Near-Field Cosmology with Dwarf Elliptical Galaxies
Proceedings IAU Colloquium No. 198, 2005
H. Jerjen and B. Binggeli, eds.

doi:10.1017/S1743921305003595

Chemodynamical evolution of dwarf elliptical galaxies

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Abstract. The growing number of observational details questions the standard picture of the evolution of dwarf ellipticals and argues for a complex evolution dominateded by environmental effects. Here we compile some standard and most recent observational issues and discuss the results of simple chemo-dynamical models in comparison with observations. The necessity of further model developments are justified and prospected.

Keywords. galaxies: dwarf, galaxies: ellipticals, galaxies: evolution

1. Introduction

Dwarf elliptical galaxies (dEs) are the most common galaxies in the local universe (see e.g. Ferguson & Binggeli (1994) for review). They are frequently cited as examples of "stellar fossil" systems in which the bulk of their star formation (SF) occurred in the past. Most known dEs are located in regions with high galaxy densities, and dEs are the most numerous type of galaxy in nearby galaxy clusters, including Coma (Thompson & Gregory 1993, Secker, Haris, & Plummer 1997), Fornax (Caldwell 1987, Rakos *et al.* 2001), Virgo (e.g., Binggeli, Sandage, & Tammann 1985), and recently Perseus (Conselice, Gallagher, & Wyse 2003a). Cluster dEs are usually almost free of interstellar gas and contain few young stars (Bothun *et al.* 1985).

In trying to understand the dE galaxies, we must also consider several regularities in their structures. A positive correlation is known since years to exist in dEs between optical surface brightness and luminosity (e.g., Binggeli *et al.* 1984, Wirth & Gallagher 1984, Kormendy 1985) and between luminosity and stellar velocity dispersion. The latter parameter also correlates with metallicity (e.g., Dekel & Silk 1986, Petersen & Caldwell 1993). Furthermore dE galaxies often have flattened profiles but are mostly kinematically supported by their stellar velocity dispersions rather than by rotation (Bender, Paquet, & Nieto 1991).

The combination of low gas mass fractions and moderate-to-low stellar metallicities in dE and the related dwarf spheroidal (dSph) galaxies, the least luminous and least massive dEs, is a key feature of this class (Grebel, Gallagher, & Harbeck 2003). In galaxies where gas is depleted by SF stellar abundances are predicted to be near the solar value. The lower abundances of stars in dEs (about 0.1 of solar or less; Gallagher & Wyse 1994, Cellone & Forte 1996, Han *et al.* 1997) suggest that extensive gas loss occurred during their evolution and SF ceased due to a lack of raw materials rather than exhaustion of the gas supply through SF. Galactic winds are therefore a hallmark of modern models for dE galaxies, starting from the basic consideration by Larson (1974) and continued with the studies by Dekel & Silk (1986) and Vader (1986) and they are commonly assumed to have cleaned out dE galaxies soon after their formation. MacLow & Ferrara (1999) have, however, demonstrated that gas exhaustion by means of galactic winds even in low-mass systems requires a dark-to-baryonic matter ratio much smaller than attributed to DGs in the classical picture (see e.g. Mateo 1998).

A variety of observations are now available which bring this standard picture for the evolution of dE galaxies into question. Recent HI studies of Virgo cluster dEs (Conselice, Gallagher, & Wyse 2003b) and also those of the Fornax cluster (see e.g. Michielsen *et al.* 2004) have unveiled that a small but significant fraction of them contains gas, has experienced recent SF, and can be argued from internal kinematics and cluster distribution data to form an infalling class of different types of gas-rich galaxies in the state of morphological transformation. Recent findings of a significant fraction of rotationally supported dEs in the Virgo cluster (van Zee, Skillman, & Haynes 2004) also supports the possibility of morphological transformation from dwarf irregular galaxies to dEs thru gas exhaustion. In addition, ultra-compact DGs have been detected and classified as a new type of cluster dEs that differ by their intrinsic structure and brightness (Phillipps *et al.* 2001). Nevertheless, if the 'threshing' scenario holds to produce this type of DG they stem from normal dEs by transformation in cluster environments (De Propris, Phillips, & Drinwater 2005). Another plausible mechanism to produce them from tidal tail compact star clusters has been elaborated (see e.g. Kroupa, this conference).

