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Gas-rich vs. gas-poor: LCID insights on the origin of different dwarf galaxy types

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Abstract. In this paper, we discuss on the origin of different dwarf galaxy types, and the possible evolutionary links among them, based on full star formation histories (SFH) obtained through the Local Cosmology from Isolated Dwarfs (LCID) project. In the case of the dIrr and dT galaxies, these are the first time that full SFHs, describing the early episodes of star formation with fine time resolution ($\simeq$ 2 Gyr), have been obtained. The LCID results show that the early SFH of dIrr galaxies is fundamentally different from that of the studied dT and dSph, in that they haven't experienced a strong early burst, followed by a very mild or nil star formation activity. Instead, they started forming stars slowly and continued similarly over most of their lifetimes. Their SFH is similar to that of the (minority) dSph satellites of the Milky Way that have important amounts of intermediate-age population (namely, Carina, Fornax and Leo I). Based on the derived SFHs, we hypothesize that there are two fundamental types of dwarf galaxies: one type started their evolution vigorously forming stars, but their period of star formation activity has been short lived (few Gyr). Another type has had a mild star formation activity at early times, and has continued forming stars to the present time (or almost). The current availability of gas or lack thereof doesnt necessarily correlate with these two globally different evolutionary paths.

Key words. galaxies: dwarf; galaxies: evolution; galaxies: stellar content

1. Introduction

The origin of the different dwarf galaxy types, and the possible evolutionary links among them is the subject of a substantial amount of research and debate. Different dwarf galaxy types (dSph, dIrr, and the so-called transition types, dT) share some similarities but also show some differences (Tolstoy et al. 2009), which can both inform on their possibly (partially) linked evolution. On one hand, they obey the same mass-metallicity relation (Kirby et al. 2013), follow similar relationships between central velocity dispersion, σ_c, core radius, r_c, central surface brightness, μ_c and absolute magnitude (Kormendy 1985; Kormendy & Bender 2012), and all *can* be fitted by exponential profiles (Lin & Faber 1983). On the other hand, most dIrr rotate while most dSph do not, they have different gas content, and they are preferentially found in different environments, the dSph usually inhabiting denser locations –the so-called morphology-density relation (McConnachie 2012).

Thanks to their proximity, the first dwarf galaxies which stellar populations were characterized in detail using color-magnitude diagrams (CMDs) reaching the oldest main sequence turnoffs (oMSTO) were the dSph satellites of the Milky Way. While most of them (UMi, Draco, Sextans, Scl, Leo II, plus most ultra-faint dwarfs) are predominantly old, some (Fornax, Carina and Leo I) host an important amount of intermediate-age population. Similarly deep CMDs for the more distant, isolated galaxies in the Local Group, which include a variety of morphological types, were available only later, when the ACS on board HST became operative (e.g. Monelli et al. 2010b). Before that, and through reliable indicators of the presence of an old population such as RR Lyrae variable stars, a bona-fide old population was routinely found in any dwarf galaxy it was searched for (e.g. Clementini et al. 2003; Gallart et al. 2004).

At early times, therefore, dwarfs of all types must have been star forming galaxies, similar to today's dIrr. Then, at some point, *some* lost their gas. The possible transformation from a dIrr to a dSph galaxy has been explored by many authors, and it is in fact a common implicit assumption: it has even been defined a "transition class" (dIrr/dSph, or dT) of dwarf galaxies! Even if there are plausible mechanisms able to transform a disk like, gas-rich, star forming dwarf galaxy into a pressure supported, gas-poor, fossil dSph-like galaxy, a question about the origin of these galaxy types (Skillman & Bender 1995) remains: are dSph and dIrr galaxies different by *nature* (i.e. were they *born* different?), or have they become different by *nurture*?

