Stellar Population Modeling of Galaxies in Nearby Groups

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Abstract: We describe the technique for determining the history of star formation in galaxies based on the photometry of the resolved stars in a galaxy. We use a library of synthetic color-magnitude diagrams from theoretical stellar isochrones, taking into account the initial mass function, distance to the galaxy, internal and external absorption, and photometric errors. We consider star formation history measurement results in the nearest galaxy groups. The Local Group is well studied now due to relatively small distances to its members. We can resolved old fainter stars including horizontal branch and red clump stars. Less information can be received on resolved stars in the other two nearest groups: Cen A and M 81. However, the Hubble Space Telescope (HST) with the new Advanced Camera for Surveys (ACS) instrument allows us to study oldest red giant population as well.

1. Introduction

The study of star formation histories of galaxies is a very important component of galaxy evolution research. Many nearby galaxies are well resolved into individual stars, which allows one to make quantitative measurements of star formation rate (SFR) as a function of age and metallicity using multi-color photometry of the resolved stars in the galaxy. Simultaneous metallicity determination gives us chemical enrichment in the process of the galaxy evolution.

Relatively simple systems (for example, globular clusters and open clusters) contain stars of nearly the same age and metallicity. Isochrone fitting to observed distribution of stars in the color-magnitude diagram (CMD) usually defines star formation history (SFH) of a cluster (see, for example, Panagia and Tosi (1980), Sarajedini (2007)). Galaxies usually contain mixed stellar populations. Simple fitting of theoretical isochrones to these populations can give us only rough estimation of the ages and metallicities of the galaxy stars, but does not allow us to determine quantitatively the star formation intensity versus time. Quantitative approach to star formation history determination in galaxies was firstly presented in a number of works in the late 80^{th} - 90^{th} years (Tosi et al. (1989), Tolstoy (1996), Aparicio et al. (1997)). All these methods involve the construction of synthetic CMDs from theoretical stellar isochrones of different ages and metallicities taking into account the observed photometric errors, distance, reddening and initial mass function (IMF). These synthetic diagrams are compared with the observed CMD. Star formation history of the galaxy is determined by the best-fitting model. Such methods of SFH study are evolving rapidly (Dolphin (2000), Harris and Zaritsky (2001), Lee and Yuk (2007)).

Dwarf galaxies are the most common objects in the Universe. Their structure is relatively simple and thus dwarf galaxies are the best places to study the processes of star formation. SFHs of the Local Group dwarf galaxies were studied in details from deep images, which were obtained with large ground-based telescopes and the Hubble Space Telescope (see, for example, Holtzman et al. (2000), Han et al. (1997), Da Costa et al.(1996), Martinez-Delgado and Aparicio (1998), Monkiewicz et al. (1999)). However, there is little information about star formation histories of more distant dwarfs outside the Local Group.

Images of about 50 galaxies within 8 Mpc were obtained with the ACS/HST during our observations, and more within previous Snapshot projects with WFPC2/HST. To analyze this large and homogeneous sample, we have created a program for quantitative analysis of star formation history taking into account a number of features of our data (the StarProbe package, Makarov and Makarova (2004)). Only the bright part of stellar population appears at CMDs of most objects. In such a case uncertainties of SFR and metallicity determination play especially important role, and we analyzed the uncertainties in some details. The influence of different input parameters on the calculation result was also analyzed for this extreme case of relatively low number of the brightest stars at the CMDs.

2. Method description

The observed photometric distribution of stars in a color-magnitude diagram can be presented as a linear superposition of stars of different ages and metallicities formed in a galaxy during its life. Several external astrophysical parameters also impact the observed distribution: the distance to the galaxy, internal and external extinction and photometric errors.

The observed data and synthetic data are stored in Hess diagram. This grid forms as a two-dimensional histogram indicating the number of stars in some range (bin) of stellar magnitudes and colors. The best choice of the bin size depends on the observed CMD. These bins have to be large enough to contain a significant number of stars, and they have to be small enough to indicate all features in the CMD distribution.

