THE EVOLUTION OF GALAXIES: CLUES FROM RESOLVED DWARF SYSTEMS
(Description of past research activity and statement of scientific research interests)

Contents

The description is split in two parts: part 1 gives the motivations underlying my past research activity, and part 2 is a short summary of the scientific results.

1 Scientific Rationale

My research is centered on the resolved stellar populations of the Local Group (LG), and in particular on Galactic globular clusters (GGCs) and dwarf galaxies. For these stellar systems, color-magnitude diagrams (CMDs) can be obtained, from which the information about their past star formation history (SFH) can be extracted. In particular, dwarf galaxies of the LG show large variations in their mass, environmental conditions, current SF, gas content and morphology, so one hopes that possible correlations of their SFHs with these parameters will shed light on the evolutionary mechanisms of these relatively simple stellar systems, and possibly of their larger "normal" counterparts (elliptical and spiral galaxies).

This rationale motivated, as a first step, the investigation of three "special" dwarfs, namely the Tucana dwarf spheroidal (dSph), the Phoenix dwarf spheroidal/dwarf irregular (dSph/dIrr), and the SagDIG dIrr galaxy (Saviane I., Held E. V., Piotto G., 1996, A&A, 315, 40; Held E.V., Saviane I., Momany Y., 1999, A&A, 345, 747; Momany Y., Saviane I., Held E.V., 2000, in preparation). Almost all LG dSph are located near the two giant spirals, but Tucana and Phoenix are an exception, being $>$ 400 kpc far from either the Milky Way or M31. In turn, SagDIG is the LG dwarf with one of the highest gas/stars ratio ($M_{\rm gas}/M_{\rm stars} \sim 0.9$). Moreover, all three galaxies contain (or were suspected to contain) young/blue stars, so it was expected that imaging done with the new generation, larger format and blue-sensitive CCDs, would have provided precious information.

New instrumentation, and properly chosen observational strategies, are able to uncover subtle evolutionary details even for "well studied" objects. This is demonstrated by our studies of Fornax and Leo I. The CMD that was obtained for the Fornax dwarf spheroidal galaxy (Saviane, Held & Bertelli, 2000, A&A, 355, 56), allowed us to study a number of previously undetected features. The improvement is due to the increased area coverage that was offered by the DFOSC imager attached to the ESO/Danish telescope. Even better coverage is provided by the new WF imager attached to the ESO/MPI 2.2m telescope, and indeed a medium-term observational program was started at ESO and is now being carried out.

In the case of Leo I, we have been able, for the first time, to unambiguously reveal the presence of a true old population (Held, Saviane, Momany & Carraro, 2000, ApJ, 530, L85). Our success, in comparison to even extensive HST studies, was due to the choice of bluer colors and to the spatial coverage of the outer regions of the galaxy.

Even the study of simple stellar systems requires basic input such as distance indicators, metallicity indices, and reliable stellar evolutionary models. Models can be tested using simple stellar populations (SSPs) such as globular clusters. However, internal dynamical processes likely affect the evolution of their stars. Then I decided to study a peculiar GGC (NGC 1851) in order to see if theoretical predictions can be reconciled with the observed CMDs (Saviane I., et al., 1998, A&A, 333, 479). Moreover, the need to obtain the metallicity distribution in old stellar systems, led me to an extensive analysis of the behavior of the morphology of the red giant branch (RGB) as a function of the metallicity (Saviane et al. 2000, A&A, 355, 966). The study was based on the largest homogeneous GGC photometric database, that was assembled for the relative age investigation (see below).

How does the SFH of LG dwarfs compare to that of other local galaxies? Is there a common zero age population? In order to begin answering these questions, a long-term observational campaign was planned in 1996, aimed at collecting homogeneous photometric data for a large sample of inner-halo Galactic globulars. The first phase of this project is now complete, and a thorough analysis of 34 CMDs is now yielding a better view of the first stages of the SF in our Milky Way (Rosenberg, Saviane, Piotto, Aparicio, 1999, AJ, 118, 2306). A complementary study of young (or suspected young) GGCs is also under way. This should clarify later stages of GC formation (e.g. a second SF episode, a delayed GC formation in outer halo, later accretion events, etc.). Two objects (Palomar 1 and Palomar 12) were studied up to now (Rosenberg A., Saviane I., Piotto G., Held E.V., 1998, A&A, 339, 61; Rosenberg A., Piotto G., Saviane I., Aparicio A., Gratton R., 1998, AJ, 115, 658; Rosenberg A., Saviane I., Piotto G., Aparicio A., Zaggia S. R., 1998, AJ, 115, 648). The first quantitative evaluation of their ages has been given, confirming the young Pal 12 age, and leading to the discovery of the youngest Galactic globular, Pal 1.