Most (mostly theoretical) research that has addressed the question of the possible morphological transformation from a dIrr to a dSph galaxy has focused on answering the following question: how did dSph galaxies lose their gas? Dekel & Silk (1986); Mac Low & Ferrara (1999); Ferrara & Tolstoy (2000); Salvadori et al. (2008); Sawala et al. (2010), among others, have explored the effects of internal feedback and the efficiency of gas ejection through star formation. In general, models indicate that internal feedback could only be able to totally remove the gas in an extremely low-mass (few 10^6 $M_\odot$ or baryonic mass) dwarf galaxy. The idea that environmental, external processes must play an important role is supported by the observed morphology-density relation. Possible external processes include tidal stirring, which has been shown to be able to transform infalling disky dwarfs into dSph-like objects in several Gyr (Mayer et al. 2001; Klimentowski et al. 2009). When combined with gas stripping, it can result in very low gas fractions (Pasetto et al. 2003; Mayer et al. 2006). These processes involve, in general, interaction of the dwarf galaxy with a massive central halo, like that of the Milky Way, and leave open the question of how isolated dSph like Cetus and Tucana have formed (possible scenarios have been discussed by Sales et al. 2007; D'Onghia et al. 2009; Kazantzidis et al. 2011a). Finally, inclusion of the effects of an ionizing UV background have been shown to increase the efficiency of gas loss due to both internal feedback and stripping (Sawala et al. 2010; Mayer 2010).

The question of whether dIrr and dSph galaxies are different 'by nature' is a difficult one, since its answer requires obtaining information on their very early evolution. The early SFHs of dwarf galaxies can provide key insight, and can be obtained reliably and in detail for the nearest Local Group galaxies. If the *nurture* hypothesis is correct, that is, if accretion onto a big halo, or interaction with another dwarf galaxy, was responsible for stopping star formation in a gas-rich dwarf that otherwise would have evolved to a "normal" dIrr galaxy, then one would expect to see, in the SFHs both i) a similar early SFH for dSph and dIrr; and ii) a variety of durations of the star formation period, or different ages for the end of star formation, in today's dSphs. In this paper, we will discuss available evidence on the early SFH of dwarf galaxies of different morphological types in different environments, in order to shed light into the *nature vs. nurture* dilemma in the case of Local Group dwarf galaxies.

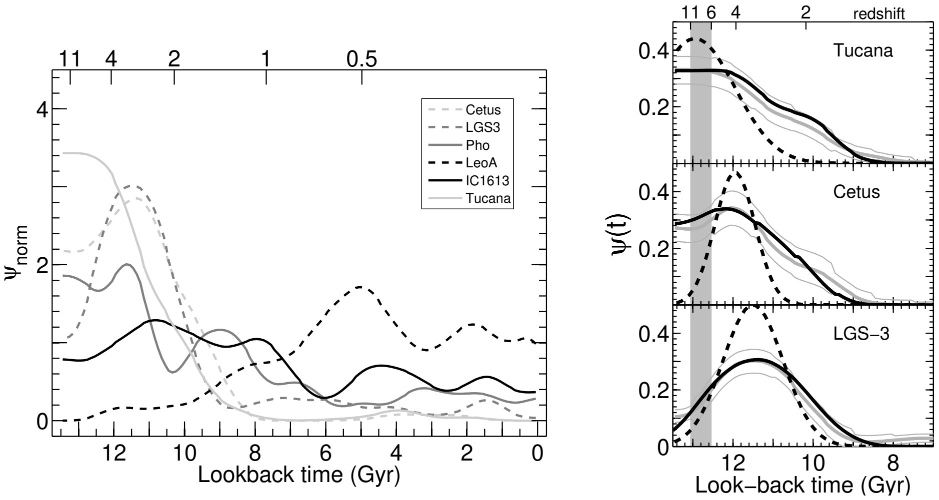

Fig. 1. Left Panel: Normalized star formation rate as a function of look-back time, for the six LCID galaxies. Error bars have been omitted for clarity (see error bars in the right panel for three of the galaxies). Right panel: Some results of the tests performed with mock stellar populations. Input Ψ(t) (dashed line) for the mock stellar population that yielded a recovered Ψ(t) (solid line) closely matching the solution Ψ(t) for each galaxy (gray line). The shaded area indicates the duration of the reionization epoch.

2. Hints from LCID SFHs

The Local Cosmology from Isolated dwarfs (LCID)[1] project is a combination of three HST programs (two using the ACS: GO 10505, P.I. Gallart; GO 10590, P.I. Cole with a total of 113 awarded orbits, and one using the WFPC2, GO 8706, P.I. Aparicio, 18 orbits). CMDs reaching the oMSTOs were obtained for six isolated Local Group dwarf galaxies (two dIrr, IC1613 and Leo A; two dIrr/dSph, LGS3 and Phoenix; and two isolated dSph in the Local Group, Cetus and Tucana). Note that these were the first CMDs reaching the oMSTO for dwarf galaxies of the dIrr and dT types.

