Morphological Mutations of Dwarf Galaxies

Gerhard Hensler

Abstract Dwarf galaxies (DGs) are extremely challenging objects in extragalactic astrophysics. They are expected to originate as the first units in Cold Dark-Matter cosmology. They are the galaxy type most sensitive to environmental influences and their division into multiple types with various properties have invoked the picture of their variant morphological transformations. Detailed observations reveal characteristics which allow to deduce the evolutionary paths and to witness how the environment has affected the evolution. Here we review peculiarities of general morphological DG types and refer to processes which can deplete gas-rich irregular DGs leading to dwarf ellipticals, while gas replenishment implies an evolutionary cycling. Finally, as the less understood DG types the Milky Way satellite dwarf spheroidal galaxies are discussed in the context of transformation.

1 Introduction

By the continuous growth of telescope size and advanced detector sensitivity the panchromatic view of galaxies is enabling us since the HST time to trace the evolution of massive galaxies observationally back to high redshifts. As examples the existence of intact gas-rich galaxy disks around redshift 2 has provided us a new insight into the gas accumulation and causes for the high star-formation rates (SFRs). Although dwarf galaxies (DGs) also exist already at that early epoch, but because of their faintness, those observations are not as feasible for them so that our wisdom of DG formation and evolution depends on assumptions from numerical simulations and from their comparison with stellar population studies of DGs in the local universe. Nevertheless, due to the improved observational facilities also for the DGs, details of their properties have affected our picture of their formation and evolu-

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tion. The first impression from decades ago, that DGs possess simple structures and evolve morphologically clearly separated, has changed totally in the sense that a classical morphological division of them is meaningless in the view of the variety of DG types: there are e.g. dwarf irregular galaxies (dIrrs) with exceedingly strong star formation (SF), called starburst DGs (SBDGs), and also short but intense epochs of SF in the past, dwarf elliptical galaxies (dEs) with recent SF or central gas content, and last but not least, dwarf spheroidals (dSphs) at the faint end of dEs as satellite galaxies down to about -5^m. "Normal" DGs have a brightness range between $M_V \geq -18^m$ to -10^m.

For this brightness reason, dSphs are only detectible within the Local Group by refined search algorithms from surveys as e.g. SDSS. Also in the Virgo Cluster an archival work of detailed dE properties is expensive in observing time. In their studies of Virgo cluster DGs already Sandage & Biggeli [87] found that dEs dominate the cluster galaxy population by far, in contrast to their number fraction in the field where dIrrs are the most common DGs. This fact cannot be interpreted from the different local origins of DGs but because matter accumulates to clusters also dIrrs fall in from the cosmic web continuously whereby they have to change their morphology. Not only because of such morphological mutation but also due to the occurrence of enhanced SF in dIrrs, [87] emphasized already the necessity of various links between the DG types by morphological transitions.

From the ΛCDM cosmology the baryonic matter should settle within Dark Matter (DM) halos, which originally preferred to form low-mass subhalos and hierarchically accumulate to massive galaxies. If the baryonic matter would follow this bottom-up structure formation, the subhalos should also assemble their gas at first and by this also evolve with SF to become the oldest galactic objects in the universe. That this picture seems to be too naive is simply understandable by three major physical principles:

1. The gas assembly timescale should behave as the free-fall timescale $\tau_{\rm ff}$, namely, dependent on the gas density as ${\rho_{\rm g}}^{-1/2}$, because gas is accreted through gravitation. Whether this accretion leads to the same enhancement of SF in DGs as observed and theoretically expected [39] is still a matter of debate (see also sect. 2). Because the virial temperature in the DG gravitational potential does not accomplish values above 10^5 K, on the one hand, cold accretion [13] is not necessarily required as for massive halos.

2. The SF timescale $\tau_{\rm SF}$ is defined as M_g/Ψ with Ψ as the SFR that, on the other hand, in the self-regulated SF mode depends on $\rho_{\rm g}^2$ [45]. Let me already emphasize here, that the theoretical treatment and modelling of SF self-regulation has to allow for the stellar energy of radiation and winds by massive stars already released in SF regions during their lives, i.e. prior to the explosion of supernovae typeII (SNeII). This necessity becomes clear when one continues a high SFR conditioned by gas infall and unaffected for a few million years until the first SNeII emerge. Since lower galaxy masses lead to less dense gas, SF is stretched over time for DGs.

And 3. As SF couples to stellar energy release, and since the counteracting cooling process depends on $\rho_{\rm g}^2$, the gas expands due to pressure support and reduces the SFR so that the effect of SF self-regulates non-linearly.

Another important effect that seems to affect the whole network of galaxy formation and evolution is ionizing radiation from the first cosmological objects (supermassive stars, black holes, galaxies). Due to the re-ionization of the gas in the universe, its thermodynamical state is changed so that its accretion onto low-mass objects was reduced [18] and gas already caught in minihalos evaporated again [2]. Since massive objects remained almost unaffected by the re-ionization phase, while DGs should have experienced delayed SF [69], this evolutionary dichotomy is observed as downsizing [10]. Nevertheless, the assumption that all DGs were affected in the re-ionization era and in the same way would request overlapping Stroemgren bubbles in an almost uniformly ionized Universe. This, however, must be questioned and is contrasted by the existence and amplification of cosmological density structures [71].

