak{M}_g$ ($\mathfrak{M}_g$ is the total mass of gas in the galaxy, $d\mathfrak{M}_*/dt = -d\mathfrak{M}_g/dt$ in the absence of accretion) and then integrate this equation, we will have exactly the exponential law for the global process of star formation in the galaxy.

So we see that in the first approximation there are four physical parameters in the evolutionary model of the integrated spectrum:

(Y,Z) is the initial chemical composition of stars;
α is the slope of the initial mass function;
β is the reciprocal to the characteristic time of star formation in the galaxy;
T is the age of the galaxy.

The evolutionary tracks of stars and the library of stellar spectra are taken from published data, and, strictly speaking, are also parameters of the model. These parameters are reserve for continuous improvement of the model.

III. DATABASE FOR EVOLUTIONARY SYNTHESIS

1. Library of stellar spectra

The library of stellar spectra must comply with the following basic requirements:

1) have a good accuracy;
2) represent the energy distribution with a constant not too large step on wavelength in a wide spectral range;
3) be complete enough, i.e. to have a set of stars of possibly all spectral and luminosity classes, metallicity values, etc.

From the available catalogues of stellar spectra described by Glushneva (1989), two are recognized as the most suitable: the Pickles' catalogue (1985) and the one by Jacoby et al. (1984) (further - the Jacoby's catalogue).

The Pickles' catalogue contains the mean energy distributions for 48 spectral groups of stars with the resolution 10-17 Å within the wavelength range 3600-10000 Å with the step 3 Å normalized by 100 in the range 5450-5500 Å. These standard groups include stars of various spectral and luminosity classes of solar chemical composition, metal rich and poor G-K giant branch stars, and horizontal branch giants. For our task we selected within 3600-8000 Å 37 average spectra of III, IV, and V luminosity class stellar groups with solar chemical composition and added to them 14 spectra of I luminosity class stars of the same solar composition from the Jacoby's catalogue, having transformed them preliminarily to the standard form of spectra in the Pickles' catalogue. The Jacoby's catalogue contains individual energy distributions for 161 stars of O-M spectral classes and V, IV, III and I luminosity classes with the resolution ~4.5 Å in the wavelength range 3510-7427 Å with the step 1.4 Å. The metallicity of the stars is mainly close to solar.

For our problem we compiled a number of stars of close spectral classes in 51 groups, having averaged their individual spectra, and transformed them to the standard form of spectra in the Pickles' catalogue, i.e. to the step 3 Å and normalization by 100 within 5450-5500 Å. The wavelength range of our library of stellar spectra transformed from Jacoby's one is 3600-7400 Å.

All calculations were performed further with both libraries for comparison. In this paper we describe only the models with approximately solar chemical composition, since at present, libraries of stellar spectra complete enough are available for the solar chemical composition only.

Now note only one potential possibility of extensive varying of metallicities, spectral classes and luminosity classes of stars: this is the work with the library of theoretical stellar spectra obtained by calculation from stellar model atmospheres, setting the metallicity, gravity acceleration (radius), and effective temperature of a star.

2. Evolutionary tracks of stars

152 theoretical evolutionary tracks of stars with masses from 0.15 to 40 $\mathfrak{M}_\odot$ and chemical abundance Y from 0.2 to 0.3 (helium abundance) and Z from 0.01 to 0.04 (metallicity) give the dependences of L_{bol} and T_{eff} on the star's age. The evolutionary tracks for stars of small masses (0.7-4.4 $\mathfrak{M}_\odot$) have been calculated by Mengel et al. (1979), and Sweigart and Gross (1978) for stars of intermediate masses (7-11 $\mathfrak{M}_\odot$) - by Becker (1981), and for stars of large masses (15-40 $\mathfrak{M}_\odot$) - by Brunish and Truran (1982).

