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Spatially resolved star formation histories in Local Group dwarf spheroidal galaxies

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Abstract. Spatially resolved star formation histories are presented for three dwarf spheroidal galaxies of the Local Group, namely Carina, Sculptor, and Sextans. All three galaxies show evidence for large morphological variations in their color-magnitude diagrams (CMD) at different distances from the centre. Radial trends in the stellar populations are presented and their analysis is combined with simulations based on synthetic stellar populations to disentangle the effects of age and metallicity on the spatial variations of the CMDs.

Key words. Galaxies: dwarf – Galaxies: evolution – Galaxies: stellar content – Local Group

1. Introduction

It is quite common for the different stellar populations of Local Group dwarf galaxies to exhibit different spatial distributions. Age and metallicity gradients in the stellar populations have been detected in almost all Local Group dwarf spheroidal galaxies (dSph) (e.g. see Saviane et al. 2000; Grebel 2000; Harbeck et al. 2001; Monelli et al. 2003). Usually the younger populations are more centrally concentrated than older ones.

In 1999, we started an observational campaign aimed at collecting photometry over large areas of the Milky Way satellites. Observations of Carina, Sculptor, Sextans, Leo I, and Fornax dSphs were collected using the Wide Field Imager at the MPG/ESO 2.2m telescope at La Silla, covering on average 0.75 square degrees per galaxy. A colour-magnitude diagram (CMD) simulation technique was applied to these data to derive their star formation histories (SFH) (Rizzi et al. 2002).

We give here preliminary quantitative estimates of the spatial variation of the SFHs. We show that the study of the gradients in CMD morphology, combined with CMD simulation techniques applied to large statistical samples, can help to disentangle the relative contribution of age and metallicity gradients in determining the CMD morphology variations across the galaxies.

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2. The Carina dwarf spheroidal galaxy

The SFH of the Carina dwarf spheroidal galaxy has been the subject of a number of previous studies (e.g. Mighell 1990; Smecker-Hane et al. 1994; Mighell 1997; Smecker-Hane et al. 1996; Hurley-Keller et al. 1998; Hernandez et al. 2000; Dolphin 2002), which revealed a complex picture, with at least three major star formation episodes at 2, 3-6, and 11-13 Gyr ago.

Wide field CMDs of this galaxy show strong morphological gradients (Harbeck et al. 2001; Monelli et al. 2003). In particular, the red clump (RC), formed by helium-burning stars younger than 10 Gyr, is significantly more populated in the inner regions with respect to other CMD features, such as the blue horizontal branch (older than 10 Gyr).

To study the spatial variation of the SFH, we applied our simulation technique to four elliptical regions whose boundaries are indicated in the labels of Fig. 1. The average SFH derived by us is in good agreement with previous results, but our analysis further shows that the evolution of the galaxy has been significantly different in the four radial zones. Moving from the centre toward the outer parts, the oldest episode of star formation becomes increasingly important with respect to the intermediate age episode. Besides, the epoch of the intermediate age episode becomes younger moving from the outer parts toward the centre. A small hint of star formation activity in the last Gyr can be traced in the inner region. The resulting picture is one in which star formation started roughly 14 Gyr ago in an extended region now traced by the distribution of the blue HB stars and RR Lyrae. Then, the star formation activity stopped, most likely because of the removal of gas via galactic winds induced by the first episode. Only the central parts of the galaxy were then able to start forming stars again. Similar trends are observed in a number of other galaxies. For Carina, the results presented here provide a reliable quantitative interpretation of the morphological variations of the CMD across the galaxy based on a scenario in which a strong *age gradient* is the major culprit.

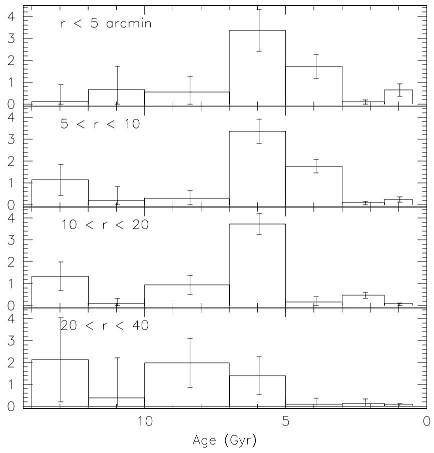

Fig. 1. Relative star formation history for the four selected regions of Carina. Rates are given normalized to the average star formation rate across the whole life of the galaxy, assumed to be $1.04 M_{\odot} yr^{-1}$, $6.21 M_{\odot} yr^{-1}$, $5.76 M_{\odot} yr^{-1}$, $2.06 M_{\odot} yr^{-1}$ from top to bottom panels.

3. The Sculptor dwarf spheroidal galaxy

Large morphological gradients across the whole extensions of the galaxy are observed in the Sculptor dwarf spheroidal galaxy, as well. A recent analysis by Harbeck et al. (2001) revealed that the red-HB stars are more centrally concentrated than those in the blue HB. A similar behaviour is observed in the RGB stars, with the redder giants being more centrally concentrated than the bluer RGB stars. Combining the information deriving from the presence of these two gradients, the conclusion is that a significant metallicity gradient must be present in this galaxy (a gradient predominantly in age would invert the direction of either the RGB or the HB gradients).