We construct synthetic Hess diagrams from theoretical stellar isochrones. Each isochrone describes magnitudes and colors of a stellar population with a particular age and metallicity. All the sample of the synthetic diagrams covers a wide range of ages and metallicities. We take into account the distance modulus and extinction in the synthetic diagrams. Different extinction value can be chosen for different age stars to simulate larger amount of gas and dust in regions of recent star formation. Photometric uncertainties and completeness values were added using results of artificial star tests, which are the only accurate way to solve the problems of photometric errors, blending and incompleteness. A linear combination of synthetic CMDs of different ages and metallicities forms a model CMD. We have to find a model CMD which fits the observed CMD in the best way. Synthetic CMD construction is the most time-consuming part of SFH calculation. We construct an analytical function of stellar distribution in Hess diagram for each particular isochrone of some age and metallicity taking into account IMF (Salpeter law), photometric errors, bin size, distance modulus and extinction. Similar way was chosen by Dolphin (1997, 2002).

We use the Padua set of theoretical isochrones from Girardi et al. (2000). The isochrones were published for a wide range of metallicities, from Z = 0.0001 to Z = 0.03, with the age range from $10^{6.6}$to $10^{10.25}$ for each metallicity. We use Salpeter law for initial mass function. Normalization was chosen such that the total integrated probability over 0.1—100 M_{solar} is unity. Stellar mass completely determines the magnitude of the star for a given isochrone. From artificial star tests we know a probability to find a star of a given magnitude, a magnitude dispersion and a magnitude shift from its input value. All these factors allow one to define a probability to observe a star of a given mass in any bin of Hess diagram. Unfortunately, the theoretical isochrones are too coarsely sampled for the probability determination. Therefore, we perform a linear interpolation of the photometry, such that the magnitude difference of the neighboring interpolated points is less than characteristic photometric uncertainties. Our experiments with more powerful interpolation methods (spline-interpolation, piecewise cubic Hermit interpolation) have shown a number of false points in the fast evolution regions of the isochrones. For each interpolated isochrone point we define a probability to form a star with a given mass using Salpeter IMF and taking into account the mass interval between adjacent points. As a result of this calculations, we obtain the star formation rate for the given epoch. Adjacent isochrones can be combined in one model CMD, assuming star formation rate to be constant.

The observed CM diagram of a galaxy can be contaminated by stars from our Galaxy. Usually one have to observe a second field near the object under study to obtain a “foreground”' CMD. This CMD can be statistically subtracted from the object CMD. However, the subtraction process usually leave residuals. The second way of the object CMD decontamination is to model foreground stars in the same manner as the object stars.

For the SFH determination we have to find the best linear combination of the partial model CMDs to match the observed data. Firstly, we find most significant variables (partial model CMDs), which differ from zero with a given probability. We use stepwise algorithm to find the best solution. Remaining variables are put to zero. Secondly, we define values of the significant variables by maximum likelihood method. Note, that the distribution of stars in Hess diagram bins follows a Poisson (not a Gaussian) statistics and the least-squares method solution (the most straightforward way) will give shifted estimation of the parameters. Therefore, we construct maximum likelihood function for our task. To define maximum likelihood estimates, we have to find such parameters of our model that correspond to the maximum value of the probability.

Note, that our solution and also other similar star formation history modeling are suffer from well-known age-metallicity degeneration effect. Additional spectroscopic data can be considered to break this degeneration. Moreover, additional models of chemical enrichment can be entered to SFH calculation (see, for example, Lee and Yuk (2007)).

3. The Local Group

The Local Group is a diverse collection of dwarf galaxies, which show wide ranges in mass, luminosity, and stellar content. The group contain about 40 objects, most of which are dwarf galaxies. The 3D structure of the Local Group is shown in Fig.1. There are many studies of star formation histories for the dwarf galaxies within the Local Group. One of the most complete and homogeneous are Grebel (2005) and Dolphin et al. (2005). In the last work HST/WFPC2 data archive was used to obtain photometric data on the Local Group dwarf galaxies. The authors have found that among the dwarf spheroidal and dwarf elliptical galaxies there is a correlation between absolute magnitude and the duration of the epoch of star formation, in the sense that more luminous galaxies generally formed their stars over a larger period of time. The dwarf irregular galaxies show another trend with absolute magnitude, as the most luminous systems have the most steady star formation. The examples of the star formation history determination of dwarf spheroidal and dwarf irregular galaxy are given in Fig.2. It is interesting fact, that besides common tendencies, there is not two galaxies with resembling star formation history in the Local Group, as many researchers have noted.