Another possible paths of DG origin is the formation of SF density enhancements in the tidal tails of merger galaxies [19]. Since they should be free of DM and it is not yet well understood whether their SF acts in self-regulation the survival probability of these galaxy-like entities needs to be explored [82].

2 Dwarf irregular galaxies and their extreme evolutionary stages

dIrrs are characterized by large gas fractions, ongoing SF, and low metallicities. That dIrrs contain the same or slightly higher gas fractions than giant spiral galaxies and mostly suffer the same SF efficiency, but appear with lower metallicity Z than spirals, cannot be explained by simple evolutionary models. When gas is consumed by astration but replenished partly by metal-enhanced stellar mass loss, the general analytical derivation relates the element enrichment $Z(t)$ with the logarithm of decreasing remaining gas fraction $\mu = M_g(t)/M_g(0)$ as $Z(t) = y[-ln(\mu)]$, where y as the slope is determined by the stellar yield (see e.g. textbooks like [70] or reviews as e.g. by [76, 35]). As demonstrated by [22] and [100], however, the effective yields of gas-rich galaxies decrease to smaller galaxy masses. This means that their element abundances, particularly O measured in HII regions, are smaller than those released by a stellar population and confined in a ”closed box”.

Two processes can reduce the metal abundances in the presence of old stellar populations: loss of metal-enriched gas by galactic outflows or infall of metal-poor (even pristine) intergalactic gas (IGM). It is widely believed, that a fundamental role in the chemical evolution of dIrrs is played by galactic winds, because freshly produced metals in energetic events are carried out from a shallow potential well of DGs through a wind (which will be therefore metal-enhanced). Some SBDGs are in fact characterized by galactic winds [58] or by large expanding supernova type II (SNeII)-driven X-ray plumes (e.g. [32, 59]). Studies have raised doubts to whether the expanding Hα loops, arcs, and shells mostly engulfing X-ray plumes, really imply gas expulsion from the galaxies because their velocities are mostly close to escape, but adiabatic expansion against external gas tends to hamper this.

As an extreme, [1] speculated that galactic winds are able to empty DGs from its fuel for subsequent SF and, by this, transform a gas-rich dIrr to a fading gas-poor system. In order to manifest this scenario and to study mass and abundance losses through galactic winds numerous numerical models are performed under various, but mostly uncertain conditions and with several simplifications (e.g. [55, 93]). The frequently cited set of models by MacLow & Ferrara [55] (rotationally supported, isothermal HI disks of dIrrs with fixed structural relations for four different gas masses between $M_g = 10^6 - 10^9 M_\odot$ and three different SNII luminosities in the center corresponding to SN rates of one per 3×10^4 yrs to 3 Myrs) is mostly misinterpreted: The hot gas is extremely collimated from the center along the polar axis, but cannot sweep-up sufficient surrounding ISM to produce significant galactic mass loss. On the other hand, the loss of freshly released elements from massive stars is extremely high. Moreover, these models lack of realistic physical conditions, as e.g. the existence of an external pressure, self-consistent SFRs, a multi-phase inhomogeneous ISM, and further more.

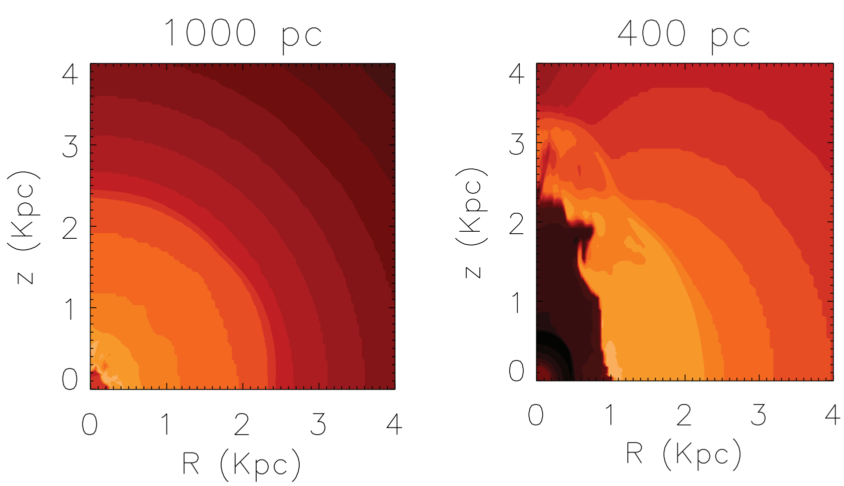

Fig. 1 Density contours after 200 Myr of evolution for models differing on the semi-minor axis b of their initial configurations (semi-minor axis indicated on top of each panel), while the semi-major axis is set to a=1 kpc: *left:* b=a=1 kpc (spherical); *right:* b=400 pc, (eccentricity of (a-b)/a=0.6). The density scale ranges from 10^{-27} (black) to $10^{-24} g/cm^3$ (brightest). *(for details see [83].)*