The question addressed in our study is whether this metallicity gradient (numerically estimated using the color gradient of the RGB) is able to explain the changes in CMD morphology. We used two different chemical evolution laws to derive the SFHs presented in Fig. 2 for the inner and outer regions. A small

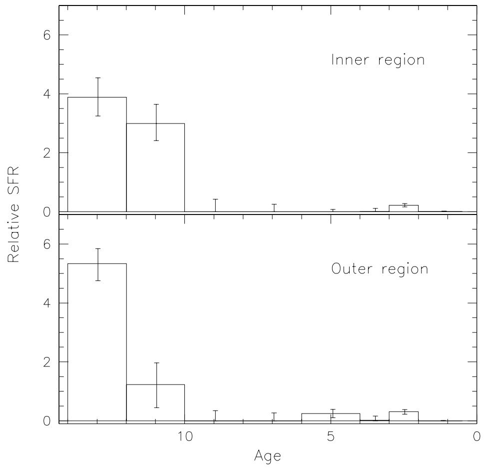

Fig. 2. Star formation history for the central region (*upper panel*) and the outer region (*lower panel*) of Sculptor. Rates are normalized to the lifetime average of $18.26 M_{\odot} yr^{-1}$ (inner region) and $15.70 M_{\odot} yr^{-1}$ (outer region).

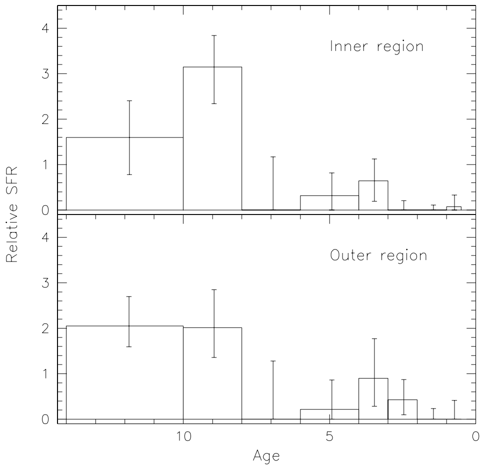

Fig. 3. Star formation history for the central region (*upper panel*) and the outer region (*lower panel*) of Sextans. Rates are normalized to the lifetime average of $3.16 M_{\odot} yr^{-1}$ (inner region) and $2.92 M_{\odot} yr^{-1}$ (outer region).

age gradient among the oldest stars is probably present, although such a conclusion is based on the ability of the isochrone set to reproduce the "second-parameter" effects. However, our analysis shows that most of the change in the CMD morphology is due to the presence of a small yet significant *metallicity gradient*. In fact, we repeated the simulation for the inner and outer parts by assuming no metallicity gradient. In that case, a star formation in the inner region continuing until 7-8 Gyr ago is found necessary to reproduce the gradient in HB morphology. Such an alternate scenario can easily be ruled out, however, because it fails to reproduce the observed RGB color gradient.

4. The Sextans dwarf spheroidal galaxy

Studies of the CMD morphology gradients in the Sextans dwarf spheroidal galaxy show properties very similar to those derived for Sculptor (Harbeck et al. 2001). Both the red HB and the red RGB stars are more centrally concentrated than blue-HB and blue-RGB stars, respectively, pointing at the presence of a significant metallicity gradient. Following an analysis similar to that used for Sculptor, we divided the galaxy into an inner and outer part and independently derived the SFH, assuming different metallicities for the two regions consistent with the RGB color gradient.

As in the previous case, we investigated the possible presence of a residual age gradient. The SFH for the inner and the outer regions are presented in Fig. 3. In this case, the inferred scenario is quite different. The inner regions shows a population of RC stars significantly larger than that present in the outer region. This implies that a sizeable age gradient is needed in addition to the metallicity gradient to explain the morphology of the HB. To further confirm the need for both an age and a metallicity gradient, we raised the inner metallicity to mimic the effect of age variations on the HB morphology, in the absence of an age gradient. To achieve this result, however, the metallicity had to be increased up to [Fe/H] ~ -1.5, which is inconsistent both with spectroscopic measurements and with the color of the RGB.

5. Conclusions

Our quantitative analysis of spatial variations in the color-magnitude diagrams of dwarf spheroidal galaxies suggests that in most cases neither age nor metallicity gradients alone can explain the range of population gradients found in the Local Group dwarfs. In particular, we have shown that the driving parameters controlling the CMD morphology variations are *age* in the case of Carina, *metallicity* in the case of Sculptor, and both *age and metallicity* in the case of Sextans. We also found that whenever age or metallicity gradients are observed, younger and higher metallicity stars are invariably more centrally concentrated than older or lower metallicity stars.

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