POPULATION GRADIENTS IN NEARBY DWARF GALAXIES

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ABSTRACT.
Recent results on the detection of substructure in dwarf spheroidal galaxies are discussed. In most cases they show that, when a galaxy experiences multiple SF episodes, the intermediate age population is more centrally concentrated than the old population, and that the recent SF is even more concentrated towards the central regions. Moreover, it appears that the spatial distribution of stars becomes more and more irregular as younger and younger subpopulations are considered. We illustrate how wide-area observations, allowing a substantial coverage of dwarf spheroidals (in particular the satellites of the Milky Way), has provided evidence for cosmologically old populations in every dSph galaxy. All these results are placed in the broader scenario of population gradients in nearby dwarf galaxies of different morphological types.

1. Introduction

The study of nearby dwarf galaxies has greatly benefited from the progress in both space- and ground-based observational astronomy. HST imaging can reach the old main sequence turnoff (TO) of objects in the Local Group (LG) even to the distance of Leo systems (Mighell & Rich 1996; Caputo et al. 1998; Gallart et al. 1999), and spectrographs attached to 10m-class telescopes now permit a study of the metal content of giant stars out to the M31 system (Côté et al. 1999).

Another major advance has been the introduction of large-format CCDs and mosaic cameras, which allow a substantial coverage of dwarf spheroidal (dSph) satellites of the Milky Way. Populations of different age are often located in different galactic regions, so that a spatially biased stellar sample can turn out a biased sample tout court. It is therefore of interest to gain a broad picture of how population gradients manifest themselves in dwarf galaxies.

2. Population gradients in dwarf galaxies: core-halo structures

In most cases, observations show that a centrally concentrated population of a given age is superposed onto a more extended older population (see below). This is a relatively recent result, since galaxies of different morphological types present different observational challenges.

Asymmetries in the spatial distribution of stars in dSph galaxies have long been known, the most striking example being that of Fornax (Hodge 1961). Centrally concentrated blue stars in the dwarf elliptical galaxies NGC 185 and NGC 205 were known since Hodge (1963), Hodge (1973), and Gallagher & Hunter (1981). Similar gradients are observed in dwarf spheroidals, seemingly the continuation of the dE sequence at fainter luminosities (e.g. Binggeli 1994). Da Costa et al. (1996) recognized a change in the HB morphology with radius in And I. The authors found that red, centrally concentrated, HB stars should be $\sim 3 \div 4$ Gyr younger than blue HB stars, and they reached a similar conclusion for Leo II and Sculptor by re-analyzing existing data.

The most impressive example of population changes with radius is perhaps the Stetson's et al. (1998) two-color investigation of Fornax. The oldest population defines an extended halo with a spatial scale length larger than that of intermediate-age red clump stars ($\sim 4 \div 6$ Gyr). The young population of blue main sequence (MS) stars (~ 100 Myr), as well the reddest AGB (carbon) stars, are even more concentrated in a bar-like distribution. The intermediate age population displays an asymmetrical structure, with a peculiar "crescent" shape. According to Buonanno et al. (1999), the central Fornax globular cluster #4 is ~ 3 Gyr younger than the rest of the clusters, which implies that it was formed in the gap between the first SF episode and the major intermediate-age one. We have been able to add to this picture with wide-area BVI imaging (Saviane et al. 2000). The RGB color distribution has a main component with a mean metallicity [Fe/H]$= -1.00 \pm 0.15$ and a low dispersion $\sigma([\mathrm{Fe/H}]) = 0.12 \pm 0.02$, and there is a secondary bluer component. In principle this could be young and metal-rich, but its radial distribution closely follows that of old-HB stars, so it is unambiguously old and metal-poor. A spatial analysis is then able to break the age-metallicity degeneracy. A similar degree of substructure was found in Phoenix (Held et al. 1999). The youngest blue stars ($1 \div 2.5 \times 10^8$ yr) form clumps near the galaxy center, and are elongated in a direction perpendicular to the major axis defined by the diffuse galaxy light (Martínez-Delgado et al. 1999a). They are slightly offset towards the H I cloud A observed by Young & Lo (1997). Martínez-Delgado et al. find that the area-normalized star formation rate for the central region of Phoenix is in the range obtained by Hunter & Gallagher (1986) for a sample of dIrr galaxies. Older and intermediate age stars are spread over a larger area. In close correspondence to Fornax, we also found that $\sim 40\%$ of the Phoenix red giants are of intermediate age, and more centrally concentrated than blue HB stars. Phoenix shows a metallicity dispersion ($\sigma_{[\mathrm{Fe/H}]} = 0.23 \pm 0.03$) around its mean [Fe/H]$= -1.81 \pm 0.10$, but the RGB sample is not large enough to allow an analysis such as that done for Fornax. An analysis of WFPC2 observations (Holtzman et al. 2000) leads to an initial SF period lasting until $t \sim 9$ Gyr ago. Intermediate-age stars are then formed ($t \sim 5$ Gyr), mildly separated in age from a strong recent burst ($t \sim 300$ Myr).