For quite low-mass stars, nonevolving dwarfs (0.15-0.60 $\mathfrak{M}_\odot$) the data have been taken from Vandenberg et al. (1983).

IV. EVOLUTIONARY SYNTHESIS PROGRAM

The evolutionary synthesis program of integrated spectra EVOLUTION was written in the FORTRAN-77 language and used with the computer EC-1035 and then with PC AT/386. This program is operative at three stages.

At the first stage (program EVTRAC), setting the parameters of the program - minimum and maximum masses ($\mathfrak{M}_{min}$ and $\mathfrak{M}_{max}$) and initial chemical composition (Y and Z) of stars, we take the evolutionary tracks of the stars that participate in the model. Then from the data on evolutionary tracks (log g and T_{eff}) for each time point of each track the luminosity and the spectral classes of the star at this moment, corresponding to these data, are selected. A star spectrum from the library of stellar spectra, corresponding to these spectral and luminosity classes, is found (program CLUSTR) by means of a code number which is formed here. Besides, a normalizing coefficient (it is determined so that L_{bol} would coincide with the theoretical one for the given T_{eff}) is calculated for the spectrum at every time point of the track.

On the basis of the evolutionary tracks selected in the EVTRAC, at the second stage (program CLUSTR) the spectral evolution of a cluster of stars, which are formed simultaneously, is calculated.

Since the algorithm allows to separate the mass and the time variables, in the CLUSTR we integrate stars only by masses. As a parameter the slope of the IMF (α) is set.

As a result of CLUSTR operation, we obtain the energy distribution in the spectrum of the stellar cluster for the certain successive moments of evolution of this cluster.

At the third stage (program SPIRAL) integration is made over time, and the energy distribution is calculated for the spectra of stellar systems with the fixed chemical composition and mass function, set at the first and second stages, and different star formation history. The parameters of the task at the third stage are the age of the stellar system and the current intensity of star formation.

As the numerical characteristics of the model spectra in their comparison with the observed spectra and other models the wide-band color (B-V) (the integrated values of B and V we derive by convolving the model spectra with the response curves of B and V filters taken from the monograph by Straizys (1977)) and the equivalent widths of some absorption lines and bands have been taken. Unfortunately we have failed to define the (U-B) color since model spectra, started from the wavelength 3000 Å, are needed for this.

Table 1 presents the lines and bands (column 2), the wavelengths of their centers (column 3), their half-widths at the continuum level (column 4), and the wavelength intervals, where the continuum values are measured to the left (column 5) and to the right (column 6) of the lines and bands.

Table 1.

No.	Line (band)	λ_0	$\pm\Delta\lambda$	Continuum left	Continuum right
1	K CaII	3933	18	3895 - 3915	4000 - 4020
2	H CaII	3969	18	3895 - 3915	4000 - 4020
3	H_δ	4102	20	4000 - 4020	4144 - 4164
4	G-band	4300	24	4246 - 4276	4360 - 4390
5	H_γ	4340	20	4246 - 4276	4360 - 4390
6	H_β	4861	20	4810 - 4840	4880 - 4910
7	MgI+MgH	5176	35	4913 - 4943	5320 - 5350
8	FeI+CaI	5270	20	4913 - 4943	5320 - 5350
9	NaI	5890	20	5840 - 5870	5920 - 5950
10	H_α	6563	20	6510 - 6540	6600 - 6630

V. RESULTS OF EVOLUTIONARY SYNTHESIS

At the first step of EVOLUTION program operation we computed the evolution of a system of stars with masses from 0.15 $\mathfrak{M}_\odot$ to 40 $\mathfrak{M}_\odot$ and with the slope of the initial mass function α=2.35 - the value found by Salpeter (1955) for the solar neighbourhood. The evolutionary tracks of these stars were taken for the following chemical composition: helium abundances 0.28-0.30, metallicity is solar one (Z=0.02).