Also more detailed numerical simulations [15, 79], show that galactic winds are not very effective in removing gas from a galaxy. Although galactic winds develop vertically, while the horizontal transport along the disk is very limited, their efficiency depends very sensitively on the galaxy structure and ISM properties, as e.g. on the HI disk shape [83]. Fig. 1 reveals clearly that the more eccentric the disk is, the more pronounced does the superbubble expand. On the one hand, the hot SN gas has to act against the galactic ISM, exciting turbulence and mixing between the metal-rich hot gas with the surrounding HI . Not taken into account in present-day models is the porosity of the ISM, consisting of clouds and diffuse less dense gas. In particular, the presence of clouds can hamper the development of galactic winds through their evaporation. This so-called mass loading reduces the wind momentum and internal energy. Since the metallicity in those clouds are presumably lower than the hot SNII gas, also the abundances in the outflow are diminished as e.g. observed in the galactic X-ray outflow of NGC 1569 [59] for which a mass-loading factor of 10 is derived to reduce the metallicity to 1-2 times solar. In recent simulations [89] demonstrate that turbulent mixing can effectively drive a galactic wind. Although they stated that their models lead to a complex, chaotic distribution of bubbles, loops and filaments as observed in NGC 1569, other observational facts have not been compared.

Detailed numerical simulations of the chemical evolution of these SBDG by [81] could simultaneously reproduce both, the oxygen abundance in the warm gas as well as the metallicity in the hot outflow. Surprisingly, [80] demonstrated that the leakage of metals from a SBDG is not prevented by the presence of clouds because the clouds pierce holes into the wind shells. This leads to a final metallicity a few tenths of dex lower than in models without clouds.

Consequently, the crucial question must be answered which physical processes trigger such enormous SFRs as observed in SBDGs and consume all the gas content within much less than the Hubble time. One possibility which has been favoured until almost two decades ago was that at least some of these objects are forming stars nowadays for the very first time. Today it is evident that the most all metal-poor ones (like I Zw 18) contain stars at least 1 Gyr old [65], and most SBDGs have several Gyrs old stellar populations. This means that SF in the past should have proceeded in dIrrs, albeit at a low intensity and long lasting, what can at best explain their chemical characteristics, like for instance the low [α/Fe] ratio [50]. The [α/Fe] vs. [Fe/H] behaviour is representative of the different production phases, α-elements from the short-living massive stars and 2/3 of iron from type Ia SNe of longer-living binary systems. If the SF duration in a galaxy is very short, type Ia SNe do not have sufficient time to enhance the ISM with Fe and most of the stars will be overabundant in [α/Fe].

In most SBDGs large HI reservoirs enveloping the luminous galactic body have been detected (NGC 1569 [91], NGC 1705 [63], NGC 4449 [36], NGC 5253 [40], I Zw 18 [103], II Zw 40 [102]) with clearly disturbed gas kinematics and disjunct from the galactic body. Nevertheless, in not more than two objects, NGC 1569 [67] and NGC 5253 [40] gas infall is proven, while for the other cases the gas kinematics obtrudes that the gas reservoir feeds the engulfed DGs. In another object, He 2-10, the direct collision with an intergalactic gas cloud [41] is obviously triggering a huge SB. Reasonably, for their measurable HI surface density the SFRs of most of these objects exceed those of ”normal” gas disks (Fig.2).

Yet it is not clear, what happens to dIrrs if they move into a region with increasing external pressure as e.g. by means of a denser IGM and of ram pressure when they fall into galaxy clusters. In sect.3 we will discuss the effect of ram pressure on the

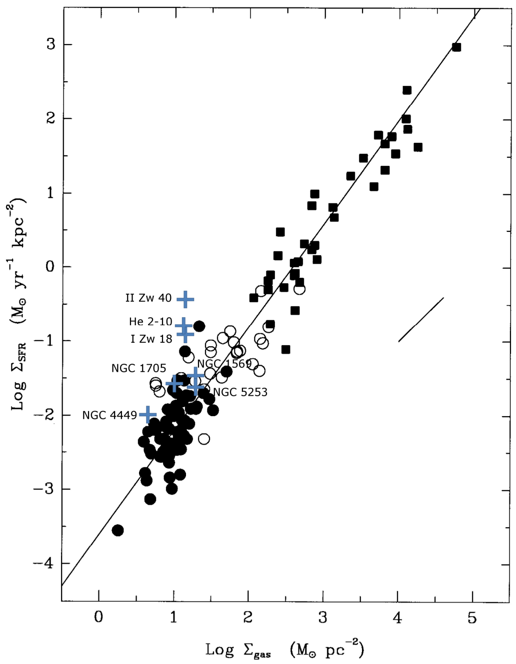

Fig. 2 Comparison of the surface star-formation rate vs. HI column density of a few prototypical starburst dwarf galaxies (SBDGs) denoted by crosses and names with the well-known Kennicutt-Schmidt relation derived by [38] with an exponent of 1.4 (long full-drawn line). The SBDGs' HI surface density is averaged over the optical galactic body *(from [49])*.

structure of the ISM for which numerical models for spiral galaxies (e.g. [85]) as well as for gas-rich DGs (e.g. [66]) exist, but only hints from observations (as e.g. for the Magellanic stream). The effect on the SFR due to compression of the ISM is observed, but not yet fully understood and convincingly studied by models. [9] e.g. observed a coherent enhancement of SF in group galaxies falling into a cluster.