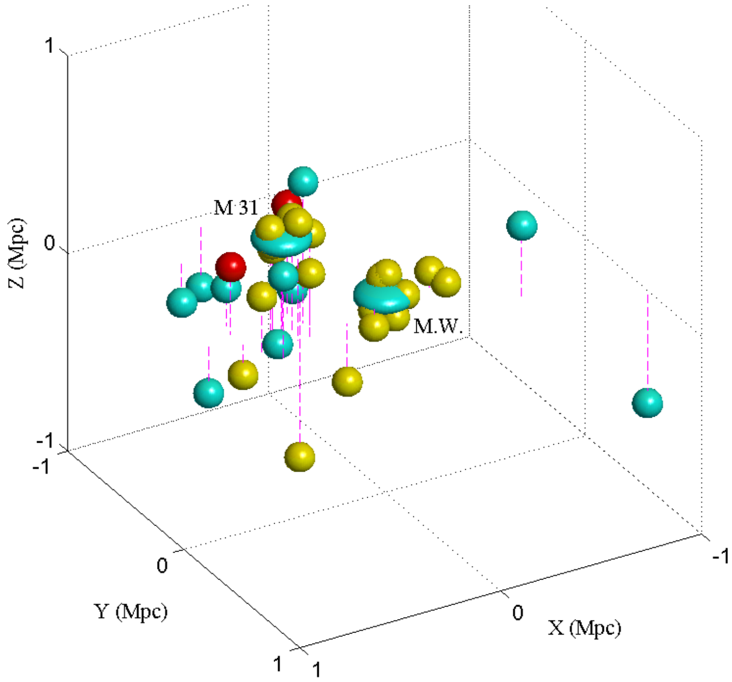

Fig.1. The 3D structure of the Local Group.

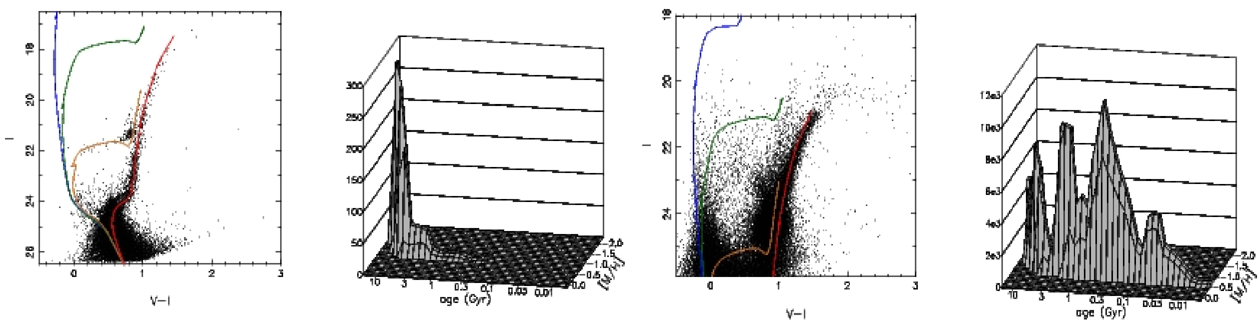

Fig.2. The CMD and star formation history for Leo II (left) and WLM (right) from the work of Dolphin et al. (2005).

4. The M 81 Group

The M 81 group is one of the nearest to us (the mean distance is 3.6 Mpc). It is also the example of dramatic interaction in its central part, as the dominant members M 81, M 82, NGC 3077, and NGC 2976 are embedded in a huge H I cloud with extended tidal H I bridges between the components (Yun, Ho and Lo (1994)). There is evidence, that the strong interaction in the past has produced at least four tidal dwarf galaxies about 200 Myr ago (Makarova et al. 2002).

Over the last several years we have participated in two snapshot surveys of nearby galaxies using WFPC2 aboard HST, which have provided us with the material for distances of about 10 percents accuracy for about 150 nearby galaxies (proj. 8192 and 8601 and references therein) and with HST/ACS pointed observations (proj. 9771 and 10235 and references therein).