The best summarizing statement of all the previous points, is that stars in the LG began forming at the very same time throughout a (current) volume of ~ 1 Mpc. Later, it is almost impossible to find common trends in SF. However, we have hints that two major SF episodes were experienced by many dwarfs, and that the second episode occurred in more central regions. This could also be true for the Milky Way halo, but a check with data for more peculiar GCs is needed.

2 Main results

2.1 Dwarf galaxies of the Local Group

1. **Tucana**

   (a) From the I magnitude of the RGB tip, the first accurate distance modulus of this galaxy has been determined ($(m-M)_0 = 24.69 \pm 0.16$). This has confirmed that Tucana is an isolated dwarf spheroidal located almost at the border of the Local Group (870 kpc from our Galaxy).

   (b) From the color of the red giant branch tip and by direct comparison with the giant branches of galactic globular clusters, a metallicity [Fe/H]$= -1.8 \pm 0.2$ dex has been estimated, and no clear indication for a metallicity spread has been found.

(c) It has been shown that the color–magnitude diagram indicates that Tucana has had a single star formation burst at the epoch of the Galactic globular cluster star formation.

(d) The V luminosity profile, and the surface density profile of resolved stars, have been derived. Consequently, the structural parameters of Tucana have been found, from which it has been confirmed that Tucana participates to the general metallicity-surface brightness-absolute magnitude relations defined by the Galaxy and M31 dwarf spheroidal and dwarf elliptical companions.

(e) It has thus been shown that Tucana is a clear exception to the scenario suggested by van den Bergh (1994), suggesting that young or intermediate-age populations are preferentially found in dSph's far from the Milky Way. In the case of Tucana, it was speculated that galactic winds expelled the interstellar medium at early epochs and halted star formation, a process apparently not dependent on environment.

2. **Phoenix**

(a) The extended HB of Phoenix has been for the first time revealed at $V_{\rm HB} = 23.78 \pm 0.05$. This demonstrates the presence of a minority yet significant population older than 10 Gyr. It has also allowed for the first time an independent estimate of the distance to Phoenix, $(m - M)_V = 23.21 \pm 0.08$. The spatial distribution of blue HB stars is significantly more extended than that of red giant stars. It therefore appears that the early star formation episode occurred in Phoenix on a larger spatial scale that subsequent bursts.

(b) A mean metal abundance $[\mathrm{Fe/H}] = -1.81 \pm 0.10$ has been obtained with a direct comparison of the upper part of the RGB with the fiducial sequences of template Galactic globular clusters. A careful analysis based on extensive artificial star tests has given a metallicity dispersion $\sigma_{[\mathrm{Fe/H}]} = 0.23 \pm 0.03$.

(c) Thanks to the wide photometric baseline, new information has been provided on the young stellar population in Phoenix. It has been found that the recent star formation episode started at least 0.6 Gyr ago. The blue stars which trace the most recent burst ($1 \div 2.5 \times 10^8$ yr ago) are concentrated in clumps or "associations" near the galaxy center, with a spatial distribution elongated in a direction perpendicular to the major axis defined by the diffuse galaxy light, and slightly offset towards the HI cloud observed by Young & Lo (1997, ApJ 490, 710). It was suggested that the neutral gas could have been blown out by the recent burst, a possibility that should be further investigated when the hypothesis of a physical link receives support by measurements of the galaxy radial velocity.

3. **Fornax**

(a) Broadband B, V, I CCD photometry of about 40 000 stars in four regions, down to $V \sim 23.5$, has been obtained, which represents the largest three-color data set available for this galaxy.