The situation in Local Group dEs is similarly complicated, with NGC 185 and NGC 205 both being well known to have cool interstellar gas and trace young stellar populations, while NGC 147 contains neither an ISM nor young stars (Young & Lo 1997). Furthermore, high-quality color-magnitude diagrams for nearby dSph and dE galaxies often reveal substantial intermediate age stellar populations (Han *et al.* 1997, Martínez-Delgado & Aparicio 1998, Hurley-Keller, Mateo, Nemec 1998, Stetson, Hesser, & Smecker-Hane 1998, Ikuta & Arimoto 2002, Tolstoy *et al.* 2003) which means that small spheroidal galaxies did not form all their stars in single events near the time of giant galaxy formation. This agrees with the findings of large internal metallicity dispersions in local dSphs from high-resolution stellar spectra (Shetrone, Cote, & Sargent 2001, Tolstoy *et al.* 2003). A second and possibly related line of evidence has come from deep surveys of faint galaxies. The frequent presence of compact, narrow emission line galaxies in moderate redshift galaxy samples (Koo *et al.* 1995, Guzman *et al.* 1996) leads naturally to the suggestion that such galaxies are small systems experiencing major starburst events perhaps 5–8 Gyr before the present, and likely predecessors of the current dE systems (Babul & Rees 1992, Babul & Ferguson 1996).

A further intriguing fact that requires explanation within the framework of evolutionary scenarios is that in the Carina dSph and in a few others almost no metal enrichment is perceivible from stellar spectra taken with UVES (Tolstoy *et al.* 2003) although SF has occurred in several distinct epochs with clear interrupts. More extremely, the $[\alpha/H]$ values in Carina and Sculptur drop significantly below zero.

Another interesting question concerns the structural discontinuity between dEs and giant Es (Kormendy 1985). This is e.g. still confirmed by De Rijcke *et al.* (2005) but questioned by Graham (see article in this volume).

All these new results have changed our impression that dEs can be easily understood from their structure and represent a simple and homogeneous evolutionary scenario. On the contrary, they gave reason for this conference and will do for a lot more in the future because they provide strong motivations for a reexamination of theoretical models for the evolution of these small spheroidal galaxies.

2. Evolutionary Models of dEs

A variety of evolutionary models for dEs have been performed by several groups. They are focussing on different aims and, by this, are constrained accordingly to the addressed questions.

For isolated dEs e.g. numerical models have been presented by several authors (Spaans & Norman 1997, Mori, Yoshii, & Nomoto 1999, Lia, Carraro, & Salucci 2000, Carraro, Chiosi, & Girardi 2001, Pasetto, Chiosi, & Carraro 2003, Hensler, Theis, & Gallagher 2004). Since dEs show clear concentrations towards galaxy cluster centers, another important perspective is the effect of the cluster gas environment. Hydrodynamical simulations of a moving gas-rich dwarf galaxy through cluster gas (IGM) in order to study the ram-pressure stripping (RPS) with particular emphasis on dEs has been undertaken by another group of authors (Murakami & Babul 1999, Mori & Burkert 2000, Marcolini, Brighenti, & D'Ercole 2003). All those models agree that for low-mass systems (around 10^9 $M_\odot$ and below) the whole gas component can be stripped efficiently by the a normal IGM. Arecent systematic study (Roediger & Hensler 2005) of the RPS phenomenon has shown that even in the outskirts of galaxy clusters infalling galaxies suffer gas stripping. Mayer *et al.* (see this conference) successfully cleaned off the Milky Way dSphs by this RPS effect acting by the hot galactic halo gas but applied a yet implausibly high gas density. Nevertheless, it is still unsolved to what extent dense cool gas can survive a RPS epoch due to the time-limited momentum transfer from the wind and whether the interstellar clouds are even compressed and stabilized instead of being swept-up and/or evaporated. This same uncertainty holds for galactic winds (MacLow & Ferrara 1999, Murakami & Babul 1999, Marcolini, Brighenti, & D'Ercole 2004). The gas expansion by winds facilitates the RPS effect because of lowering its gas binding energy.

In present cosmological scenarios small galaxies ought to be formed as the oldest objects if cold dark matter (CDM) fluctuations harbor sufficient baryonic substrate. Lateron larger galaxies are assembled by hierarchical accumulation of smaller units. Since the gas must cool and, subsequently, collapse so that those condensations led to enhanced SF such scenarios would expect a very early epoch of dwarf galaxy (DG) formation and their early appearance in the universe. This, however, stands in conflict with the abovementioned observations that they seem to have formed at around $z = 1$ and that even the dSphs with old stellar populations show evidence for SF extending over several Gyr. This obvious inconsistency is not yet resolved, but could be due to the impact of the intergalactic UV radiation field that slowed the evolution of DG formation (e.g., Kepner, Babul, & Spergel 1997, Barkana & Loeb 1999, Grebel & Gallagher 2004).