Although the mass-metallicity relation also holds for dIrrs and even steepens its slope [97], what can be interpreted by galactic mass loss and the corresponding lower effective yield [22], the abundance ratios are unusual. As mentioned above, O/Fe reaches already solar values for subsolar oxygen or iron abundances. While this can be explained by a long SF timescale, another characteristic signature is that the ratio log(N/O) stays at about -1.6 to -1.5 with O abundances below 1/10 solar and with an increasing scatter with O (see Fig.3). Their regime of N/O–O/H values overlaps with those of HII regions in the outermost disk parts of spirals at about 12+log(O/H) = 8.0 ... 8.5 [101].

In the 90th several authors have tried to model these observations by SF variations with gas loss through galactic winds under the assumptions that these dIrrs and blue compact DGs (BCDs) are young and experience their first epochs of SF (for a detailed review see [33]). Stellar population studies contradict this youth hypothesis, so that another process must be invoked. Since these objects are embedded into HI envelops and are suggested to suffer gas infall as manifested e.g. in NGC 1569 (see above, [91, 67]), the influence of metal-poor gas infall into an old galaxy with continuous SF on particular abundance patterns were exploited by Koeppen & Hensler

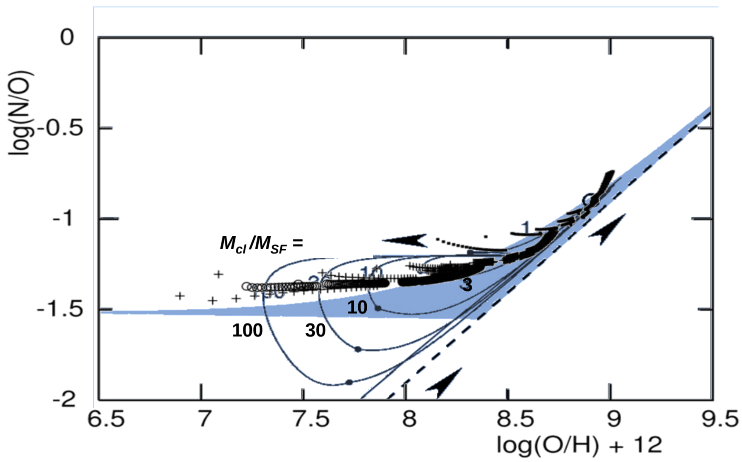

Fig. 3 The abundance ratio N/O as a function of oxygen abundance observed in spiral and irregular galaxies (shaded area, after [101]) overlayed with evolutionary loops due to infall of primordial intergalactic gas clouds. These have different mass fractions M_{cl}/M_{SF} with respect to the mass involved in the SF region The crosses represent evolutionary timesteps of models, the arrows depict the direction of the evolutionary paths. The dashed straight line represents a simple model relation for purely secondary nitrogen production. *For discussion see [44].*

[44]. With the reasonable assumption that the fraction of infalling-to-existing gas mass increases with decreasing galaxy mass, their results could match not only the observational regime of BCDs in the [12+log(O/H)]-log(N/O) space but also explain the shark-fin shape of observational data distribution [44].

Fig.3 demonstrates how self-enriched galaxies which have reached the secondary nitrogen-track already within 2-3 Gyrs of their evolution are thrown back in O abundance by gas infall while N/O stays the same. After a time delay depending on the mass fraction of infalling gas to that existing already within the SF site, along a loop-like evolutionary paths in the [12+log(O/H)]-log(N/O) diagram the ISM abundances reach again the starting point. In summary, one can state that old dIrrs *mutate* temporarily to youngly appearing examples with respect to their gas abundances.

3 Dwarf elliptical galaxies

dEs are frequently denoted as examples of “stellar fossile” systems in which the bulk of their SF occurred in the past. They are preferentially located in morphologically evolved environments [98], i.e. in regions with high galaxy densities and dominate the morphological types of galaxies in clusters, as e.g. Virgo, Coma, Fornax, and Perseus. Furthermore, dEs cluster strongly around luminous elliptical/S0 galaxies

[99]. The evolution of this galaxy type should be mainly caused by gas and tidal effects on SF and structure and indicates that it is strongly affected by environment.

Already [6] found that cluster dEs are usually almost free of interstellar gas and contain few young stars. In trying to understand the dE population, structural regularities and correlations must be studied, as it is known since the 80th, between optical surface brightness and luminosity [47, 20] and between luminosity and stellar velocity dispersion which also correlates with metallicity (e.g. [73]). Boselli et al. [5] proposed to understand these "Kormendy" relations by processes having transformed dIrrs after their cluster infall, but accuse the still existing lack of numerical simulations of such transformation.

