Chin. J. Astron. Astrophys. Vol. 5 (2005), No. 4, 347–355
(*http://www.chjaa.org*)

Chinese Journal of
Astronomy and
Astrophysics

Stellar Population Analysis of Galaxies based on Genetic Algorithms

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Received 2004 August 18; accepted 2005 April 5

Abstract We present a new method for determining the age and relative contribution of different stellar populations in galaxies based on the genetic algorithm. We apply this method to the barred spiral galaxy NGC 3384, using CCD images in U, B, V, R and I bands. This analysis indicates that the galaxy NGC 3384 is mainly inhabited by old stellar population (age $> 10^9$ yr). Some problems were encountered when numerical simulations are used for determining the contribution of different stellar populations in the integrated color of a galaxy. The results show that the proposed genetic algorithm can search efficiently through the very large space of the possible ages.

Key words: methods: numerical – galaxies: stellar population – galaxies: individual (NGC 3384).

1 INTRODUCTION

Science often benefits from the sharing of information between different disciplines. One example of this is the invention of genetic algorithms (Holland 1975). Inspired by the natural evolution, genetic algorithms (hereafter GAs) use artificial selection and genetic crossover and mutation operators to manipulate strings of numbers which encode the variables of the problem, thereby reaching better and better solutions to the problem. GAs are used in many branches of science. However, in astrophysics there have, as yet, only been a few applications of GAs, in the fields of solar coronal modeling (Gibson & Charbonneau 1996), pulsar planet searching (Lazio 1997), eclipsing binary stars (Hakala 1995), gamma-ray astronomy (Lang 1995), and determining the orbital parameters of pairs of interacting galaxies (Wahde 1998). For an excellent review of GAs in astronomy and astrophysics, see Charbonneau (1995).

NGC 3384 is classified as an SB galaxy by de Vaucouleurs et al. (1991). It is a member of the Leo I galaxy group. The central region of NGC 3384 shows multi-structures with spatial orientation related to that of the super giant intergalactic HI cloud discovered by Schneider et al. (1989). The HI gas was swept into the galaxy center during the tidal interaction between the galaxies NGC 3384 and other two neighbor galaxies NGC 3368 and 3379 in the galaxy group.

The present observation of NGC 3384 shows that the central part of the galaxy is composed of different morphological components, i.e., different stellar populations. The stellar populations and the history of star formation of a galaxy can be studied in two ways, i.e., by constructing and analyzing the color-magnitude diagrams for the resolved luminous stars in the galaxy, or by studying instead the integrated color of the galaxy in case of difficulty of observing the stellar knots in the galaxy, which is the case with NGC 3384.

An optimization scheme based on a genetic algorithm (GA) can avoid the problems inherent in the traditional approach. Restrictions on the range of the parameter space are imposed only by observational constraints and by the physics of the model. Although the parameter space so defined is often quite large, GA provides a relatively efficient means of searching globally for the best-fit model. While it is difficult for GAs to find precise values for the best-fit set of parameters, they are very good at finding the region of parameter space that contains the global minimum. In this sense, GA is an objective means of finding a good first guess for a more traditional method, which can then narrow in on the precise values and uncertainties of the best-fit set of parameters.

The basic idea is to solve an optimization problem by evolving the best solution from an initial set of completely random guesses. The theoretical model provides a framework within which evolution takes place, and the individual controlling parameters serve as the genetic building blocks. Observations provide the selection pressure. For a detailed description of genetic algorithms, see Charbonneau (1995) and Attia (2002).

In this paper the stellar population of NGC 3384 is analyzed using four broad band color indices $U-B$, $B-V$, $B-R$ and $B-I$. The analysis algorithm is based on the assumption that the integrated color of the galaxy results from a combination of two stellar populations with different metallicity and different ages. Our aim is to identify properties of these two populations; their spatial distribution and their relative contribution in the galaxy. This paper is organized as follows: In Section 2 we report the observations and the data reduction. The stellar analysis method is presented in Section 3, while the proposed Genetic Algorithm for the stellar population analysis is explained in Section 4. In Section 5, an application of these algorithms on NGC 3384 is presented. We discuss our result in Section 6.