(b) The resultant color-magnitude diagrams, based on a wide color baseline, show a variety of features tracing the history of star formation of this dwarf galaxy, and many age-tracers have been investigated: the conspicuous young main sequence, the helium-burning phase of the young population, the extended upper AGB tail, the prominent red HB clump pertaining to the dominant intermediate-age population, and the extended HB of an old population.

(c) New CMD features has been detected: we show that blue HB stars may be present in the outer regions, and measure the luminosity of the AGB bump. These are examples of the short-lived evolutionary phases that can be revealed in stellar populations using adequately large star data samples, whose measurements provide powerful tests of theoretical models.

(d) Based on precise detection of the tip of the RGB in a selected RGB sample, a corrected distance modulus $(m - M)_0 = 20.70 \pm 0.12$ has been measured. An independent estimate of the distance to Fornax is also obtained from the mean magnitude of old horizontal branch stars, yielding a distance modulus $(m - M)_0 = 20.76 \pm 0.04$, in good agreement with the distance estimated from the red giant branch tip.

(e) It has been found that the color distribution of the red giant stars can be approximately described as the superposition of two populations. The dominant component, comprising $\sim 70\%$ of the red giant stars, consists of relatively metal-enriched intermediate-age stars ([Fe/H]$= -1.39 \pm 0.15$). Once the younger mean age of Fornax is taken into account, the best estimate for the mean abundance becomes [Fe/H]$\simeq -1 \pm 0.15$. The dominant intermediate-age component has been shown to have an intrinsic color dispersion corresponding to a relatively low abundance dispersion, $\sigma_{[\mathrm{Fe/H}]} = 0.12 \pm 0.02$ dex. In addition, there is a distinct small population of red giants on the blue side of the RGB. While these stars could be either old or young red giants, it has been shown that their spatial distribution is consistent with the radial gradient of old horizontal branch stars, and completely different from that of the younger population. This unambiguously qualifies them as old and metal-poor.

(f) The above result has clarified the nature of the red giant branch of Fornax, suggesting that its exceptional color width is due to the presence of two main populations yielding a large abundance range ($-2.0 <$ [Fe/H] < -0.7). This evidence suggests a scenario in which the Fornax dSph started forming a stellar halo and its surrounding clusters together about 10-13 Gyr ago, then a major SF episode occurred (probably with a discontinuous rate) after several Gyr.

4. **Leo I**

(a) A wide-area search with the ESO New Technology Telescope lead us to the discovery of a significant old population. The color-magnitude diagram now reveals an extended horizontal branch, unambiguously indicating the presence of an old, metal-poor population in the outer regions of this galaxy.

(b) The presence of an old stellar population is now demonstrated in *all* of the Local Group dwarf spheroidals.

(c) We have found little evidence for a stellar population gradient, at least outside $R > 2'$ (0.16 kpc), since the old horizontal branch stars are radially distributed as their more numerous intermediate-age helium-burning counterparts.

(d) The discovery of a definitely old population in the predominantly young dwarf spheroidal galaxy Leo I points to a sharply defined first epoch of star formation common to all of the Local Group dSph's as well as to the halo of the Milky Way.

2.2 Results from simple stellar populations

1. **NGC 1851**

(a) This is one of the few examples of pre-wide-field era where a GGC has been totally covered with a mosaic. The photometric data set has allowed a V vs. $V - I$ color-magnitude diagram for ~20500 stars to be constructed.

(b) A detailed study of the peculiar HB morphology has been carried out (the cluster has a clearly bimodal horizontal branch). We have shown that standard evolutionary models are not able to reproduce the observed bimodal distribution of stars along the HB. Synthetic HR diagrams demonstrate that the problem could be solved by assuming that the efficiency of the RGB mass loss actually encompasses values going from 0.25 to 0.48. We have found evidence that the radial distribution of the blue HB stars is different from that of red HB and SGB stars. The BHB stars are significantly more concentrated than the SGB stars for $r > 100$ arcsec. Though this distribution cannot be easily interpreted in terms of dynamical evolution, it might be related to the anomalous distribution of the BSs (see below).

(c) With an accurate inspection of the cluster bright-blue objects, and a comparison with the numbers predicted from the background field and the Galactic count models, the presence of seven "supra-HB" stars has been confirmed. We have shown that six of the "supra-HB" stars could be evolved descendants from HB progenitors (post-HB or planetary nebulae).