Furthermore, dEs often have flattened profiles but are mostly kinematically supported by their stellar velocity dispersion rather than by rotation.

The combination of low gas-mass fractions and moderate-to-low stellar metallicities in dE (about 0.1 of solar or less) is a key feature of this class. Their lower stellar abundances [28] suggest that extensive gas loss occurred during their evolution and SF ceased due to a lack of raw material rather than exhaustion of the gas supply through SF. Galactic winds are therefore a hallmark of modern models for dE evolution, starting from the basic consideration by [51] and continued with the study by [11]. They are commonly assumed to have cleaned out DGs soon after their formation. As mentioned in sect. 2, however, gas expulsion by means of galactic winds is inefficient from our understanding of the multi-phase ISM and requires even in low-mass systems a DM-to-baryonic matter ratio [55] much smaller than assigned to DGs in the classical formation picture (e.g. [60]).

There are two competing scenarios for the origin of cluster dEs. On the one hand, those low-mass galaxies are believed to constitute the building blocks in ΛCDM cosmology and should therefore have evolved congruently with the mass accumulation to more massive entities, galaxies and galaxy clusters. For those, orbiting in a cluster the stellar component must be heated continuously by harrasment of more massive cluster galaxies and thus be pressure supported. On the other hand, a variety of observations are available which also support discrepant scenarios of dEs evolution. Recent HI studies of Virgo cluster dEs [8] and also those of the Fornax cluster (see e.g. [64]) 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 represent an infalling class of different types of gas-rich galaxies in or after the state of morphological transformation. Further findings of a significant fraction of rotationally supported dEs in the Virgo cluster [104] and also disk features as e.g. spiral arms and bars [52] support the possibility of morphological transformation from gas-rich progenitor DGs to dEs thru gas exhaustion. Boselli et al. [4] have comprehensively discussed the different processes of dE origin.

A separation into dE subclasses with respect to their origin should also be visible in an intermediate-age stellar population, blue centers, and flatter figure shape. Indeed, dEs in the Virgo cluster can be divided into different subclasses [53] which differ significantly in their morphology and clustering properties, however, do not show any central clustering, but are distributed more like the late-type galaxies. These types of dEs show different disk signatures, such as bars and spiral structures, are not spheroidal, but rather thick disk-like galaxies. Similar shapes were also found for the brighter, non-nucleated dEs. There is only a small fraction of nucleated dEs whithout any disk features or cores, which keep the image of spheroidal objects consisting of old stars.

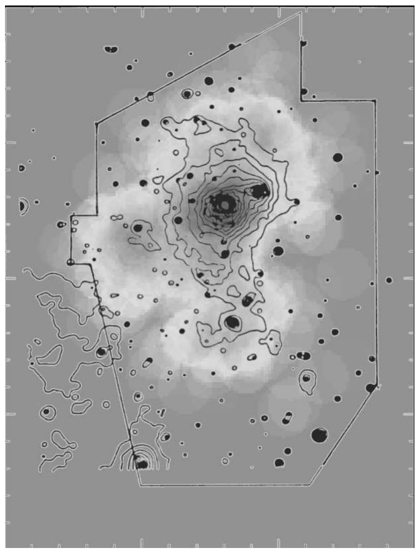

Fig. 4 Distribution of dEs in the Virgo Cluster divided into rapid (white) and slow objects (darker central part) overlaid with X-Ray brightness contours *(courtesy by Thorsten Lisker)*.

A figure analysis of Virgo dEs correlates with the averaged orbit velocity in the sense that flatter dEs show on average a larger orbital velocity (700 km/s) than those originating within the cluster (300 km/s) [54] (see Fig. 4). This kinematical dichotomy is expected because galaxies formed in virial equilibrium within the cluster retain their initial kinetic energy while the cluster mass grew. Galaxies falling into the present cluster potential must therefore possess larger velocities. To obtain information about both evolutionary stages, the young infalling vs. the late cluster members, [24] studied SDSS data. The basic model is that dIrrs which are formed outside the Virgo Cluster and becoming stripped on their infall, by this being transformed into dEs, should reveal properties recognizably different from dEs which have already aged in the cluster, as e.g. colors, effecitve radius, radial stellar distribution, and abundances. One result by [24] is that for the two dE populations, with and without cores, distinguished by their Sersic parameter, there is only a slight indication that non-nucleated dEs are more concentrated towards the inner cluster regions, whereas the fraction of nuclated dE is randomly distributed, while [53] found it to increase with distance. An analysis of the relation between the central surface brightness and the Sersic parameter shows the expected tendency to higher values for brighter galaxies. Furthermore, there were no further relations found of the Sersic parameter, the effective radius, or the distance from M 87.

Deeper insights are provided by spectra. Koleva et al. [46] found most dEs in the Fornax cluster to be roundish and to contain significant metallicity gradients already in the old stellar population. They argue that this is due to a lack of sufficient mixing. In contrast, rotationally supported dEs have flat metallicity distributions. Compared with simulations this can be attributed to galactic winds, but the picture of metallicity and gradients is not yet clear. While [92] show a tight positive correlation between the total metallicity [Z/H] and the mass, [46] do not find any trend involving [Fe/H] for Fornax-cluster and nearby-group dEs.