2 OBSERVATION AND DATA REDUCTION

CCD Observations of NGC 3384 were carried out using the 1.23 m telescope of Calar Alto observatory in February 1995. The telescope is equipped with a Tek 1024×1024 pixel CCD camera, each pixel covers 0.502 arcsec on the sky. Sets of science and calibration frames were taken with the Johnson-Cousins U, B, V, R and I filters. All reductions were performed using the image-processing program MIDAS. Instrumental signatures such as bias subtraction and flat field correction were done. All frames are matched carefully in position using foreground stars and then referred to a common coordinate system. The instrumental magnitude was transformed to the standard magnitude using photometric zero points determined by the compilation of photoelectric aperture magnitude of galaxies published by Longo & de Vaucouleurs (1983, 1988).

3 STELLAR POPULATION ANALYSIS

Abdel-Hamed & Notni (2000) have presented an analytical method for checking the stellar population in a galaxy. The method is based on the integrated color indices and a population

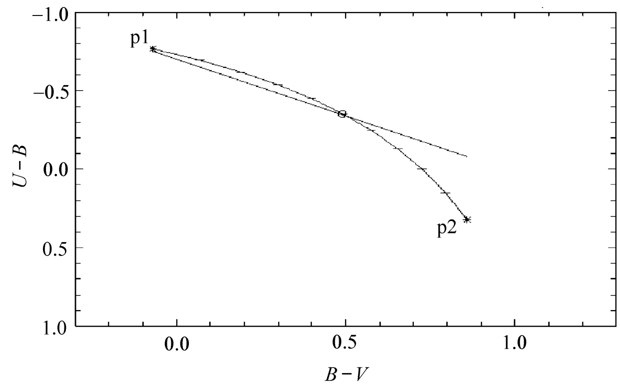

Fig. 1 Two color diagram in which Population I and Population II mix to produce the observed color. The mixing goes along the curved track. Ticks at steps 0.1 on the mixing track mark different contributions of the two populations. The open circle marks the observed color when 50% of its total light comes from Population I. The solid line is the reddening line.

synthesis model that relates the metallicity, age and color of stellar populations. They assumed that the observed light of a galaxy comes only from two stellar populations with different colors, i. e., with different ages, metallicity, etc. Figure 1 gives a graphical representation for the mixing track for different contributions of the intensity of the populations in the observed light in the color-color diagram.

The relations describing the mixing-tracks of the two stellar populations are given as:

$$\begin{aligned}(U-B)_m &= (U-B)_{II} - 2.5\log\left(1-\beta_b+\beta_b\cdot 10^{(-0.4\triangle(U-B)_I)}\right),\\ (B-V)_m &= (B-V)_{II} + 2.5\log\left(1-\beta_b+\beta_b\cdot 10^{(0.4\Delta(B-V)_I)}\right),\\ (B-R)_m &= (B-R)_{II} + 2.5\log\left(1-\beta_b+\beta_b\cdot 10^{(0.4\Delta(B-R)_I)}\right),\\ (B-I)_m &= (B-I)_{II} + 2.5\log\left(1-\beta_b+\beta_b\cdot 10^{(0.4\Delta(B-I)_I)}\right),\end{aligned} \tag{1}$$

where β_b gives the percentage of the intensity of population I in the total B intensity of the galaxy, ($\beta_b = \frac{b_I}{b_m}$), where b_m is the observed total light intensity. The suffixes m, I, II, refer to the total, Population I and Population II, respectively, and

$$\begin{aligned}\Delta(U-B)_m &= (U-B)_m-(U-B)_{II}, & \Delta(U-B)_I &= (U-B)_I-(U-B)_{II},\\ \Delta(B-V)_m &= (B-V)_m-(B-V)_{II}, & \Delta(B-V)_I &= (B-V)_I-(B-V)_{II},\\ \Delta(B-R)_m &= (B-R)_m-(B-R)_{II}, & \Delta(B-R)_I &= (B-V)_I-(B-V)_{II},\\ \Delta(B-I)_m &= (B-I)_m-(B-I)_{II}, & \Delta(B-I)_I &= (B-I)_I-(B-I)_{II}.\end{aligned} \tag{2}$$