(d) All the 27 known variable stars have been identified, and 26 have been measured in both colors (the remaining one being saturated). Twenty-two of them are RR Lyr variables. The positions and photometry for seven new RR Lyr candidates have been given. With these additional variables the ratio of the two types is now $N_c/N_{ab} = 0.38$, which reduces the current estimate (=0.47; Wehlau et al. 1982).

(e) From a sample of 25 globular clusters a new calibration for $\Delta V^{\rm HB}_{\rm bump}$ as a function of cluster metallicity has been derived. It has been found that NGC 1851 follows this general trend fairly well. From a comparison with the theoretical models, some evidence has also been found of a younger age for metal rich clusters.

(f) 13 blue straggler stars have been identified. These objects do not show any sign of variability. It has been shown that the blue stragglers are less concentrated than the subgiant branch stars with similar magnitudes for $r > 80''$.

(g) We have been able to derive a complete LF down to $V \simeq 23.5$ mag for stars in the region $190'' < r < 650''$, and down to $V \simeq 22$ mag in the region $120'' < r < 189''$. The external LF is steeper than the internal one, and we have interpreted this result as a sign of mass segregation. By using the most updated mass-luminosity relations we have obtained MFs which can be well fitted by power laws with distinct exponents x. The observed value for the external MF is $x = 1.52 \pm 0.18$, which is steeper than the value 0.89 ± 0.20 found for the internal one.

(h) The global MF has been determined correcting the two observed mass functions for the effects of mass segregation, as predicted by the multi-mass King-Michie model which best fits the observed light profile of NGC 1851. The two values for the slope of the MF are compatible with the model if a global MF exponent $x_0 = 0.2 \pm 0.3$ is adopted. This value for the global MF slope is marginally smaller (MF flatter) than what would be expected from the relation between the slope of the MFs and the position in the Galaxy and the metallicity of the cluster proposed by Djorgovski et al. (1993). This might indicate that NGC 1851 has had a stronger gravitational interaction with the Galactic disc than the average of the Galactic GCs with similar position and metallicity.

(i) In conclusion, the above results indicate that NGC 1851 is a cluster where the dynamical evolution has affected both its evolved and unevolved stellar content. While the single findings are not of high statistical significance (mostly due to the small size of the stellar samples), taken together they give a coherent picture. Stellar encounters have led to mass segregation, as shown by the MF, which is steeper and steeper going from external to internal regions. They have probably contributed to the creation of the observed group of blue straggler stars, and possibly have triggered the formation of a blue tail in the HB. The internal dynamics of NGC 1851 has therefore influenced the evolution of its stars, introducing effects not reproducible by standard models. In turn, the dynamical evolution induced by the external gravitational field of the Galaxy has also very probably contributed to the modification of the present-day stellar population of NGC 1851, as strongly suggested by the anomalously flat global mass function.

2. The red giant branch of Galactic globular clusters

(a) Using the photometric V, I database for Galactic globular clusters, that was assembled for the relative age investigation (Rosenberg et al. 1999, AJ, November issue) a complete set of metallicity indices has been measured, based on the morphology and position of the red-giant branch.

(b) In particular, the first calibration of the S, $\Delta V_{1.1}$ and $\Delta V_{1.4}$ indices in the $(V-I, V)$ plane has been obtained.

(c) The indices have been calibrated in terms of metallicity, both on the Zinn & West (1984) and the Carretta & Gratton (1997) scales. Our new calibrations of the $(V-I)_{0,\mathrm{g}}$, $\Delta V_{1.2}$, $(V-I)_{-3.0}$ and $(V-I)_{-3.5}$ indices are consistent with existing relations.

(d) Using a grid of selected RGB fiducial points, it has been possible to define a function in the $(V-I)_0, M_I,$ [Fe/H] space which is able to reproduce the whole set of GGC giant branches in terms of a single parameter (the metallicity).

(e) It has been shown that the function is able to predict the correct trend of the observed indices with metallicity.

(f) The usage of this function will improve the current determinations of metallicity and distances within the Local Group, since it allows to easily map $(V-I)_0, M_I$ coordinates into [Fe/H], M_I ones. To this aim the "synthetic" RGB distribution has been generated both for the currently used Lee, Demarque and Zinn (1990) Local Group distance scale, and for the most recent results on the RR Lyr distance scale.