There is, however, at present still a lack of global models that account self-consistently for all the different processes in scope to be affecting the evolution of dEs. This means that calculations must combine a large spatial range with a high complexity of spatially resolved processes and with different timescales, a yet unfeasible task.

Progress, however, also requires a detailed and appropriate despription of the coexisting gas phases, their mutual interactions and plasmaphysical processes, and of the stellar component, its formation, death and energetic coupling to the multi-phase interstellar medium (ISM). Such basic recipes are combined in the chemo-dynamical prescription of galaxy evolution (see reviews by Hensler 2000, Hensler 2003 and also Samland, Hensler, & Theis 1997).

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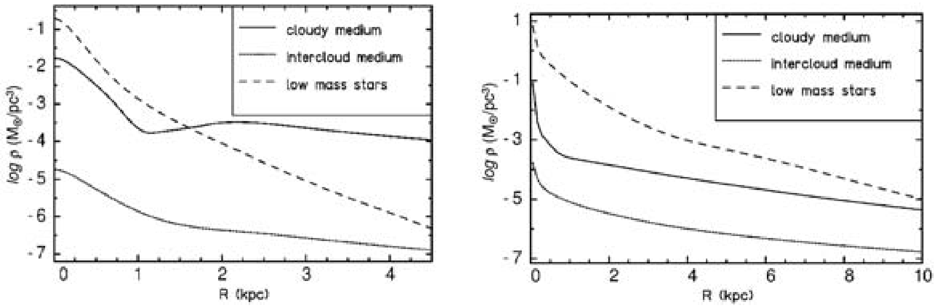

Figure 1. Radial density distribution of cloudy and intercloud medium as well as low-mass stars after an age of 10 Gyr of the 10^9 $M_{\odot}$, 1σ model (*left*) and the 10^{10} $M_{\odot}$, 3σ model (*right*) (from HTG).

3. Chemodynamical models

In a series of papers we have applied the chemodynamical treatment to various galaxy types. These models range from 1d to 3d Since chemo-dynamical simulations are numerically highly complicated and not always numerically stable because of the various competing timescales and large discontinuities it took years from the principle formulation until the first set of models. And even these could only be constructed one-dimensionally like for non-rotating massive galaxies (Theis *et al.* 1992), for dwarf ellipticals (Hensler, Theis, & Gallagher 2004, hereafter: HTG) and for the vertical settling of the galactic disk (Burkert, Truran, & Hensler 1992). The next step to 2d models was rough. At first again we started with more massive disk galaxies (Samland & Hensler 1996) and in particular the MWG (Samland, Hensler, & Theis 1997) and moved to dwarf irregular galaxies (dIrrs) where in a series of papers various aspects have been illuminated (Hensler, Rieschick, & Köppen 1999, Hensler & Rieschick 2002, Rieschick & Hensler 2000, Rieschick & Hensler 2004). In this review I wish to refer to recently published simple 1d chemodynamical models of dEs by us (HTG). The motivation of these studies was to extent the models of massive non-rotating galaxies, plausibly giant Es, to the low-mass regime.

Since our aim here is to consider isolated entities as a first chemo-dynamical approach to DG evolution, i.e. systems unperturbed by external effects and without inherently implied absolute timescales, on the one hand, our model evolution can be considered to start after the delayed recombination of the embedded gas. Moreover, the existence of a DM halo is expected to accelerate the collapse and to lead to enhanced SF (Mori, Yoshii, & Nomoto 1999). If the local dSph system is produced in a merger event of our Milky Way, an attractive scenario in order to understand the pecularities of this system, they should by free of DM.

HTG have presented 1d models of diffuse dEs in the mass range from 10^9 to 10^{10} $M_{\odot}$ that collapse from 1σ and 3σ cosmological perturbations consisting only of baryonic matter. These highly idealized models of dE galaxies fit already qualitatively quite well to several key observations and are briefly summarized here (For further information and discussion of the results see HTG.):

1) These models experience rapid compression of their initial gas content and undergo violent initial starbursts. As anticipated by earlier models, such as Dekel & Silk (1986), this leads to extensive gas loss and a re-expansion of the remaining stellar system. However, due to the inclusion of a multi-phase representation of the ISM in our models, gas ejection is not complete and some of the model galaxies can sustain SF for extended

