LUMINOUS RED STARS IN LOCAL GROUP DWARF ELLIPtical GALAXIES: AN INTERMEDIATE-AGE POPULATION? 1

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ABSTRACT
In this Letter, we show that the optically bright stars above the tip of the first red giant branch (TRGB) in the color-magnitude diagrams (CMDs) of nearby dwarf elliptical (dE) galaxies, commonly interpreted as indication of the existence of an intermediate-age population, may be, in certain circumstances, an artifact of observational effects on a pure old population system.

For this purpose, model CMDs have been computed, simulating the observational effects that can be found in different regions of a Local Group dE galaxy. The starting synthetic CMD represents a pure old system, with star formation extending only from 15 to 12 Gyr ago. Based on those model diagrams, we analyze the conclusions that a hypothetical ground-based observer might reach concerning the presence of a population of stars above the TRGB, which could be interpreted as an intermediate-age population, by using two age indicators extensively employed in the literature: (1) the bolometric magnitude at the tip of the asymptotic giant branch (AGB) phase and (2) the ratio of AGB to red giant branch (RGB) stars present in the CMD. Our analysis shows that, if observational effects are overlooked, then application of both methods would result in finding a fictitious intermediate-age population in the inner regions of the galaxy, where crowding is more severe.

Subject heading: Hertzsprung-Russel diagram—galaxies: elliptical and lenticular, cD — galaxies: stellar content — Local Group — stars: AGB and post-AGB

1. INTRODUCTION
Since Baade (1944) succeeded for the first time in resolving the brightest stars of the dwarf elliptical (dE) satellites of Andromeda, the elliptical galaxies remained as simple old stellar systems, with a stellar content resembling that of Galactic globular clusters (Population II). Nevertheless, data accumulated during the last decades, including the early discovery by Baade himself of blue stars in dE galaxies, provide evidence of varied, and in some cases complex, star formation histories (SFHs) among the Local Group (LG) dE galaxies (see Hodge 1989 and Freedman 1992a for recent reviews). Although there are several indications about the existence of intermediate-age population stars (age between 1 and 10 Gyr) in dE galaxies, the controversy over the existence of a substantial amount of intermediate-age star formation in the Andromeda companions (M32, NGC 205, NGC 147, NGC 185) remains open.

The study of the stellar content of dE galaxies by means of the analysis of the distribution of stars in the color-magnitude diagram (CMD) provides the most direct way of studying their SFH and testing whether they have formed stars for extended periods of time. Freedman (1989) resolved individual stars in M32 and found evidence of a range of metallicity in the stellar content as well as a significant population of stars more luminous than the tip of the red giant branch (TRGB). Freedman (1992a, 1992b) and Elston & Silva (1992) discussed several possibilities to explain this optically bright population (high-metallicity old stellar population, old long-period variables, old merged binaries, intermediate-age population), reaching the conclusion that these stars probably belong to an intermediate-age asymptotic giant branch (AGB) population. Since then, several studies on the resolved stellar population have found significant numbers of these bright stars in the central regions of NGC 205 (Lee 1996), NGC 185 (Lee, Freedman, & Madore 1993; Martínez-Delgado, Aparicio, & Gallart 1996), and NGC 147 (Davidge 1994). All these data suggest that the star formation in the Andromeda companions has occurred over an extended period of time and are also consistent with recent population synthesis results that point to the possibility that elliptical galaxies, dE galaxies in particular, may have a significant intermediate-age stellar population (see Grillmair et al. 1996).

Nevertheless, there is some evidence that the bright stars above the TRGB could be an artifact of the severe crowding in the central regions of these galaxies. Crowding is indeed among the most important observational limitations in the study of the stellar populations of these systems. The idea that these bright stars are just blends of two or more fainter stars is supported by the recent Hubble Space Telescope (HST) data of M32 (Grillmair et al. 1996), because the CMD of these high-resolution observations shows these bright stars much less. Careful analysis of the observational effects in NGC 185 (Martínez-Delgado et al. 1996) points to similar conclusions.