For the model calculation we have used one age value of the system, T=10 billion years, basing on the inference of Silchenko (1982) and Zasov and Sil'chenko (1983), that all elliptical galaxies are approximately of the same age, about 15 billion years, with a small dispersion of $\leqslant 3$ billion years, the spectral evolution of galaxies being slow after $T \geqslant 10$ billion years.

As for the parameter β, which characterizes the decrease of the star formation rate, our computations were made for the interval of the parameter β: $0 \leqslant \beta \leqslant 10^{-9}$ yrs^{-1} (in general β varies within $0 \leqslant \beta < +\infty$, where $\beta=0$ implies constant intensity of star formation, and $\beta=+\infty$ is the case of initial star formation burst with its subsequent complete termination - the case of elliptical galaxies).

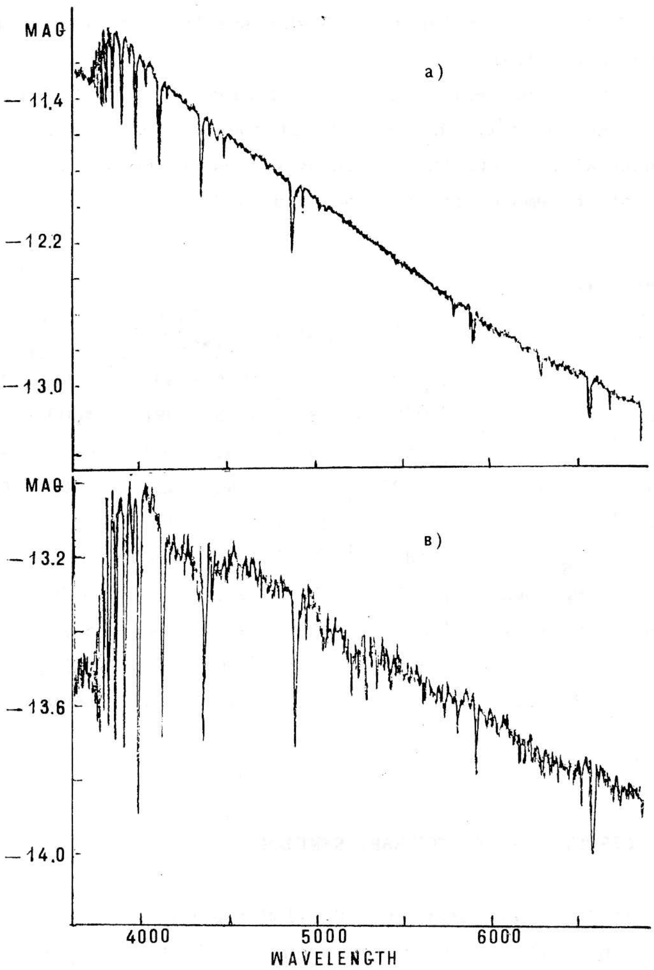

Fig. 1. *Energy distribution in the spectrum of the model stellar cluster as a function of age:*
a) 10^7 *years;*
b) $9 \cdot 10^7$ *years;*
c) $2 \cdot 10^9$ *years;*
d) 10^{10} *years.*

The current star formation rate is convenient to be characterized by the ratio of the mass of the stars formed during the last 10^8 years to the total mass of stars in the galaxy $K = \mathfrak{M}_{10^8} / \mathfrak{M}_t$.

This ratio is related to the parameter β in the following manner:

$$\lg K = \lg \mathfrak{M}_{10^8}/\mathfrak{M}_t = \begin{cases} \lg\,(10^8/T) & ,\ \text{if } \beta = 0 \\ \lg\,((\exp\,(10^8\cdot\beta)-1)/(\exp(T\cdot\beta)-1)), & \text{if } \beta \neq 0, \end{cases}$$

where T is expressed in years, and β - in inverse years. With β varying in the interval $0 \le \beta \le 10^{-9}$, K varies from 10^{-2} to $5\cdot10^{-6}$.