Solving Equation Set (1) for β_b, we obtain,

$$\begin{aligned}\beta_b &= \tfrac{1-A}{1-X_0}\\ &= \tfrac{1-B}{1-X_1}\\ &= \tfrac{1-C}{1-X_2}\\ &= \tfrac{1-D}{1-X_3},\end{aligned} \tag{3}$$

with

$$X_0 = \text{dex}(-0.4\Delta(U-B)_I)\,, \quad X_1 = \text{dex}(0.4\Delta(B-V)_I)\,,$$

$$X_2 = \text{dex}(0.4\Delta(B-R)_I)\,, \quad X_3 = \text{dex}(0.4\Delta(B-I)_I)\,.$$

Note that X's are functions of the colors of Populations I and II.
In addition,

$$A = \text{dex}(-0.4\Delta(U-B)_m)\,, \quad B = \text{dex}(0.4\Delta(B-V)_m)\,,$$

$$C = \text{dex}(0.4\Delta(B-R)_m)\,, \quad D = \text{dex}(0.4\Delta(B-I)_m)\,,$$

A, B, C and D are functions of the observed Population II colors.

A common wavelength band (e.g., b in our case) in the color indices is essential to obtain the relative abundance of the intensity of the populations in the observed intensity.

4 GENETIC ALGORITHM FOR STELLAR POPULATION ANALYSIS

Global optimization utilizes techniques that can distinguish between the global optimum and numerous local optima within a region of interest. Recently, GA as a global technique has received considerable attention regarding their potential. One of the modified techniques for greater speed and accuracy is the procedure "Linear Adapted Genetic Algorithms" with an adjustable Population size (LAGA-POP) (Attia & Horacek 2001; Attia 2002). Here we shall see how GA operates. GA is used to solve for β_b in Equation Set (3) and then several parameters must be selected initially. They are: the population size, Popsize = 500; the maximum number of generations, Maxgen = 20; the precision error, $\eta = 0.01$; the search for both Population I and II ages is made in steps of years for each color; the length of chromosome is required for specifying each gene (Populations I and II) for each color.

Once these parameters are defined then from the integrated light of the galaxy, the ages of Populations I and II for each broad band colors and the relative contribution of Population I will be optimally determined at the minimum value of standard deviation of β_b. The main aspects of the genetic algorithms for determining the ages of Populations I and II, contribution of Population I for each broad band colors are discussed below and a block diagram for the process is shown in Figure 3.

4.1 Representation of Parameters

The color indices of Populations I and II are the parameters, which will be represented in the required domain of search. These domains correspond to the domain of search for the ages of the Populations I and II. The parameters are represented using the LAGA-POP approach, where all the parameters are stored in a chromosome.

4.2 Coding of Parameters

Based on the number of parameters and the length of the chromosome the binary form of these parameters is represented in codes. The coded parameters are arranged as shown in Figure 2 to form the chromosome of the population.

4.3 Selection Function

The selection strategy decides how to select chromosomes to be the parents for the next generation. The selection usually applies some selection pressure, favoring chromosomes with better

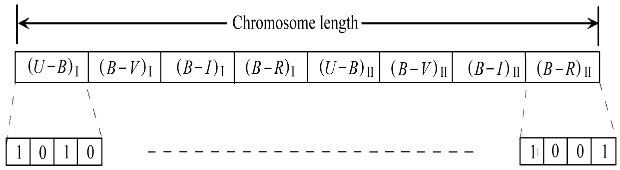

Fig. 2 Coded scheme for the color indices of Populations I and II.

fitness. Each chromosome has been evaluated and associated with a fitness. The current population undergoes a reproduction process to create the next population, and the "roulette wheel" selection scheme is used to determine the member of the new population. It means for every chromosome we calculate four β_b images, one for each observed colors, and standard deviation of these values in every pixel, the (σ_β) image. This was done for the whole chromosomes at the same time and means we have 500 (σ_β) images. The chance on the roulette-wheel is adaptive and is given as $\frac{f_l}{\sum f_l}$. Here, $f_l = \frac{1}{1+\sigma_\beta}$, $l\epsilon\ \{1, ..., L\}$ and f is used as a fitness function. So, the minimum value of σ_β from these 500 (σ_β) images will be chosen, and the corresponding ages of Populations I, II and β_b will be determined keeping in mind that the population synthesis model (Kennicuit et al. 1980) is used to relate the age and metallicities with the color indices for the two populations.