The histograms in Fig.3 summarize the results of our star formation history determination for the 15 irregular dwarfs within the M 81 group. Larger and brighter galaxies of the sample (for example, NGC 4236, IC 2574 and NGC 2976) show evidence of continuous star formation, whereas in the galaxies of lower surface brightness and smaller sizes two or three distinct episodes of star formation can be seen. The metallicity of the resolved stellar population is high enough (up to [Fe/H] = -0.4) with high spread of about 1 dex.

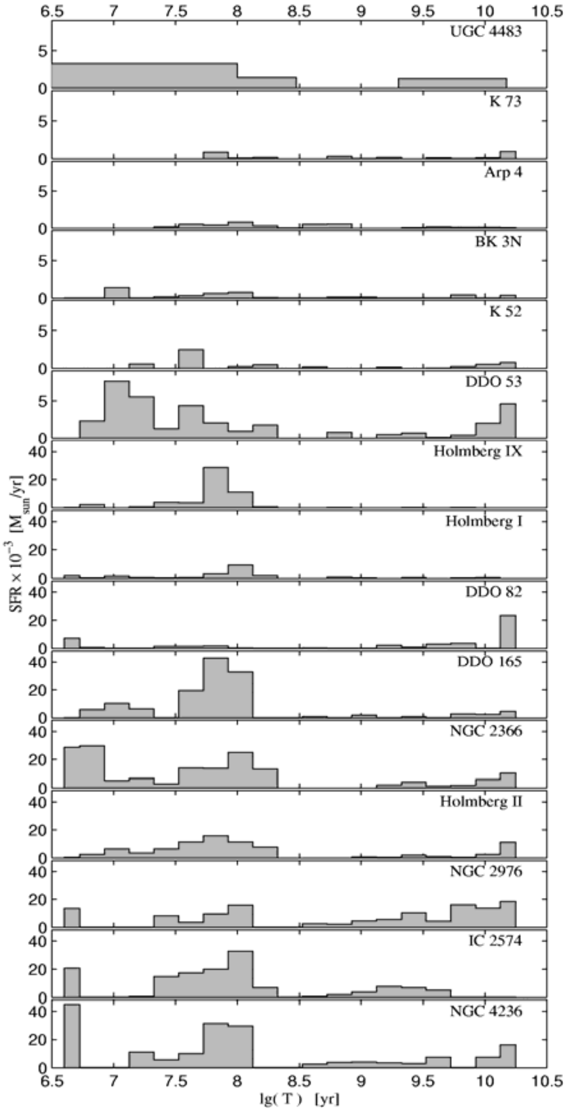

Fig.3. Star formation histories of the dwarf irregular galaxies in the M 81 group.

Further progress has been made with our HST/ACS observations and also the archival data. We studied detailed star formation histories of 9 dwarf galaxies in the central part (< 300 Kpc) of the M 81 group. Photometry of the resolved stars in the galaxies was made with the DOLPHOT package (Dolphin (2002)) for crowded field photometry. Photometric distances for all galaxies in the sample were obtained using tip of the red giant branch (TRGB) distance indicator and our maximum-likelihood program of TRGB determination (Makarov et al. 2006). Star formation history determination was made using our StarProbe package (see Fig.4). Note the similarity of ages (about 300 Myr - 1 Gyr) of last star formation episode for most studied galaxies in the M 81 group. The mentioned features of star formation can probably be explained by past strong interactions in the group.

Further HST/ACS archival data reduction and SFH determinations for dwarfs within M 81 group are under way.