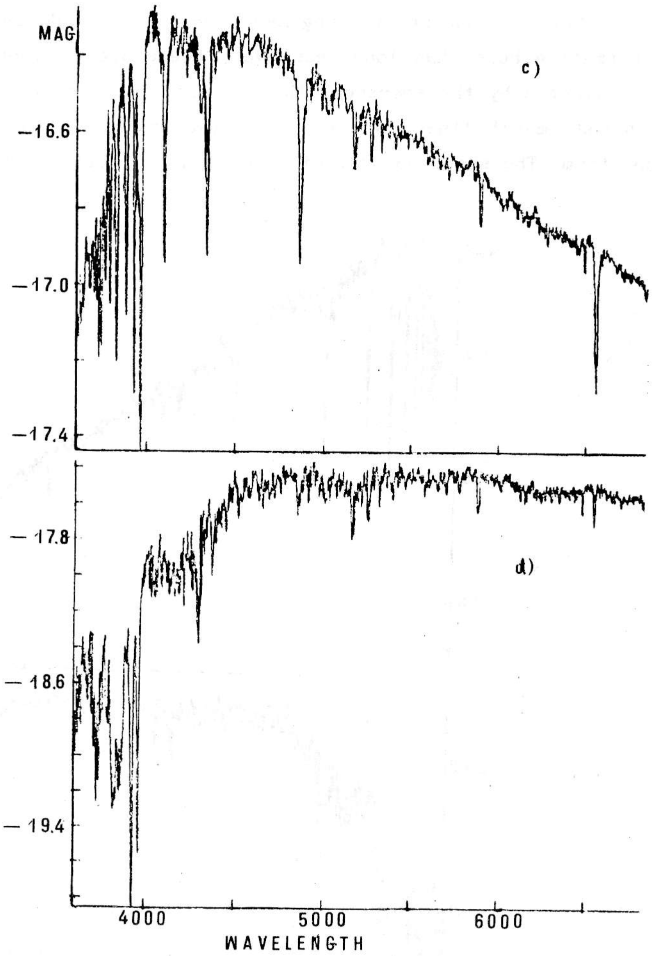

Fig. 1 c,d.

Fig. 1 presents the results of CLUSTR program operation - the energy distributions in the stellar cluster spectra for four ages: 10^7, $9\cdot10^7$, $2\cdot10^9$, and 10^{10} years. Spectral evolution of the stellar cluster is clearly seen here. The color of the young cluster is blue, the spectrum is "fallen down" redward and resembles the spectrum of early-type stars: there are hydrogen lines, metal lines are very weak or practically absent. Hydrogen lines became weak with age increasing, metal lines (Ca, Mg, Na, Fe) and the molecular bands (CN, MgH, G-band) arise and grow stronger. The spectrum becomes flatter redward, and its color becomes redder.

Fig.2 shows the results of SPIRAL program - the energy distribution in the stellar system spectra with different star formation rates: $\beta=0$ ($K=10^{-2}$) and $\beta=10^{-9}$ ($K=5\cdot10^{-6}$). In the case $\beta=0$ the star formation rate is constant throughout the entire lifetime of the galaxy, along with metal lines the strong hydrogen lines are present in the spectrum. All this and the slope of the spectrum, obviously "early", argue for the presence of a sufficient number of young new-formed stars. However, in the case $\beta=10^{-9}$ the star formation burst has long been over, there are no young stars in the system, which is indicated by the spectrum: the absence of hydrogen lines except H_β, the presence of strong metal lines in the "late" (according to the general energy disrtribution) spectrum. The spectrum is typical of a normal elliptical galaxy.