4.4 Crossover and Mutation Operators

For the next generation, crossover is applied and followed by a mutation operation following the LAGA-POP approach given by Attia (2002). Finally, after these three operations, the overall fitness of the whole chromosomes is improved. The procedure is repeated until the termination condition is reached. The termination condition is the maximum allowable number of generations or a certain value of σ_β required to be reached. Alternatively the procedure is repeated until a relative precision error of $\frac{f^*(g)-f^*(g-1)}{f^*(g)} < \eta$ is satisfied, where f^* is the maximum fitness value.

5 SIMULATION RESULTS AND DISCUSSION

We applied the method of genetic algorithm described above to the observational data of NGC 3384. The population synthesis model presented by Bressan et al. (1994) was adopted as a reference for the age, metallicity and color of both young ($< 10^8$ yr, $Z = 0.05$) and old (10^8 yr to 10^9 yr, $Z = 0.08$) populations. Four color indices $U - B$, $B - V$, $B - R$ and $B - I$ either in the form of two dimensional frames (case I, more later) or in the form of integrated color for some bright knots (case II, more later) are essential to solving Equation Set (3). Each equation of the set gives the relative contribution of the population I in the observed B-intensity (β_b) using one color index. From theoretical point of view the four β_b values at each pixel in the galaxy should be the same, but due to uncertainties coming either in the observation or in the model, the minimum standard deviation of the β_b values is chosen at each pixel as well as its corresponding physical parameters for Populations I and II (the age in the above chosen range or their color indices).

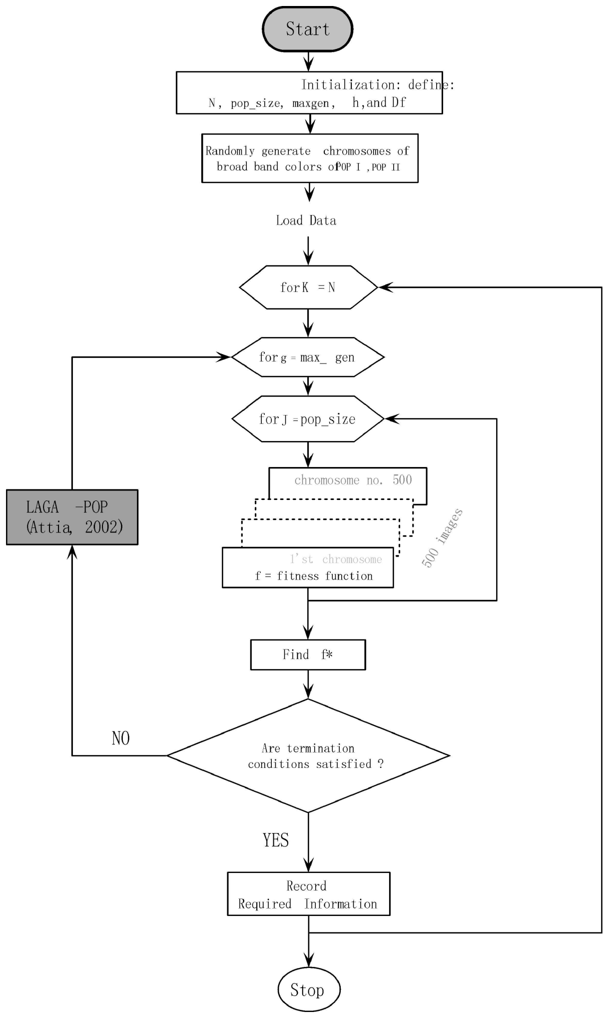

Fig. 3 Flow chart for the procedure used to determine ages for each stellar population based on GA.