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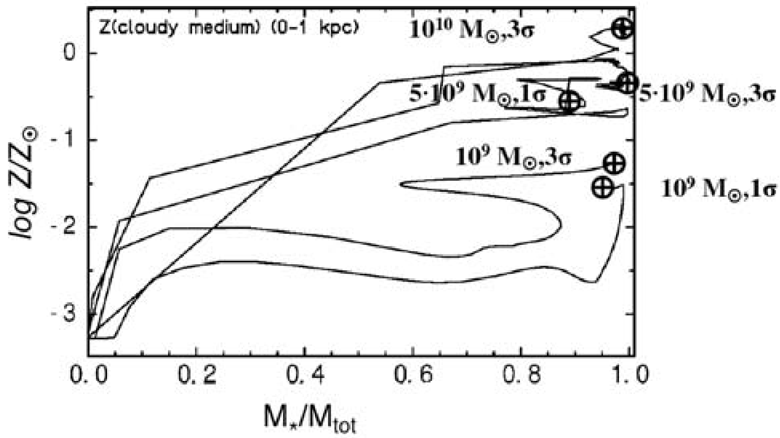

Figure 2. Evolutionary tracks of the total metallicity Z of the cloudy medium with the stellar mass fraction for the inner 1 kpc radius after 10 Gyr of the 5 models (labelled) presented in HTG. The final state is marked by the plus.

time periods (>5 Gyr) after the initial collapse. The initial behaviour is the same in the presence of a DM halo, while the dominance of the DM potential on larger scale canmore easily capture the expanding gas.
2) They predict that dE galaxies will contain a range of stellar ages and stellar metallicities, and that dEs do not have to be gas-free systems, what is consistent with some observations.
3) A 10^9 $M_\odot$ galaxy suffers a dominant single SF event within the first 200 Myrs in which 10% of the gas are converted into stars but 80% gas are lost instantaneously, driven by SNeII. The key issue is that the stellar component dominates the central range of 1 kpc by 90% of the included mass and drops exponentially, while the remaining gas extends radially over more than 5 kpc with almost constant density (see Fig. 1). Such gaseous halo is ideally exposed to tidal stripping as well as RPS.
4) In the mass range of $5{\times}10^9$ $M_\odot$ the chemo-dynamical models separate in their evolution: the 1σ model ceases to form stars after a single initial peak as a consequence of the lower gas density where self-regulation acts efficiently. More gas remains available than in the 3σ model that consumes most of its gas in an initial rapid starburst but only some gas remains gravitationally bound and supports oscillating SF on a 300 Myr timescale. These details of the SF history would be difficult to observe in present-day DGs but the model allows to understand a SF history stretch over billion years even with low gas content but SF fluctuations.
5) A 1σ initial density fluctuation for $10^{10} M_\odot$ starts with an initial collapse at a low-level SF followed by a violent initial starburst. A peak SF rate of about 100 $M_\odot$ yr^{-1} is sustained for about 60 Myr and declines below 10 $M_\odot$ yr^{-1} 200 Myr after the beginning of the starburst. This active phase is followed by a 3 Gyr plateau of SF oscillations between 0.01 and 1 $M_\odot$ yr^{-1}. At an age of almost 6 Gyr the system is seriously depleted in CM gas. Thus a key feature of these models is that the bulk of the stars in dE galaxies should have ages of $\geqslant$8 Gyr for galaxies which formed 10 Gyr ago. The radial density distribution of the long-living low-mass stars (fig. 1) traces the dissipational evolution of the collapse and the radial brightness has not developed a single exponential profile.
6) The stellar metallicities increase with higher masses as is observed (see Fig. 2);

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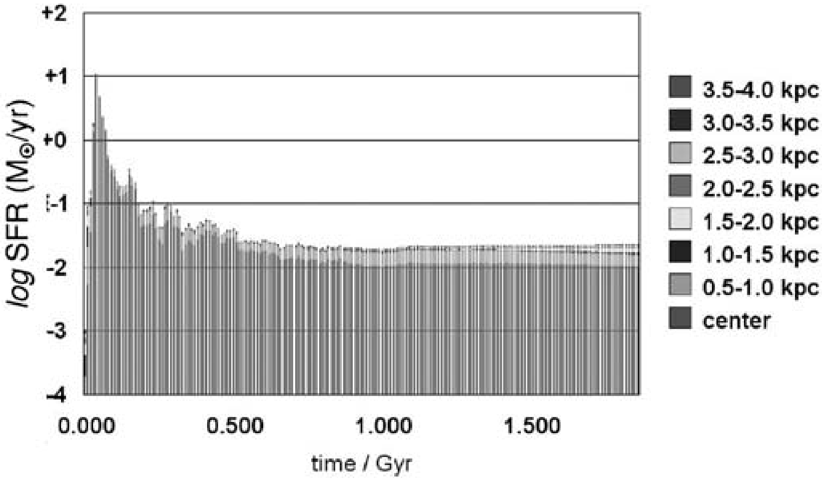