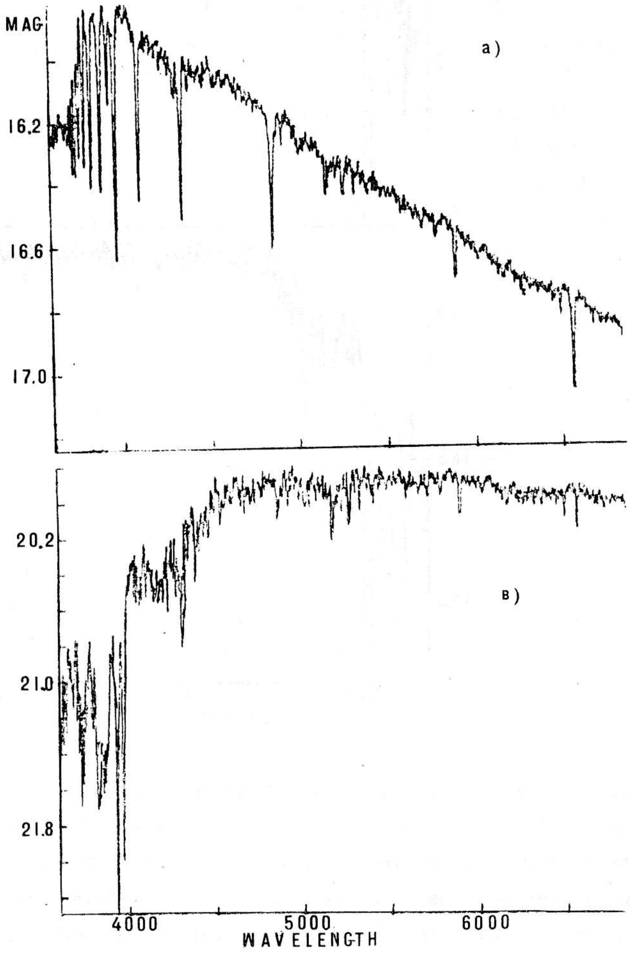

Fig.2. *Energy distribution in the spectrum of the model stellar system at different star formation rate:*
a) $\beta=0$; *b)* $\beta=10^{-9}$ yrs^{-1}.

Consider in more detail the evolution of color, metal and hydrogen lines in the stellar cluster. As the numerical characteristics, as said above, we have taken the equivalent widths of lines and bands (see Table 1).

Fig.3 shows the run with time of a) the equivalent widths of metal lines, b) the equivalent widths of hydrogen lines, c) (B-V) colors. The equivalent widths of metal lines increase, and those of hydrogen lines have a maximum at the age of $\sim 5\cdot 10^8$ years.