2.3 Formation of normal galaxies: the Milky Way halo

1. **The relative ages of inner-halo globular clusters**

(a) The largest homogeneous photometric database of Galactic globular clusters has been assembled (34 objects), based on observational runs carried out along two years, both with Southern and Northern telescopes.

(b) This database (+ Pal 12) has been used to measure a set of distance and reddening independent relative age indicators, which have been compared to the relations predicted by two recent updated libraries of isochrones.

(c) Using these models and two independent methods, we have found that self-consistent relative ages can be estimated for the GGC sample. In turn, this demonstrates that the models are internally self-consistent. Based on the relative age vs. metallicity distribution, the following conclusions have been reached.

(d) There is no evidence of an age spread for clusters with [Fe/H]< -1.2, all the clusters of our sample in this range being old and coeval.

(e) For the intermediate metallicity group ($-1.2 \leq$ [Fe/H] < -0.9 there is a clear evidence of age dispersion, with clusters up to $\sim 25\%$ younger than the older members.

(f) The clusters within the metal rich group ([Fe/H]≥ -0.9) seem to be coeval within the uncertainties (except Pal 12), but younger ($\sim 17\%$) than the bulk of the Galactic globulars. The latter result is totally model dependent.

(g) From the Galactocentric distribution of the GGC ages, GGCs can be divided in two groups: The old coeval clusters, and the young clusters.

(h) From this distribution, a possible scenario for the Milky Way formation has been presented: The GC formation process started at the same zero age throughout the halo, at least out to ~ 20 kpc from the Galactic center. According to the present stellar evolution models, the metal-rich globulars are formed at a later time ($\sim 17\%$ lower age). And finally, significantly younger halo GGCs are found at any $R_{\rm GC} > 8$ kpc. For these, a possible scenario associated with mergers of dwarf galaxies to the Milky Way is suggested.

2. **Young clusters in the Galactic halo**

(a) Palomar 1

i. A color magnitude diagram down to $V_{\rm lim} \sim 24$, and a luminosity function complete down to $V_{\rm lim} = 23.25$ have been constructed.

ii. A distance modulus $(m - M)_0 = 15.25 \pm 0.25$ has been obtained, indicating that Pal 1 is located 3.7 ± 0.4 kpc above the Galactic disk and 17.3 ± 1.6 kpc from the Galactic center.

iii. The metallicity has been determined using the equivalent widths of the CaII triplet on medium resolution spectra. From the comparison of the luminosity corrected equivalent widths in four stars of Palomar 1 with those of a sample of stars in each of three calibration clusters (M2, M15, and M71), [Fe/H]$=-0.6 \pm 0.2$ on the Zinn & West (1984) scale has been found, or [Fe/H]$=-0.7 \pm 0.2$ on the Carretta & Gratton (1997) scale. The radial velocity has been also obtained, $V_{\rm r} = -82.8 \pm 3.3$ Km/s .

iv. A comparison with 47 Tuc and M71 has shown that Pal 1 must be significantly younger. The best fitting Bertelli et al. (1994) isochrones have given an age between 6.3 and 8 Gyrs, which would make Pal 1 the youngest Galactic globular cluster so far identified. The luminosity function shows some evidence for mass segregation, consistent with the very short relaxation time. The global mass function can be fitted with a power law of slope $x = -1.4 \pm 0.7$. This mass function is anomalously flat, suggesting either a strong dynamical evolution or an initial mass function significantly different from most of the other halo globular clusters.

(b) Palomar 12

i. Broadband V, I CCD photometry for ~ 1700 stars, covering a field of 10×10 arcmin^2, has been obtained. From these data, a color-magnitude diagram from the red giant branch tip to ~ 2 mag below the cluster's turn-off has been constructed.

ii. From a comparison with the color magnitude diagrams of 47 Tuc and M5, and using different theoretical models, it has been confirmed that Pal 12 is younger, finding an age $68 \pm 10\%$ that of both template clusters.

iii. Revised structural parameters have also been obtained: $r_{\rm c} = 37.8 \pm 0.6$ and $c = 1.08 \pm 0.02$.

Los Angeles, September 10, 2000

Ivo Saviane