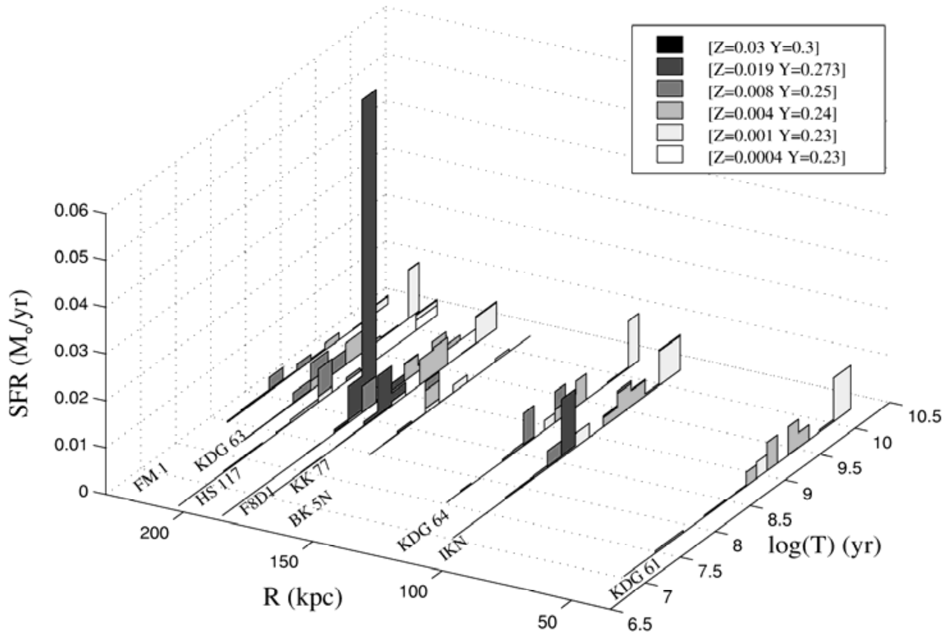

Fig. 4. Star formation histories of the dwarfs in the central part of M 81 group.

5. The Centaurus A group.

One another nearby group of galaxies is the Centaurus A group. It is situated in the southern hemisphere at nearly the same mean distance from us (3.8 Mpc), as the M 81 group. Interestingly, that structure of these two groups (and also the structure of our own Local Group) has similar features, in the sense that the groups have split into two distinct subgroups (Wilky Way – M 31, M 81 – NGC 2403, Cen A – M 83). But the morphology of the Cen A /M 83 region is particularly interesting because one of the dominant galaxies Cen A is a giant elliptical. The only other nearby large elliptical galaxy is the highly obscured Maffei 1. The Cen~A group is probably more dynamically evolved than others in the Local Volume, like Local group or M 81 group, which have a spiral galaxy as central body. The 3D structure of the Cen A group is shown in Fig.5.

Most of known dwarf members of the Cen A/M 83 complex were imaged within the framework of our HST/ACS and HST/WFPC2 projects. Photometric distances for all galaxies in the sample were obtained using Tip of the Red Giant Branch distance indicator (Karachentsev et al. (2007)). Star formation history determination was performed with the StarProbe package. The galaxies from the central part of the group (within 300 Kpc) are shown in Fig.6.