This Letter is devoted to analyzing the observational effects in the upper part of the RGB locus and to what extent conclusions about the presence of an intermediate-age population in dE galaxies are influenced by such effects. Our analysis is based on model CMDs. 2 The starting point is a synthetic diagram simulating a pure old population system.

1 Based on observations made with the William Herschel Telescope, operated on the island of La Palma by the Royal Greenwich Observatory in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias.

2 We use the same terms as Gallart et al. (1996), calling synthetic CMDs those resulting from a computer code, and model CMDs the same after simulation of observational effects.
Crowding effects determined from real ground-based observations of a dE galaxy (the data by Martínez-Delgado et al. 1996 for NGC 185 have been used) are simulated in this synthetic diagram. The resulting model diagrams are then analyzed using the same methodology widely applied to real dE galaxies to explore the conclusions that a hypothetical ground-based observer would reach concerning the existence of an intermediate-age population. Section 2 presents the model CMDs. Sections 3 and 4 discuss the effects of an intermediate-age population in the model CMDs based on the properties of the bright stars above the tip of the AGB (TAGB). In §5 the results are discussed, and a summary of the conclusions is given.

2. THE MODEL COLOR-MAGNITUDE DIAGRAMS

For the present analysis, a synthetic CMD with 20,000 stars brighter than $M_i = 0$ has been computed using the Padua stellar evolutionary library (Bertelli et al. 1994 and references therein), following the procedure described in Chiosi, Bertelli, & Bressan (1988) and Gallart et al. (1996). The empirical mass-loss relation for AGB stars by Vassiliadis & Wood (1993) has been used to model the AGB phase.

The adopted evolutionary scenario corresponds to a hypothetical representation of a dE galaxy in which the stars have formed at a constant rate from 15 to 12 Gyr ago and no more star formation has been produced since then. In other words, the synthetic CMD corresponds to a pure old system. The initial mass function (IMF) by Kroupa, Tout, & Gilmore (1993) for the solar neighborhood has been used, and a linear chemical enrichment law has been adopted starting in $Z_i = 0.0001$ at $T_i = 15$ Gyr and finishing in $Z_f = 0.004$ at $T_f = 12$ Gyr (time is expressed in terms of age, i.e., increasing toward the past and 0 being the present time).

What we want to study is how observational effects affect the quantity of stars located above the TRGB. By observational effects we mean crowding and any other observational limitation distorting or affecting the quality of the CMD. Observational effects are mainly of three kinds (Aparicio & Gallart 1995; Gallart et al. 1996): (1) loss of stars; (2) shifts in magnitudes and color indices and (3) increased external photometric errors. A Monte Carlo procedure is used to simulate properly all the observational effects, regardless of the nature of the source producing them. We use here the procedure explained in Aparicio & Gallart (1995) and in Gallart et al. (1996). The reader is referred to those papers for details. Suffice to say here that the method uses the observational effects on a large sample of artificial stars and that it avoids binning or any parametric or analytical modelization.

A crowding-trial table (see Aparicio & Gallart 1995) of 72,000 stars has been used to simulate the observational effects in the model CMDs. Crowding decreases in typical LG dE galaxies as distance to the center increases. To introduce this in our model diagrams, the crowding-trial tables obtained from three regions of NGC 185 (Martínez-Delgado et al. 1996) have been used: (1) inner region, $0'' \approx a < 118''$; (2) intermediate region, $118'' \leq a < 236''$; and (3) external region, $236'' \leq a < 360''$, where $a$ is the semimajor axis of the ellipses fitting the brightness distribution of NGC 185. It is not the aim of this Letter to interpret the stellar content of NGC 185. This galaxy is used only for convenience as a template of the observational effects that can be expected in LG dE galaxies. It is convenient to quantify somewhat the observational scenario that led to the three former crowding-trial tables. Pixel size, seeing, and surface brightness can be used as unbiased indication of that scenario. Pixel size used was $0''41$, and seeing was always approximately $0''9$. The average surface brightness of the inner part of NGC 185 is about $21.0$ m arcsec$^{-2}$, that of the intermediate region is about $23.5$ m arcsec$^{-2}$, and that of the external region is about $25.0$ m arcsec$^{-2}$ (Hodge 1963). From now on in this Letter, and only for convenience, the observational or crowding conditions of the inner part will be termed severe; those of the intermediate region, moderate; and those of the external region, fair. Figure 1 shows the initial synthetic CMD (a) and the models obtained after simulating in it the former three levels of crowding.