Figure 4 presents the distribution of the color index $U - B$ for Population I in the central part of the galaxy. In this region the color index lies in the range –0.9 to –0.3 but with very low contribution with the β_b values in the range 0.05 to 0.4.

Figure 5 shows the observed color index $(U-B)_m$ of NGC 3384 as an example of using the color index in a comparison with the calculated color index $(U-B)_{II}$ of the old population shown in Figure 6. This similarity of the distribution of in Figures 5 and 6 suggests that the galaxy NGC 3384 is mainly dominated by the old Population II objects with an age around 3∼5 Gyr.

To make clear that the dominated population in NGC 3384 is the old population, we tested other kind of data (case II). The galaxy surface brightness contours are fitted by ellipses, then the integrated color indices as a function of the distance from the galaxy center are calculated. The algorithm is run again for various points at different locations in the galaxy to obtain the parameters of the young and old populations at these positions.

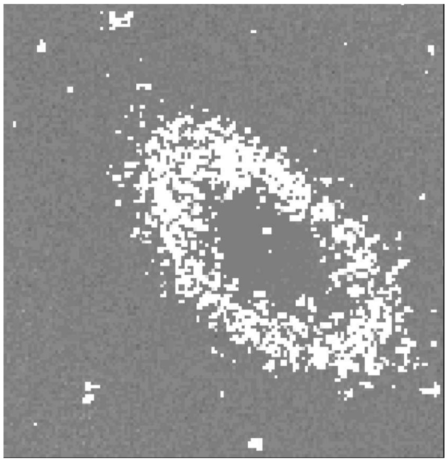

Fig. 4 Color index $U - B$ of Population I in the central part of the galaxy (the dark region) lies in the range between –0.9 and –0.3 with β_b values between 0.05 to 0.4.

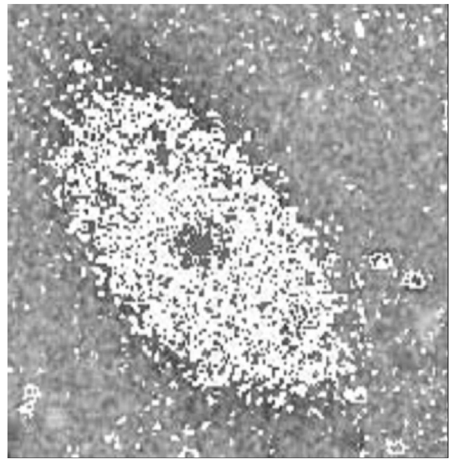

Fig. 5 Distribution of observed color index $(U - B)_m$ of NGC 3384.

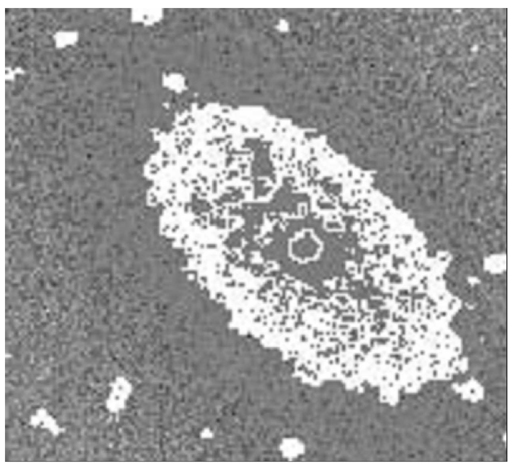

Fig. 6 Color index $U - B$ of Population II in the galaxy has values between 0.3 and 0.85.

Figure 7 presents the distribution of the color indices of the test points as well as that of the calculated color indices for both young and old population in color-color diagram, in comparison with that from the population syntheses model (Bressan et al. 1994). The figure shows that the color of Population II has the same location as the observed color.

The contribution of the young population (age less than 10^5 yr) to the total intensity is small: $0.1 \leq \beta_b \leq 0.4$.