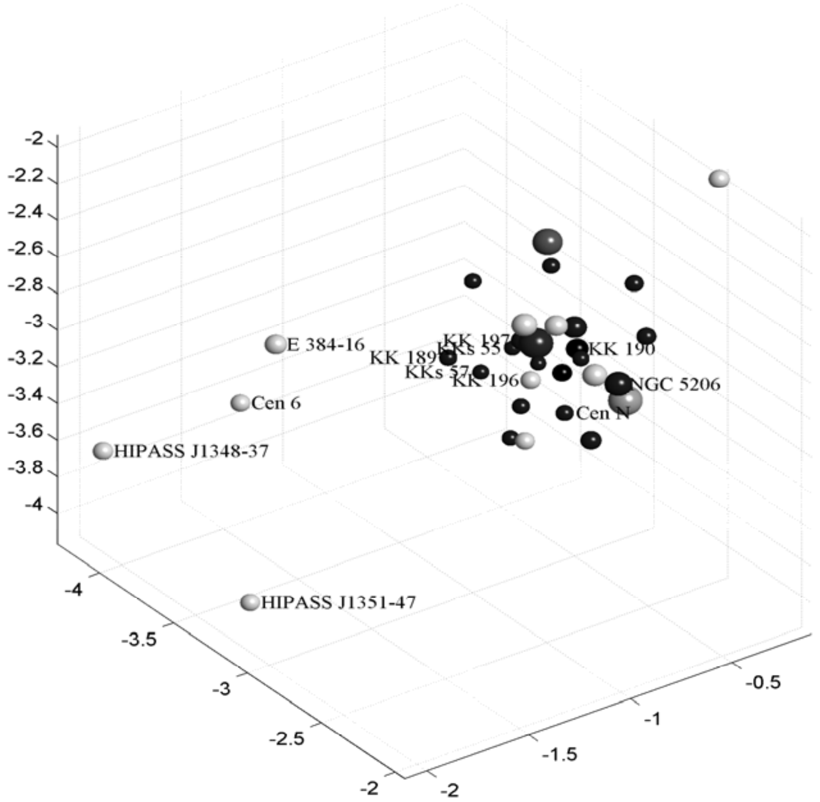

Fig. 5. 3D structure of the Cen~A group is shown. Size of the spheres corresponds to absolute magnitude of a galaxy. Grey spheres represent dIrr galaxies and black spheres are dSphs. Three largest spheres are central body of the group (Cen~A elliptical galaxy) and two spiral members. Names of the galaxies with SFH measured by us are indicated in the figure. Well known morphological segregation between dSph and dIrr galaxies can be recognize in the picture. The dwarf spheroidals are closer to the central body, whereas the dwarf irregulars mostly situated in the outer part of the group.

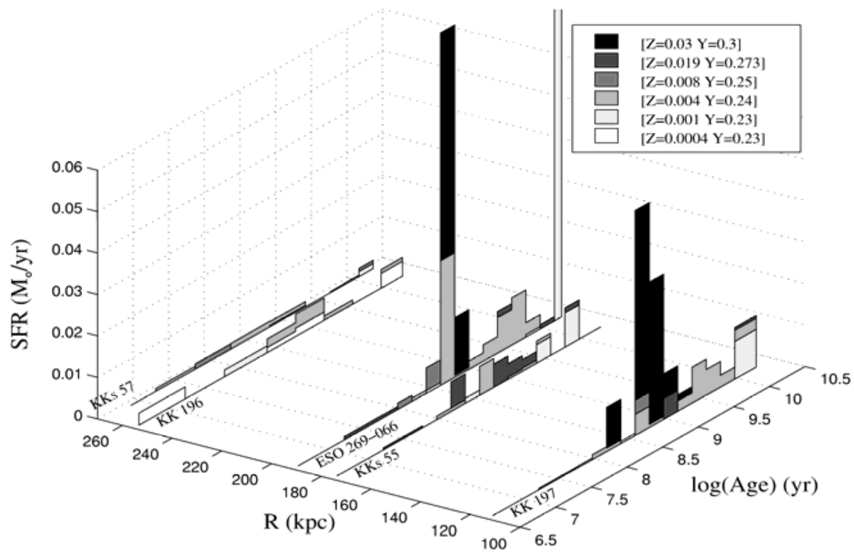

Fig. 6. Star formation histories of the dwarfs in the central part of Cen A group.

Several star formation features can be recognized from our measurements. First, most galaxies demonstrate two distinct (and similar) star formation episodes. An ancient episode has an age of about 10--13 Gyr and low metal abundance. The galaxies under study also show enhanced star formation about 0.1--1 Gyr ago. Dwarf irregulars has some ongoing star formation, too. Second, several dwarfs under study have unusual rate of metal enrichment, with the metallicity level of recent star formation episodes of about solar and probably higher (like KK 197 and ESO 269--066). Possible explanation of this high enrichment level can be due to interaction and merging of some galaxies during the evolution of the Cen A group. Sales et al. (astro-ph/0706.2009v3, Millennium simulations) have demonstrated high matter spread (up to 2 virial radii) in such evolutionary processes. Smaller members in the group can experience enhanced star formation due to these interactions and merging using the processed in larger galaxies matter of higher metal abundance.

6. Conclusions

We describe the technique for determining the history of star formation in galaxies based on the photometry of the resolved stars in a galaxy. The dwarf irregular and dwarf spheroidal galaxies from the Local Group are studied in high details, because stellar populations in these dwarfs can be resolved from the ground till to very faint and less massive. One of the most homogeneous and complete work on this subject is the paper of Dolphin et al. (2005). However, there is little information about star formation histories of more distant dwarfs outside the Local Group. In the last decade a number of galaxies from the nearby groups (within 5-8 Mpc) has been imaged with HST/WFPC2 and HST/ACS.

Using our StarProbe package of star formation history determination we have obtained SFH for more than 40 dwarf galaxies in the nearby M 81 and Centaurus A group. The galaxies under consideration demonstrate a wide range of star formation activity. Similar to the Local Group of galaxies, the more luminous galaxies show larger period of star formation and they have the most steady star formation rate. The smaller system have several shorter episodes of star formation.

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