3. THE BOLOMETRIC LUMINOSITY FUNCTION OF ASYMPTOTIC GIANT BRANCH STARS

The bolometric luminosity function (LF) of AGB stars has been used as an indication of the presence of an intermediate-age stellar population in nearby dE galaxies. The luminosity of the TAGB can provide the minimum age of the intermediate-age stars and, therefore, evidence for episodes of star formation in the recent past of the galaxy's history. Table 1 shows the bolometric magnitudes derived for the TAGB for the Andromeda companion dE galaxies. The references from which the values have been taken are listed in the last column. These values have been considered a sign of the presence of a stellar population as young as just a few Gyr in these galaxies.

Let us focus now on the effect of crowding on the observed cutoff of the AGB bolometric LF. To make a quantitative analysis, the bolometric LF has been computed for the synthetic CMD and the three-model CMDs shown in Figure 1 counting stars redder than $(V-I) = 1.48$, as proposed by Reid & Mould (1984). Bolometric corrections were calculated adopting the calibration by Da Costa & Armandroff (1990).
Results are shown in Figure 2, which displays the bolometric LF of AGB stars for the models of fair, moderate, and severe crowding, as well as for the synthetic diagram. The latter would correspond to the actual LF, i.e., that which would be found in the absence of any observational effect.

The LF of the synthetic CMD cuts off at $M_{bol} = -4.1$. The interesting point is that the tip of the bolometric LF of model CMDs moves to brighter magnitudes when crowding effects are larger, i.e., toward the center of galaxies. For the severe crowding case, the LF extends at least to $M_{bol} = -4.8$, although a few stars are found at still brighter magnitudes ($M_{bol} \sim -5.2$). We adopt the first magnitude because the LF is zero between $-4.8$ and $-5.1$. For the fair and moderate crowding cases, the TAGB is located at $M_{bol} = -4.3$. These results are listed in Table 2: the first column identifies the model, referring to Figure 1; the second column gives the qualitative indication we are using here for the crowding level; and the third column contains the bolometric magnitude of the TAGB derived from the bolometric LF.

In summary, the simulation shows how observational effects can result in raising the luminosity of the TAGB. If they are not taken into account, a pure old stellar population could be interpreted as being much younger than it actually is. Interestingly, the cutoff of the bolometric LF under severe crowding conditions is quite similar to those obtained for real galaxies, listed in Table 1.

4. THE RELATIVE NUMBER OF ASYMPTOTIC GIANT BRANCH STARS

An alternative quantitative test for the presence of intermediate-age stars is derived from the observed ratio of the AGB to RGB stars in the CMD. The number of stars in these evolutionary phases is related to the amount of time that stars spend in them. This time is in turn a function of the mass and hence of the age. Therefore, the observed ratio can be compared with the prediction of stellar evolutionary theory for different ages to ascertain the presence of an intermediate-age population. The ratio of the number of stars 1 mag above and below the TRGB has been estimated to be $N_{AGB}/N_{RGB} = 0.17–0.25$ (Elston & Silva 1992) when a significant intermediate stellar population is present. The $N_{AGB}/N_{RGB}$ ratio determined from observations must be corrected to allow the fact that 20% of the stars in the 1 mag bin below the TRGB are actually AGBs (Lee 1977; Mould, Kristian, & Da Costa 1983).