Moreover, from the deconvolution of the SF history of their sample dEs with respect to the central 1 arcmin and within the effective radius [46] draw the conclusions that for a few objects SF episodes occurred in the very center even within the last 1 Gyr. From a systematic study of the central Fornax-cluster dEs' dynamics [16] conclude that these objects stem from an infall population of late-type DGs and has been transformed to dEs by ram-pressure stripping (RPS).

Toloba et al. [94] derive for Coma cluster dEs to be weaker in carbon than dEs in low-density environments, while similar in nitrogen. Actually, they [95] also find that pressure supported Virgo dEs show higher dynamical mass-to-light ratios than rotationally supported dEs of similar luminosity and further that dEs in the outer parts of the cluster are mostly rotationally supported with disky shapes. Rotationally supported dEs even follow the Tully-Fisher relation. One fundamental and most spectacular result [95] is, however, that dEs are not DM-dominated galaxies, at least up to the half-light radius.

Correlations of both signatures, SF history and metallicity gradients, for cluster-member dEs vs. infall dEs should be derived for more clusters, but observations are unfortunately very time-expensive if possible at all.

In addition to classical dEs, ultra-compact DGs (UCDs) have been detected and classified as a new type of cluster dEs that differ by their intrinsic structure and brightness (see e.g. [75, 27]). The origin of these peculiar DGs is mysterious and not yet understood but requests transformation if they are surviving nuclei of tidally stripped nucleated DGs [23].

4 Morphological transitions

As the transformation picture from late-type dwarfs into dEs is still not completely understood and only qualitative, in sect.3 we tried to shed light on the expected witnesses of differences in system parameters which allow to distinguish between two different populations of dEs. That almost all DGs can be associated with morphological types and that only a few exceptions show morphological transformations, implies that the act of mutation seems to happen rapidly and thus to be observable with only low probability.

During the approach to galaxy clusters, ram pressure should act on dIrrs already at group conditions or in the outskirts of clusters [56, 85]. When this process pushes the gas out of dIrrs, wouldn't one expect to observe many head-tail structures of stellar body vs. stripped-off ISM? Several candidates exist which, however, are characterized as BCDs with decentered bright star-forming knots (see e.g. [68]). The recently detected best candidate in the rapid phase of RPS in the Virgo cluster is VCC1217/IC4318 [21]: A main almost old stellar body of $3 \times 10^8 M_\odot$ leaves behind a bundle of Hα and near-UV emitting knots. Nevertheless, the gas distribution and SF progression within some blobs are not fully understandable. It is still, in general, unclear to what extent the ram pressure can trigger SF by compression of the ISM.

Other BCDs are observed although their gas is already exhausted [14]. Peebles et al. [72] find a number of dIrrs with excessively high metallicity, what they interpret as the last stage of gas consumption before they reach the dE state.

On the other hand, rejuvenation of a fraction of cluster dEs seems also to occur which are found to harbour central warm gas [64]. Whether this fact is indicative of a possible re-transformation from gas-free to gaseous DGs by gas accretion is a matter of debate, since it seems impossible within cluster environments, but plausible in less dense regions where gas infall enhances SF or even triggers starbursts (see sect.2) and should not only affect dIrrs.

5 Dwarf spheroidal galaxies

The possible cycle of morphological mutations, i.e. from gas-rich objects to gas-poor systems by means of gas expulsion and back to a significant gas content by gas accretion, can be explored in the local environment, namely, in the galaxies around the Milky Way, their satellites. Except the Magellanic Clouds most of these can be characterized as gas-free spheroidal systems which manifest the faint end of dEs. Since these dSph are gathered around massive galaxies like our MWG and M31 orbiting them as satellites, go down to the lightest and most metal-poor end of galaxies, they have attracted increasing attention over the last years with the advent of more advanced observing facilities. Understanding their formation and evolution is of substantial relevance for our astrophysical picture of cosmological structure formation and of galaxy evolution. Four main questions are addressed:

1. How and when did they form? They all harbour a very old stellar population [96] and, therefore, seem to have been unaffected by the re-ionzation era [25].
2. Is their existence as satellite system typical for all massive galaxies? Their origin and DM content is still questioned by some authors [48] because of the large discrepancy of the number of objects really observed vs. expected from ΛCDM cosmology and because of their orbit concentration to the so-called disk-of-satellites, also found around M 31. This invokes the preference of their tidal-tail origin [62]. The observed large velocity dispersions, which are otherwise applied as representative to derive the M/L ratio is then caused by tidal effects.
3. How is their evolution determined by the vicinity of the massive mature galaxy? Not only the tidal field must have a disruptive effect, but also a gaseous halo of the central galaxy will interact with the ISM of the dSphs [61]. That the relation

of the gas fraction bound to the dSphs is increasing with distance from the MWG [29], points into that direction.

4. Vice versa the question arises, how do the satellites influence the structure and evolution of the mature galaxy, here the MWG.