Complete SFHs were derived for all the galaxies in the sample, through comparison with synthetic CMDs. Figure 1 (left panel) displays the SFHs obtained with IAC-star, IAC-pop and Minniac (Aparicio & Gallart 2004; Aparicio & Hidalgo 2009; Hidalgo et al. 2011). The two dSph, Cetus and Tucana share the common characteristic of having formed over 90% of their stars before 10 Gyr ago, and host no stars younger than 8-9 Gyr old (Monelli et al. 2010b,a). The SFHs of the two dT galaxies (Hidalgo et al. 2009, 2011) are remarkably similar to those of the dSphs: they formed over 80% of their stellar mass before 9 Gyr ago. The only difference with dSphs is that they maintained a residual amount of star formation during the rest of their evolution. In contrast, the SFHs of the two dIrr galaxies are remarkably different: they don't present a dominant early burst of star formation, and they formed an important fraction of their stars at intermediate and young ages (over 60% of their stars formed *after* 9 Gyr ago, Cole et al. 2007; Skillman et al. 2014). Their SFHs are similar to those of the larger irregulars LMC and SMC (e.g., Noël et al. 2009; Meschin et al. 2014), and also similar to the extremely small star forming galaxy Leo T (Clementini et al. 2012; Weisz et al. 2012).

The SFHs of the LCID galaxies, therefore, provide some indication that dIrr and dSph galaxies may be different *by nature*, since their early SFHs appear to be substantially different. This is particularly true in the case of Leo A, which contains a very small amount of RR Lyrae stars (Bernard et al. 2013), which are

[1] http://www.iac.es/project/LCID/

considered bona-fide tracers of a population older than $\simeq$ 10 Gyr. If Leo A had lost its gas $\sim$9 Gyr ago, and had no subsequent star formation, it would be an extremely low mass, low surface brightness dwarf today.

In the introduction we also argued that, if the *nurture* hypothesis was correct, then one would expect to see a variety of durations of the star formation period, or different ages for the end of star formation in today's dSphs, which would depend on when they experienced an interaction with the environment leading to total or substantial gas removal, and therefore, on their orbits.

Taken at face value, the LCID SFHs for dSph and dT dwarf galaxies indicate similar epochs (within $\simeq$ 1 Gyr) for the end of the star formation in the four galaxies (Figure 1, left panel). Through careful tests with mock stellar populations (Figure 1, right panel), we have shown (Monelli et al. 2010a; Hidalgo et al. 2011) that, despite the fact that observational errors tend to broaden the features measured in the SFH, particularly at old ages, we can confidently conclude that all three galaxies (Cetus, Tucana and LGS3) had formed the bulk of their stars by 11 Gyr ago, well beyond the end of the epoch of reionization ($z \simeq 6$, i.e. $\simeq$12.5 Gyr ago; Becker et al. 2001), and then, shut off at remarkably similar epochs. One of the main conclusions of LCID is, in fact, that the SFHs of the LCID galaxies did not show any feature directly related to the reionization epoch, and thus, that reionization, by itself, can be ruled out as the cause of the end of star formation in these galaxies (Monelli et al. 2010a,b; Hidalgo et al. 2011).

3. Comparing with the Milky Way dSph satellites

The SFHs of LCID galaxies have been determined in an homogeneous way, and therefore, differential age measurements are meaningful and reliable. Quantitative SFHs have also been derived for a number of dSph satellites of the Milky Way (Aparicio et al. 2001; Carrera et al. 2002; Dolphin 2002; Lee et al. 2009; Weisz et al. 2011; de Boer et al. 2012; del Pino et al. 2013). Even though they are not homogeneous among them or with LCID SFHs, the published results generally agree on the finding that all Milky Way satellites *that are predominantly old* have formed most of their stars before $\simeq$ 10 Gyr ago. Among the more distant dSph galaxies, Fornax, Leo I and Carina do show a substantial amount of intermediate-age and young population: the peak in their SFHs took place at ages younger than 10 Gyr, and most star formation occurred at intermediate-ages (Hurley-Keller et al. 1998; Gallart et al. 1999; Rizzi et al. 2003; del Pino et al. 2013). These findings have been usually described as 'a large variety in dSph SFHs' (e.g. Grebel & Gallagher 2004), but the SFHs of LCID dSph and dT add arguments toward some homogeneity in the SFHs, and particularly, in the age of the end of the star formation activity in *most* well studied dSph galaxies.