The influence of observational error on the analytical method has been discussed in detail by Abdel-Hamid & Notni (2000). We present here the propagated errors based on the observation and our Genetic algorithm as shown in Figure 8.

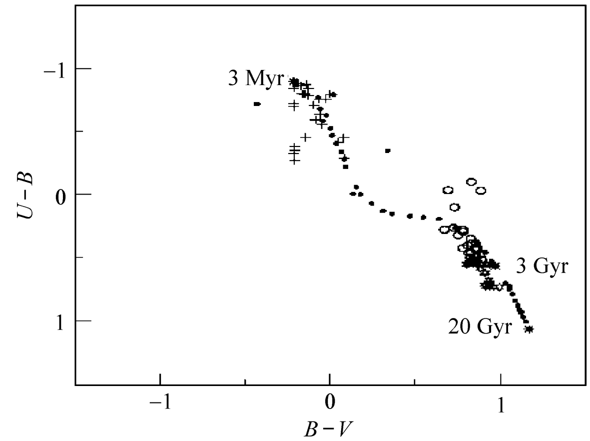

Fig. 7 Color of young (crosses), old (open circles) population and the total observed color of the test points (see text) in comparison with that from the Bressan model (dots).

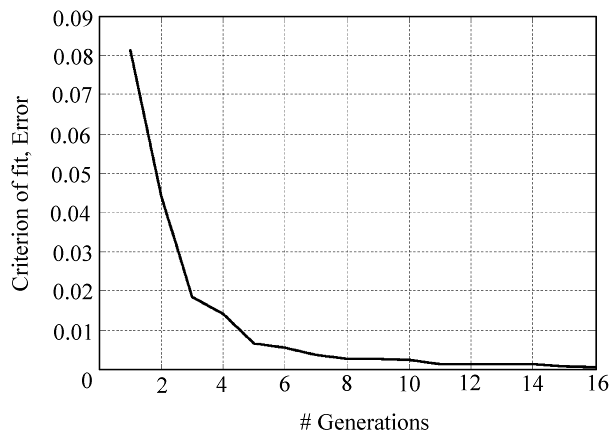

Fig. 8 LAGA-POP convergence rate.

Figure 8 shows the effectiveness of LAGA-POP approach for optimizing the model parameters and for reducing the computation time. This means also a better performance. Figure 8 also presents the variation in the standard deviation (σ_β) as a function of the generation number. It peaks Generation 1, and decreases rapidly in Generation 3 to nearly 18% of the peak, then further downs to 0.002 through 10 generations, and to nearly zero at generation 16.

6 CONCLUSIONS

Old stellar population dominates the integrated light of early type galaxies (ellipticals and lenteculars), and the contribution of Population I is relatively small. The colors of galaxies give information on how long star formation can continue. It is particularly useful to compare the colors of lenticular galaxies, whose entire population is believed to be very old. The genetic algorithm for stellar population analysis has turned out to be very fruitful. We are now confident that we can rely on this new approach to perform global searches to solve the set of equation on β_b, the fractional contribution by Population I in the total luminosity of NGC 3384. A common wavelength band (e.g. β_b in our case) in the color indices is essential to obtain the relative abundance of the stellar populations in the observed intensity. With $Z = 0.008$ for Population II and $Z = 0.05$ for Population I and observed data of NGC 3384, a value of $(B - V) \sim 0.7$ with age > 5 Gyr was found. This may mean that the main contribution of the luminosity of NGC 3384 comes from objects of Population II while Population I lies far away from observations of NGC 3384.

These results fit well with Bressan et al. (1994). The relative contributions of Population II and Population I in NGC 3384 can be found from Figs. 4, 5, 6 and 7. This indicates that the galaxy NGC 3384 is at least inhabited by more than 80% with Population II objects. Arunav et al. (2001) found that 90% of lenticular galaxies are dominated by old globular clusters, i.e., stellar Population II, which significantly supports our results.

Acknowledgements The authors are thankful Prof. Dr. Peter Notni, Astrophysikalishes Institut Potsdam, Germany, for providing the CCD observations used in this work. Also, the authors greatly thank anonymous referee for very useful comments that improved the presentation of the paper.

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