The first three questions also concern the morphological transition from gas-rich satellites to dSphs. Nevertheless, dSphs follow a mass-metallicity relation [12, 26] and continue the total brightness vs. central surface-brightness relation from normal dEs to the faint end [26].

As the first models, Hensler et al. [34] performed *chemo-dynamical* simulations [31] of spherical low-mass galaxies in order to study galaxy survival, SF epochs and rates, gas loss, and (final) metallicity. They demonstrate that due to the SF self-regulation only short but vehement initial SF epochs occur and lead to mass-dependent gas loss. Nonetheless, the DGs remain gravitationally bound with the further issue that more cool gas survives than it is observed, but it forms a halo around the visual body. Although the stellar energetic feedback is the driving mechanism to expel the gas, its effect is not as dramatic as obtained in semi-analytic models [86] and the amount of unbound mass is considerably lower. To get lost, this gas has to be stripped off additionally [26] what probably happens by means of ram pressure of the galactic halo gas [61] or by tidal stripping [78]. Otherwise it can return to the DG and produce subsequent events, from a second SF epoch to SF oscillations. The external gas reservoirs around some dSphs [7], in particular also the HI that is kinematically coupled with the Scl dSph, might witness this effect.

The fascinating wealth of data and their precision on stellar ages and kinematics, on their chemical abundances, abundance gradients, and tidal tails of dSphs (for most recent reviews see e.g. [43] and [96]) have triggered numerous numerical models. Although they are advanced since [34] to 3D hydrodynamics (see e.g. [57] and [84]), they still lack of a self-consistent treatment of both, internal processes, as e.g. SF self-regulation (see sect.1), and the environmental influences as e.g. tidal effects, external gas pressure, gas inflow, etc.

In a recent paper [84], e.g. a large set of DG models is constructed with the method of smooth-particle hydronamics (SPH), but considers all of them in isolation. In most of their models sufficient gas mass is retained and can fuel further SF epochs, if it would not be stripped of by ram pressure or tidal forces, as the authors mention. Those models that fit the presently best studied dSphs Fnx, Car, Scl, and Sex, are than chosen as test cases for further exploration. Although their results do not deviate too much from the further observational data, in addition to the already mentioned neglections, three further caveats exist: 1) If models are selected according to any agreement with one or two observed structural parameters, it is not surprising if also other values would not deviate significantly. 2) The numerical mass resolution of the SPH particles is too low to allow quantitative issues of galactic winds, heating and cooling, etc. 3) Because of the single gas-phase description released metals are too rapidly mixed with the cool gas and the metal-enrichment happens too efficiently. Despite these facts, with appropriate initial conditions always models in agreement to observations can be found.