The list of dSph/dE showing population gradients is now fairly extended. A centrally concentrated intermediate-age population is found in NGC 147 (Han et al. 1997) and ESO 410-G005 (Karachentsev et al. 2000). In NGC 185, recent star formation (up to 100 Myr) is only detected in the central $\sim 0.2 \times 0.1$ kpc^2 (Martínez-Delgado et al. 1999b). SFRs during the formation of the intermediate-age and old populations were lower in the outer regions. Red HB stars are more centrally concentrated than blue HB stars in Sculptor (Hurley-Keller et al. 1999; Majewski et al. 1999) and Sagittarius (Bellazzini et al. 1999). In both cases, the interpretation is made controversial (age vs. metallicity) by the yet unsolved 'second parameter' problem. Some counterexamples do exist where population gradients were not detected. Among the best studied LG dwarf spheroidals, population gradients could not be detected in Leo I (Held et al. 2000a; at least outside 0.16 kpc), Carina (Da Costa et al. 1996), Tucana (Saviane et al. 1996), and And II (Da Costa et al. 2000).

Dwarf irregular (dIrr) and blue compact dwarf (BCD) galaxies are generally located far from the Galaxy or the LG, yet population gradients are readily recognized in optical and IR surface photometry investigations. An almost ubiquitous presence of a halo of red stars surrounding the star forming regions has been established. As an example, Patterson & Thuan (1996) show that the majority of galaxies in their dIrr sample is composed of objects having nuclear star-forming regions superimposed to an underlying exponential component, whose color is compatible with that of a K0 main-sequence star or G5 giant. K and M giants are also the probable old population in the BCD and dIrr samples of Thuan (1983, 1985). Other examples of extended halos in BCDs are found in Loose & Thuan (1986), Kunth et al. (1988), Meurer et al. (1994), Papaderos et al. (1996), Telles & Terlevich (1997), Doublier et al. (1997; 2000), Marlowe et al. (1999). Interestingly, Doublier et al. (2000) revealed an underlying (unresolved) red population in POX 186, the prototype of a subclass of BCDs that seem to have no extended halos. Kunth and Östlin (2000) have recently reviewed this subject.

3. The age of the extended halos: ubiquitous old populations?

How old are these halos? This is an important question, since a definite proof that any dwarf galaxy contains a truly old population (i.e. *at least* as old as Milky Way halo globulars), would tell us that star formation began at the very same time throughout the Universe, and that dwarf galaxies, irrespective of their present morphology, are truly primordial objects. According to current stellar evolution theories, the only unambiguous signature of a metal-poor, > 10 Gyr population is the presence in color-magnitude diagrams (CMDs) of an *extended* horizontal branch (HB). Indeed, even if the TO is reached, the uncertainties on the distance can hamper the age-dating process, since a typical 0.1 error in distance modulus (rising often to 0.2 magnitudes), translates into a $\sim 1 \div 2$ Gyr age uncertainty. The HB can be betrayed by the presence of RR Lyr variables, but in order to constrain their age range, a detailed study of their properties (e.g. metallicity, period distribution, period-amplitude relation, etc.) should be done. In fact, RR Lyr can exist for ages significantly younger than Milky Way halo GCs (e.g. Olszewski et al. 1987).