Figure 3. Star-formation history of an almost non-rotating ($\lambda \approx 0.001$) 2d 10^9 $M_\odot$ chemodynamical model for different radial zones. While the darker much extended plot region belongs to the very central 0.5 kpc the next annulus between 0.5-1.0 kpc contributes only almost 10%. Significantly, the star-fromation rate is actively self-regulated after already 0.5 Gyrs

Some problems and caveats are discussed in this paper (HTG). These include:
The models predict more cool gas than is observed in dE galaxies.
The modelled cores are very compact with implicitly high central surface brightnesses.
While the models make some intermediate-age stars, most stars are made in less than 1 Gyr after formation.
The very simple nature of these 1d chemo-dynamical models overestimates the momentum transfer between the gas phases and leads to an overly efficient gas removal.
No environment could be included that would lead to an extended period of inflow delayed due to the ionization of the IGM and feedback from SF within the DG.
No external pressure on the galaxy from an IGM that could hamper the gas expansion.

More complex models are required to bring the qualitative agreement with observations into the quantitative regime.

Therefore the chemo-dynamical treatment was soonly extended to 2d mainly to explore the evolution of dwarf irregular galaxies but can also be applied to slowly rotating dEs. Already a first rough comparison with a 2d chemo-dynamical model of 10^9 $M_\odot$ even with DM halo of additional 10^{10} $M_\odot$ demonstrates how self-regulated and smoothly the evolution proceeds (Fig. 3). After a very short (100 Myrs) initial burst due to the collapse of the gas after recombination, the central 1 kpc region cooks at a moderate SF rate of 10^{-2} $M_\odot$/yr while the annulus between 0.5 and 1 kpc reaches an almost constant SF rate of almost three times the center according to its larger area. At radii larger than 1.5 kpc the SF becomes negligible.

4. Conclusions

One further observation can basically demonstrate the complexity of the dE evolution we are faced with and that should be treatible in models: Sub-solar [α/Fe] abundance ratios are derived by Hill *et al.* for many stars of the Sculptur dSphs with VLT/FLAMES (Tolstoy 2005; see also talk by Eline Tolstoy, this conference) set a clear sign that SNII gas from an earlier SF epoch was lost from the galaxy so that the ISM capable for the

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most recent SF event consisted predominantly of elements released on longer timescales, i.e. from intermediate-mass stars that replenished the evacuated gas. The recurrent SF episode argues in favour of additional gas infall.

The aims to simulate these coupled evolutionary processes and their effects on both, internally and externally, are highly challenging tasks to computations. Although 1d chemodynamics have their limitations by the lack of spatial degrees of freedom for the gas and stellar flows, the multi-phase description and the interaction network (Hensler 2003) are the substantial requirements for any reliable chemo-dynamical modelling of galaxy evolution. While a grid-based treatment reaches its computational limits at 2d or low spatial resolution in 3d, the new strategy aims to treat also the *Smooth Particle Hydrodynamics* (SPH) chemo-dynamically. Developments from the single-gas phase SPH programs are under way (e.g. Semelin & Combes 2002, Berczik *et al.* 2003, Harfst, Theis, & Hensler 2004, Harfst, Theis, & Hensler 2005).

Acknowledgements

I would like to thank Bruno Binggeli and Helmut Jerjen for the organisation of this excellent and most interesting IAU Coll. The participation on this conference was suppted by a travel grant from the University of Vienna.

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Discussion

KROUPA: It is to be noted that the star-formarion timescale for your low-mass models (no DM) is about 2-3 Gyrs which is what we see in the low-mass dSph satellites.

HENSLER: Wonderful indeed, isn't it? Yes, the typical timescales of star-formation relevant processes are all in the same range for an individual galaxy and governed by the gravitational energy density.

READ: How do you decide what fraction of supernova energy to pump into the gas and to what extent does this affect your results?

HENSLER: As we could show in a few papers (see e.g. Köppen, Theis, & Hensler 1995,1998, Samland, Hensler, & Theis 1997) and in PhD theses, the network of self-regulation processes makes the models almost unaffected by the applied supernova energy within one order of magnitude. We imply 10^{51} ergs per SN Ia and II, 72% as thermal, the rest as kinetic energy.

SAVIANE: Do you predict metallicity gradients? What is their amount?

HENSLER: As I mentioned in the 1d models the metallicity gradient is positive for the least-massive models and changes sign towards higher masses and initial densities.

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