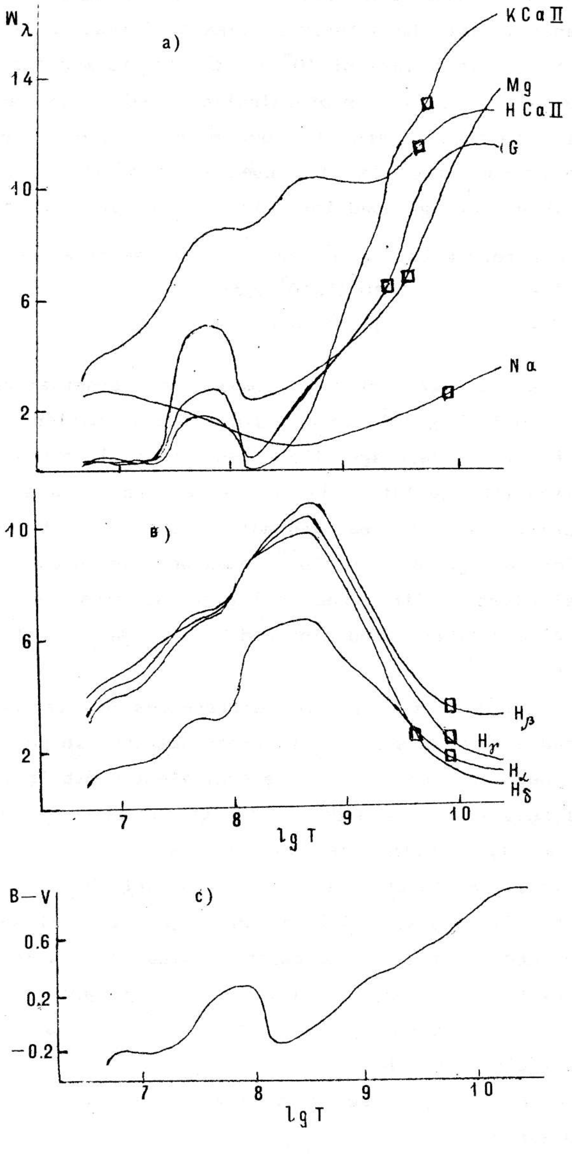

Fig.3. *The run with time of:*
a) equivalent widths of lines and bands of metals;
b) equivalent widths of hydrogen absorption lines;
c) (B-V) color of the model cluster.

The (B-V) color value rises in the course of evolution from -0.22 to +0.93. Nonmonotony of these curves (rise in the values of metal line equivalent widths, drop in those for hydrogen, and "reddening" of (B-V) colors) at the age of about 10^8 years may result from red supergiants originated from intermediate mass stars. How close are the results of our calculations to actually observed spectra of stellar systems - clusters and galaxies?

Generally speaking an application of the dependences of Fig.3 to the observations of globular and open clusters of various ages is not fully correct due to the difference in the characteristic time of formation of a real and model cluster. If real clusters with a mass of 10^5-10^6 $\mathfrak{M}_\odot$ are formed for about 10^6 years (a characteristic free-fall time of a protogalactic cloud), and the same is the scatter of ages of their component stars, for our model clusters the picture is more complex. Taking into account the aim of consequent numerical integration by ages, in the program CLUSTR we have grouped into clusters the stars with ages in the following intervals:

for clusters with $T \leqslant 10^8$ years - the age of stars is in the interval $[T-10^7, T]$
- " - $10^8 < T \leqslant 10^9$ years - - " - $[T-10^8, T]$
- " - $T > 10^9$ years - - " - $[T-10^9, T]$

Thus, it makes sense to compare with observations of only very "old" model clusters, with $T \gtrsim 10^{10}$ years, since the formation time for them (10^9 years) is much shorter than their age, the stars of 9 billion years differ slightly from those of 10 billion (the evolution is very slow here); and so the difference in the dispersions of stellar ages in real and model clusters can be neglected.

For the age of about 10^{10} years we have compared the line equivalent widths of the model cluster with three real globular clusters of the Galaxy investigated by Bica and Alloin (1986), and Zinn and West (1984) (see Table 2) whose metallicity is nearly solar.

It can be seen that the differences of our data from the observed ones do not exceed a natural scatter of points obtained in observations of different authors, but for the magnesium line, whose equivalent width is larger in the model cluster than in real ones. In Fig.4 a comparison of our results - evolution of the equivalent widths of some lines with time (dotted line) - with the observational results by Bica and Alloin (1986) is presented. The values of the equivalent widths, as a function of age and metallicity (solid line, where the vertical segments are their error estimates) have been taken from the paper by Bica and Alloin. They were obtained from spectral observations of stellar clusters in Magellanic Clouds and globular clusters of our Galaxy. It is seen that for old stellar systems of 10 billion years the agreement is satisfactory enough.

To test the program, we have also used the spectra of Bo 225 kindly rendered to us by B.Marano.

Table 2.