The problem arising is that $N_{AGB}/N_{RGB}$ is very sensitive to observational effects. They affect this ratio in mainly three ways (see Aparicio & Gallart 1995): (1) loss of stars is more important at fainter magnitudes, and thus the number of RGB stars could be underestimated, thereby yielding larger

| Galaxy     | $M_{bol, TAGB}$ | Reference |
|------------|-----------------|-----------|
| M32        | ~5.0            | 1         |
| NGC 147    | ~5.0            | 2         |
| NGC 185    | ~5.0            | 3         |
| NGC 185    | ~4.9            | 4         |
| NGC 205    | ~5.7            | 5         |

References.— (1) Freedman 1989; (2) Davidge 1994; (3) Lee, Freedman, & Madore 1993; (4) Martínez-Delgado et al. 1996; (5) Lee 1996.

![Image](https://example.com/fig2.png)

Fig. 2.—Bolometric luminosity functions of bright, red stars obtained for the synthetic CMD and for the three model CMDs plotted in Fig. 1. The solid line and filled circles correspond to the LF of the synthetic diagram. The dashed line and open circles correspond to the LF of each model diagram, after the observational effects have been simulated. *Severe, moderate, and fair* refer to the observational effects (see the text for a quantitative definition of these terms).
crowding becomes more severe. In the \textit{fair} and \textit{moderate}
crowding cases, $N_{\text{AGB}}/N_{\text{RGB}}$ are respectively 0.09 and 0.14 and are hence still compatible with a system lacking a significant population of intermediate-age stars. But $N_{\text{AGB}}/N_{\text{RGB}} = 0.20$ for the \textit{severe} crowding case. This result would be interpreted as the galaxy having an important intermediate-age population. But this is again a deceit of observational effects.

5. CONCLUSIONS

Our analysis based on model CMDs of a pure old stellar population of age greater than 12 Gyr shows evidence that the luminous extended giant branch observed in many LG dE galaxies could be an artifact of observational effects. We have checked two methods extensively used to test the presence of intermediate-age stars in dE galaxies: the tip of the bolometric LF of AGB stars as an age indicator, and the ratio of the number of stars above and below the TRGB ($N_{\text{AGB}}/N_{\text{RGB}}$). Application of both methods to our simulated old stellar population results in finding a significant amount of stars resembling an intermediate-age population in regions where crowding is severe, as well as a false gradient of inferred age from the center to the external parts of galaxies. These effects are produced by the raising of the $N_{\text{AGB}}/N_{\text{RGB}}$ ratio simultaneously with the apparent TAGB moving up to brighter luminosities when crowding is severe.

In light of these results, the simple presence of bright stars populating the region of the CMD above the TRGB of nearby galaxies should not be considered as unambiguous proof of the existence of an intermediate-age population in these systems if observational effects are not under control. Furthermore, gradients in the number of these bright stars as a function of the Galactocentric distance could also be the result of changing crowding conditions, and care should be taken in interpreting the former as a gradient in the age of the stellar population. Careful analysis of the observational effects in each particular case is called for to test whether or not an intermediate-age population is actually present in the galaxy and what its distribution is. Unfortunately, observational effects are of random nature. They depend on many subtle factors difficult to take under control, and the simple knowledge of the surface brightness, the seeing, or the pixel sampling is probably not enough to characterize them. The only secure procedure is, in our opinion, performing Monte Carlo simulations using as a reference a crowding-trial table generated in the same frames under analysis and containing information for a large number of artificial stars, in order to minimize undesirable systematic effects on the simulations (see Aparicio & Gallart 1995).

The above reasoning shows that severe crowding is a sufficient condition to find a large number of bright stars over the TRGB. But it is still possible that dE galaxies do have a significant intermediate-age population and that some of the bright stars over the TRGB are actually intermediate-age stars. However, indications exist that the intermediate-age population might best be looked for in the AGB red tails appearing in many CMDs of dE galaxies.

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TABLE 2

| Figure | Crowding | $M_{\text{AGB}}/N_{\text{AGB}}$ | $N_{\text{AGB}}/N_{\text{RGB}}$ |
|--------|----------|-------------------------------|-------------------------------|
| a      | None     | $-4.1$                        | 0.08                          |
| b      | Fair     | $-4.3$                        | 0.09                          |
| c      | Moderate | $-4.3$                        | 0.14                          |
| d      | Severe   | $-4.8$                        | 0.20                          |