The earliest detections of a blue HB in dSph are those of Draco (Baade & Swope 1961) and Ursa Minor (van Agt 1967), so there is no question about the fact that at least some spheroidals do contain very old stars. Some clues on the presence of an old stellar population in *all* of the Local Group dwarf spheroidals came by recent results. Smith et al. (1998) and Bellazzini et al. (1999) provided evidence for an old/metal-poor population in the Sagittarius dwarf, and a wide-area search with the ESO New Technology Telescope led our group to the discovery of a significant old population in the Leo I dSph (Held et al. 2000a). Wide-field ESO 2.2m data are being analyzed with the aim of discovering and studying the Leo I RR Lyr population (Clementini et al. 2001, in preparation).

A special case is represented by a class of dwarf galaxies with characteristics intermediate between those of dwarf irregulars and dwarf spheroidals. Mateo (1998) lists 5 galaxies in this class: Phoenix, LGS3, Antlia, DDO 210 and Pegasus. Whether or not these are dIrr in the process of transforming into dSph, they are expected to contain an old population. Indeed, this is probably the case. A blue HB was revealed in Phoenix by Held et al. (1999), by selecting stars in the outer regions (outside 0.16 kpc from the center), while detection of a large number of candidate RR Lyrae variables has been reported by Held et al. (2000b). An old population has also been detected in DDO 210 (Tolstoy et al. 2000).

For star forming dwarf galaxies, the identification of the extended HB is more difficult, since it can be masked by an intermediate-age subgiant branch of ~ 1 Gyr (depending on the metallicity) or by the blue MS of the youngest populations. HST studies of the resolved populations in BCD's have been carried out for, among others, VII ZW 403 (Schulte-Ladbeck et al. 1999), I ZW 18 (Aloisi et al. 1999; Östlin 2000), UGC 6456 (Lynds et al. 1998) and SBS 1415+437 (Thuan et al. 1999). The first three all show populations of giants compatible with an age of several Gyr, but in all cases the HB is beyond the reach of the HST. Further circumstantial evidence of the existence of a cosmologically old population in BCDs is the existence of a system of globular clusters around Mrk 996 (Thuan et al. 1996), whose integrated colors are similar to those of NGC 6752 or ωCen.

Evidence for old populations is stronger in dwarf irregulars. RR Lyrae variables were detected in the field of IC 1613 (Saha et al. 1992), and there are also some hints of a blue HB in the CMD of its central regions (Cole et al. 1999), but it is confused among young main sequence stars. The HB is visible in the CMD of WLM presented in Rejkuba et al. (2000), for a region between disk and halo imaged with HST/STIS. A blue HB was also revealed in the WLM globular cluster (Hodge et al. 1999).

To summarize all these results, it appears that, when careful investigations are carried out, old populations invariably come out even in galaxies clearly dominated by young or intermediate age stars.

4. Summary

A real understanding of the evolution of nearby dwarfs requires data samples that are both deep and provide full coverage of the galaxy extension. When such samples are available, cosmologically old populations almost invariably turn up. It therefore appears that there has been a generalized primordial SF episode in any dwarf galaxy (besides the yet undetected population III). Successive evolution is much varied and not fully understood, although initial gas density, angular momentum and later mutual interactions all may have a role. It also appears that, when SF is not prematurely halted (e.g. by SNII explosions and removal of the ISM), a major intermediate age episode is often experienced by dSph. Later SF is also observed in some dSph, and recent SF becomes active or very active in dIrr and BCDs. The luminosity-weighted SFH for five Galactic dSph of Hernandez et al. (2000) seems to support this scenario.

In most cases galaxy evolution leads to more centrally concentrated younger populations, so apparently the gas contracts while forming new stars. Moreover, there is evidence that the central populations are also more metal-rich (for example in NGC 147: Han et al. 1997), so it is plausible that the gas becomes enriched by each SF burst. Small remaining amounts of gas are observed in some objects, that could have been released by the last generation of stars, and either retained (e.g. NGC 185 – Martínez-Delgado et al. 1999b) or blown out (e.g. Phoenix – Young & Lo 1997). The spatial distribution of stars becomes more and more irregular as younger and younger subpopulations are considered, a fact that resembles what is observed in more active dwarf irregular galaxies.

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