Object	NGC 6440		NGC 6528		NGC 6553		model
T(years)	$1.65\cdot10^{10}$		$1.6\cdot10^{10}$		$1.65\cdot10^{10}$		10^{10}
λ W_λ	(1)	(2)	(1)	(2)	(1)	(2)	
K CaII 3933 Å	14.6	17.1		15.9	15.3	18.6	16.1
H CaII+H_ε 3969 Å		12.5		12.4		18.0	12.7
H_δ 4102 Å	2.9	7.2	2.4	5.2	2.6	0.4	1.6
G-band 4300 Å	8.8	9.3	11.9	8.3	9.3	14.0	11.4
H_γ 4340 Å	2.1	7.4	2.8	6.3	2.2	5.4	1.6
H_β 4861 Å	2.4	4.8		4.3	2.7	6.2	3.4
MgI+MgH 5176	6.4	7.8	7.7	8.4	6.7	8.5	13.5
FeI+CaI 5270 Å		4.2		4.6		4.5	5.3
Na 5890 Å		4.5		6.1		4.2	3.6
H_α		2.3		3.1		4.2	1.4

Notes: (1) - data by Zinn and West (1984)
(2) - data by Bica and Alloin (1986)

Bo 225 is a globular cluster in the galaxy M31, the radial velocity standard. The spectra of Bo 225 were taken by Federici et al. (1991) at the Nasmyth-1 focus of the 6 m telescope with the 1000-channel scanner (Drabek et al., 1986). The observations were obtained within 3700-7400 Å with a resolution of 8-10 Å and a 2″ round diaphragm. The spectra were processed with a standard package of programs (Somov, 1986; Afanasiev et al., 1987). At the same time the UBV photometry was performed by S. Neizvestny on the electrophotometer at the Nasmyth-1 focus (Vikul'ev et al., 1991), and the colors of the cluster were obtained: V=14.18, (U-B)=0.52, (B-V)=0.95.

After correction for the absorption in our Galaxy we have $(B-V)_0=0.84$, $(U-B)_0=0.44$. The color of our model spectrum for $T=10^{10}$ years is somewhat redder, (B-V)=0.93, the difference can be due to slightly different metallicities or ages.

The metallicity value [Fe/H]=-0.37 of Bo 225 was derived by Bonolli et al. (1987). Considering the metallicity of Bo 225 to be close to the solar one, one can use our model calculations of evolution of the absorption line equivalent widths to determine the age of the cluster.

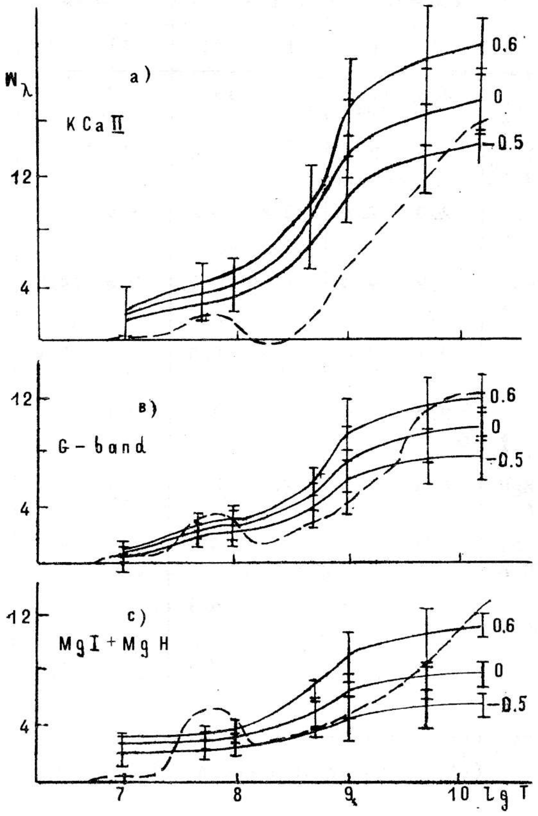

Fig. 4. *Comparison of equivalent widths as a function of age of the model cluster (dotted line) and real clusters observed by Bica and Alloin (1986) (solid line, vertical lines are the error etimates, numbers denote the metallicity values [Fe/H]).*

The absorption line equivalent widths of Bo 225 computed from 9 observed spectra are listed in Table 3 with their mean square errors.