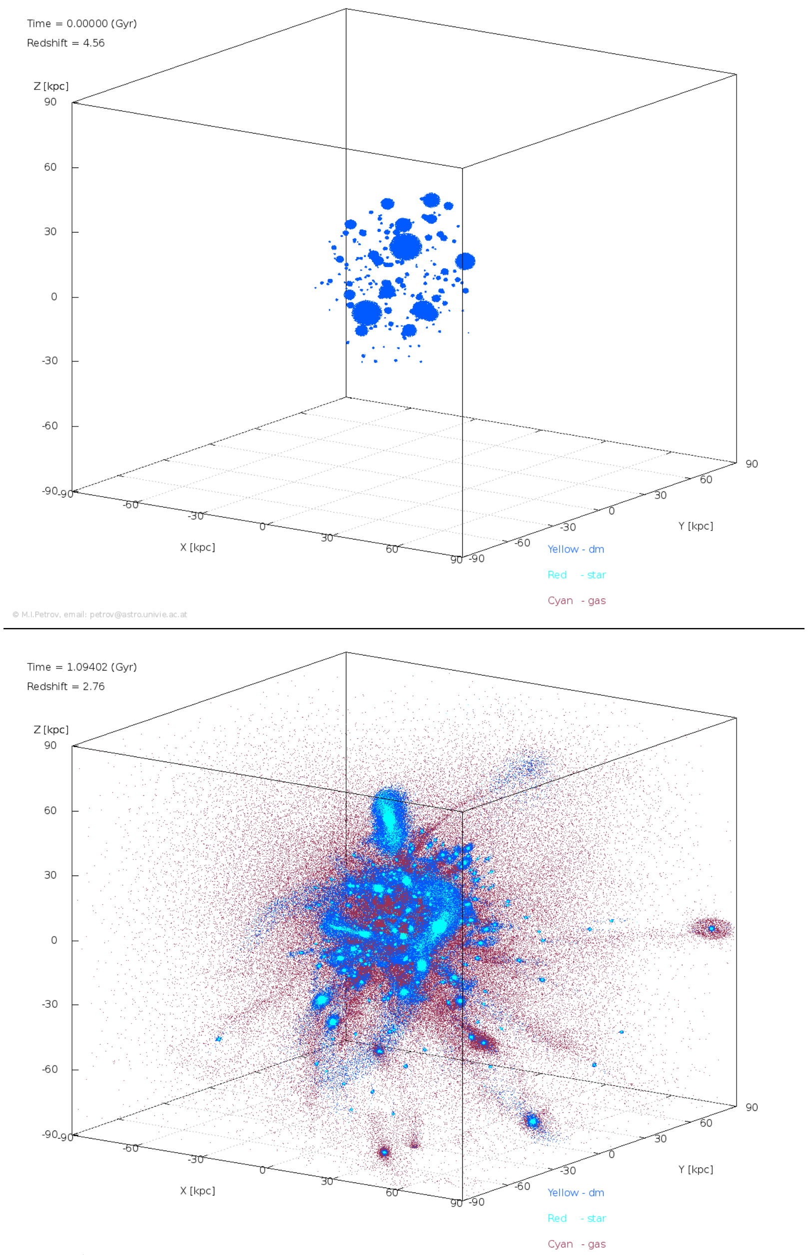

Fig. 5 Cubes of 200 kpc length around the Milky Way (at their center). *upper panel:* Initial conditions of the Milky Way's satellite system: Distribution of Dark Matter (DM) subhalos within a sphere of 40 kpc radius around the Milky Way at redshift z=4.56. *lower panel:* Snapshot of the satellites' dynamical evolution 1 Gyr after the numerical onset, i.e. at redshift z=2.76. The DM subhalos are filled with baryonic gas of mass fraction of 17%, form stars, and lose mass of all constituents due to tidal interactions among the satellite system. For discussion see text.

Although the advancement to a two-phase ISM treatment in SPH is not trivial and implies various numerical problems, but is not impossible [3, 30, 88], such treatment would be absolutely necessary in order to approach reality and to achieve reliable results. In addition, the *chemo-dynamical* interaction processes must be applied [3].

From the ΛCDM structure-formation paradigm and from numerical simulations with different computational tools, subhalos are expected to assemble around massive halos and to accumulate their masses. If they have already experienced SF, their stars should be merged into a spheroid and be identifiable by their kinematics and chemical abundances. Although these low-mass subhalos, their baryonic content as dSphs, and the accretion scenario [37], therefore, serve as the key to pinpoint this cosmological paradigm, observational detections of stellar streams within the Milky Way (MW) halo are rare [90]. Furthermore, the stellar abundances in present-day dSphs deviate mostly from the halo, in particular α/Fe with Fe/H, which characterizes the SF timescale ([96] and e.g. for the Car dSph [42]).

Yet evolutionary models of dSph with respect to SF, chemistry, and gas expulsion and their comparison with the Milky Way halo are still too simplistic. While their accretion epoch occurred continuously over the Hubble time some models [77] only considered it as a short early event; their gas is not only removed by tidal stripping and RPS [61] but also re-accreted on their orbits around the MW [7]; in general, consideration as isolated systems lacks reality [84].

To model instead of isolated subhalos the evolution of the system of dSphs in the gravitational field of the MWG for which the accretion by the host galaxy is probable over the Hubble time, the Via Lactea II [17] simulation was used. Since an acceptible computational time limits the number of gas particles to two million as also for the DM and in order to reach a high mass resolution of $10^3 M_\odot$ per SPH particle, only 250 subhaloes as DM progenitors of dSphs in the mass range of $10^6 < M_{sat}/M_\odot < 6 \cdot 10^8$ from $z = 4.56$ could be followed. Unfortunately, this fact limits the radius of consideration to within a radius of 40 kpc around the MW's center of mass. In order to study the construction of the MWG halo by accretion of subhalos including baryonic matter, both gas and stars, as a first step, the *chemo-dynamical* evolution of the dSph system is followed for the first Gyr, i.e. until redshift $z = 2.76$ [74] (see Fig.5). For the simulations an advanced version of the single-gas chemo-dynamical SPH/N-body code is applied, treating the production and chemical evolution of 11 elements.

Starting with a 10^4 K warm gas of 17% of the subhalo masses in virial equilibrium and under the assumption that re-ionization is improbable to have affected the Local Group dSphs [25], cooling allows the gas particles to achieve SF conditions in all satellites, but its efficiency directly depends on the mass of a satellite and its dynamical history (merging with other satellites or disruption by the MW gravitational potential). The stellar feedback by SNeII releases sufficient energy to expel hot gas from the main bodies of less massive dSphs, facilitated by tidal interactions. This gas accumulates in the MW halo while massive dSphs merge and continue SF. For the first 10^8 yr of the simulation there is a considerable variance of stellar oxygen abundance in the whole system $(-5. \leq [O/H] \leq -0.5)$ reflecting the very inhomogeneous production and distribution of enriched gas. After 10^8 yrs the merging of satellites' ISM promotes the mixing of heavy elements. Finally, almost completely recycling of the gas erases the abundance inhomogeneities so that O in stars converges to $-1. \leq [O/H] \leq 0.$ with a small dispersion.

Detailed analyses of the SF history, gas exchange, stellar abundance evolution of dSphs and the MW halo in the early universe are presented in a comprehensive paper [74] and will be discussed with their implications for our cosmological picture.

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