4. Can a dSph-like galaxy be formed in isolation?

The possibility that environment has played a determinant role in the case of the LCID isolated dSph and dT cannot be totally ruled out. The radial velocities of Tucana and Cetus (Lewis et al. 2007; Fraternali et al. 2009; Kirby et al. 2014) are not incompatible with a passage through the inner parts of the Local Group in their very early evolution, in such a way that tidal stirring could have affected them. It has been shown that, in the case of disk dwarfs with shallow dark matter density profiles, the transformation into a dSph-like object can occur even after a single pericenter passage (Kazantzidis et al. 2013). Other possibilities, such as the merging of two disky dwarfs (Kazantzidis et al. 2011b), or that they could be the lighter members of a satellite pair, ejected to a highly energetic orbit (Sales et al. 2007) have been proposed. However, it seems contrived that galaxies with such similar properties as, for example, Tucana and Sculptor may be the product of very different evolutionary histories.

In fact, a number of different models are capable of producing a dSph-like galaxy in isolation (Carraro et al. 2001; Valcke et al. 2008; Salvadori et al. 2008; Revaz et al. 2009;

Sawala et al. 2010, 2012), even though a total removal, or blow-out of the gas by means of feedback processes only is difficult, except for very small galaxies (Mac Low & Ferrara 1999; Revaz & Jablonka 2012).

5. Conclusions

In this paper, we have explored existing evidence, both observational and theoretical, providing insight on the origin of the different dwarf galaxy types. The ACS camera on board HST has enabled obtaining, for the first time, CMDs reaching the oMSTO for a number of isolated dwarf galaxies. From them, accurate SFHs, including those for the very ancient star forming epochs, have been derived. Out of seven galaxies observed with the HST with the required depth, three are dIrr galaxies, IC1613, Leo A and Leo T (Cole et al. 2007; Clementini et al. 2012; Weisz et al. 2012; Skillman et al. 2014), two are dT, Phoenix and LGS3 (Hidalgo et al. 2009, 2011), and two are the isolated dSph Cetus and Tucana (Monelli et al. 2010a,b). We have shown that the early SFH of the dIrr galaxies is fundamentally different from that of the other two types, in that they havent experienced a strong early burst, followed by a very mild or nil star formation activity. Instead, they start forming stars slowly and continue similarly over most of their lifetimes. The isolated dT and dSph types have very similar SFHs among them, and compare to the *old* Milky Way dSph (Ursa Minor, Draco, Sextans, Sculptor, LeoII). The remaining Milky Way 'classical' dSphs (Fornax, Carina and Leo I) are dominated by intermediate-age stellar populations, and don't have a strong early star formation episode. Except for the fact that they lack gas and current star formation, their SFHs are more similar to those of the well studied dIrr galaxies than to those of the rest of dSph and dT.

We have also noted that the *old* dSph galaxies have all a very short star forming period, and have ended star formation at a very similar epoch, within 1-2 Gyr. If the accretion onto a big halo or the merging or interaction with another dwarf galaxy were the main responsible of this truncation of their star formation, one would in principle expect a larger variety of epochs of end of star formation, depending on the infall time.

These results point to the existence of differences in *nature* between dwarf galaxy types. We hypothesize that there is one type of dwarf galaxies that have started their evolution with a vigorous star forming event, but their period of star formation activity has been short (few Gyr). Another type of dwarf galaxy has had a mild star formation activity at early times, and has continued forming stars to the present time (or almost). The current availability of gas or lack thereof doesn't necessarily correlate with these two globally different evolutionary paths: the dSphs that have important amounts of intermediate-age and young population have SFHs that resemble those of dIrr. They just were "accidentally" classified as dSph because of their lack of gas and current star formation.

In this paper we have, purposely, taken a extreme vantage point to discuss dwarf galaxy evolution; one in which environmental effects play a secondary role: we have argued that the early SFH of dIrr and dSph/dT galaxies is different, and that the formation of dSph-like objects can be understood without necessarily invoking the effects of interactions. Of course, the models involving environmental effects to explain the formation of dSph galaxies and the morphology-density relation are successful in explaining the observations and involve strong and well motivated physical arguments. In our scenario, they are certain to play a key role in the final removal of gas in today's gas free galaxies. We are suggesting, however, that an avenue paying full attention to the initial conditions of dwarf galaxies should be further explored from the theoretical point of view.

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