These values are plotted on the theoretical dependence of the equivalent widths on the age of the model spectrum (squares in Fig. 3). We have made an attempt to determine the age of the cluster Bo 225 from each of the measured lines. The result is given in column 5 of Table 3. The fact, that the ages for Bo 225, which we have derived from metal and hydrogen lines agree with each other, is a rather well evidence for applicability of our solar metallicity model for these globular clusters. Having averaged the derived values of T over all lines, we estimated the age of Bo 225 to be ~ 6 billion years.

In Fig. 5 a dependence is shown of the line equivalent widths and the (B-V) color of the galaxy model on the star formation rate. Under the constant star formation the values of the equivalent widths of the metal and hydrogen lines are comparable. The longer time elapsed from the fundamental star formation, the redder is the color (B-

V) and the more distinctly the equivalent width values are divided into two groups: strong metal lines (> 8 Å) and weak hydrogen lines (< 4 Å).

Table 3.

No.	Line (band)	λ_0	$W_\lambda \pm \Delta W_\lambda$	lg T (years)
1	K CaII	3933	12.8 ± 0.5	9.8
2	H CaII+H_ε	3969	11.2 0.3	9.7
3	H_δ	4102	2.4 0.5	9.6
4	G-band	4300	6.4 0.5	9.4
5	H_γ	4340	2.3 0.2	9.9
6	H_β	4861	3.4 0.3	9.9
7	MgI+MgH	5176	6.8 0.6	9.6
8	NaI	5890	2.7 0.6	9.9
9	H_α	6563	1.6 1.2	9.9

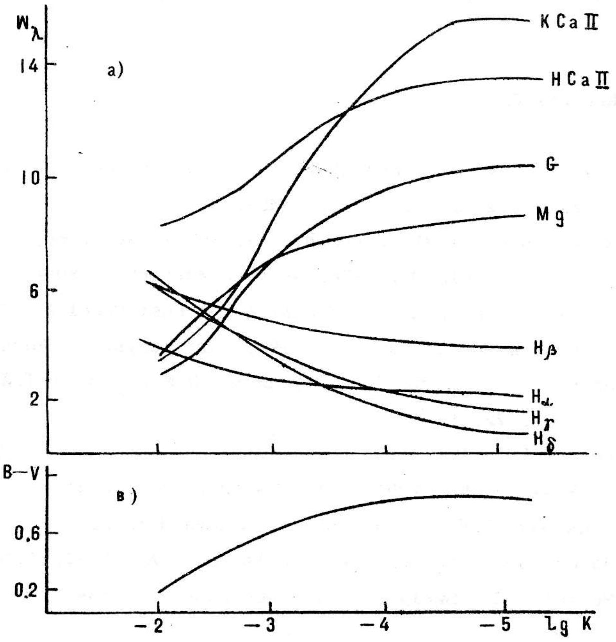

Fig.5. *Dependence of a) equivalent widths of spectral lines and b) (B-V) color of the model stellar system on the star formation rate.*

Thus, the color (B-V) and the equivalent widths of hydrogen and metal lines in galaxies may be a characteristic of both the current star formation rate and the characteristic time of early star formation.

CONCLUSION

From the above said, it seems to us that the evolutionary model we have described is in a satisfactory agreement with actual observations of stellar clusters and galaxies of composition close to solar and needs further calculations with modification of all variable parameters. The next step is computations using a uniform system of evolutionary tracks of stars and also tracks with chemical composition poorer and richer than solar. For the calculations with modification of chemical composition we plan to extend the library of stellar spectra with the computed theoretical stellar spectra.

Acknowledgements

We would like to thank B.Marano and S.Neizvestny for the observational material and Astronomical Data Center NASA (Goddard Space Flight Center) for the Jacoby's library of stellar spectra on magnetic tape.

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