Dwarf Galaxies as ideal Laboratories to study astrophysical Processes

(a madley of research)

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and the SMAKCED team

Morphological division of DGs
DG gas evacuation by galactic winds; Starbursts?
Transformation channel for dIrrs → dEs?
Starbursts by gas infall
dEs dominate in galaxy clusters: transformation by gas stripping
Self-regulated star formation at low rates
DG formation from merger events? Tidal DGs!
Smaller editions of Hubble-type galaxies? $10^6-10^{10}\, M_\odot$, 1-10 kpc, $M_V>-18$.

Transformation paths from one morphological type to the other are proposed.

All "normal" DGs, dEs and dIrrs follow the same relations even to their faintest end, but differ from UCDs+GCs and from the Hubble-type galaxies.
Questions:

- Are Dwarf Galaxies as simple as they look like?
- Can one therefore understand their formation and evolution as simply?
- Did they have the same origin?

Why are Dwarf Galaxies so interesting?
They are extremely sensitive to
1) their formation epoch,
2) their internal evolution,
3) their environmental influence.

⇒ different formation epochs
⇒ large variety of evolutionary paths
⇒ morphological transformations

DGs are extremely interesting AP objects
DGs as building blocks in the hierarchical CDM scenario

Dark Matter substructures form first and assemble to larger structures

but:

• Downsizing
• No clear DM content
• TDGs?
Arp 188, the Tadpole Galaxy: bright knots as DG precursors?

bright star-formation knots are structured within the tail.

The Large Magellanic Clouds - a dIrr on its passage of the Milky Way: smooth evolution in interaction
**Starbursts + Galactic Wind**

Possible dIrr → dE transformation

DGs can show very active modes of star formation, which can be triggered by environmental effects like e.g. gas infall or mergers.

Starburst can drive galactic winds!
Can these winds evacuate dIrrs from their gas, i.e. transform them to dEs?

Understanding the cause of enhanced SF and the impact of massive stars on their environment is of fundamental relevance for:

- understanding the SF process,
- galaxy evolution also in the Early Universe.
In NGC 1569

2 Super Star Clusters at the base of the gas stream are the engines of the galactic wind due to their cumulative supernova II explosions.

Dwarf Galaxies are strongly affected by Galactic Winds.

Model:
- bipolar outflow;
- the S part towards observer is unobscured;
⇒ disk inclination known
- metal-enhanced wind: 1-2 $Z_\odot$.
The mass loss can be determined from the \textit{effective yield} $y_{\text{eff}}$ of the HI ISM.

The \textbf{loss of metals} should be visible in the hot gas outflow.

\textbf{Metal loss through galactic outflows!}

Effective yields $y_{\text{eff}}$ of dIrrs < solar! Outflow of SNII gas reduces e.g. O.

\textbf{but:}
simple outflow models cannot account for gas mixing + turb. heating
Galactic winds in Dwarf Galaxies?

Continuous mechanical $L_{\text{over 50 Myrs}}$ for various galaxy masses $M_g$ and gas densities $n$: at $t=50$ Myrs

No consistent star formation!

10/21/2018
MacLow & Ferrara (1999)

but too simple because of various reasons:
- disk structure, star formation,
- no external pressure,
- no cool cloudy phase,
- no radiative energy release,
- mismatch with chemical abundances,
Galactic winds in DGs and the fate of metals

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Mass ejection efficiencies
Metal ejection efficiencies

Mass (M_\odot)

Can strong Galactic Winds solve the CDM cusp/core problem? Loss of low-ang.mom. gas!

Bulgeless dwarf galaxies and dark matter cores from supernova-driven outflows

Figure 4: A comparison between the angular momentum distribution of the stellar disk and the dark matter halo in the simulated galaxy DG1. The panel shows the present-day time angular momentum probability distribution p(\lambda | M_{\odot}) of disk stars (shaded area) and dark matter particles (area below the continuous line) normalized by the average for the whole dark-matter halo (\lambda_{\odot} = 1). The angular momentum distribution of star particles has a narrower distribution, a higher average and significantly less low-angular-momentum material than the dark matter, owing to centrally concentrated outflows preferentially removing low-angular-momentum baryons. As a result, the radial stellar distribution is similar to that measured for normal dwarf galaxies (see also Fig. 2).

Figure 3: The DM density profile of a dwarf galaxy in our sample, at z = 4, 3, 1, 0. The prolonged process of cusp flattening due to many separate outflows results in a shallow inner profile at z = 0. For comparison, the density profile of the same galaxy, but simulated with DM only, is shown in the black dot-dashed line. In the DM-only simulation, the DM profile is cuspy density profile at all radii.
Starburst DGs and BCDGs remain gas-rich and are not exploding, but show perturbed gas dynamics. 

Observed gas outflows below escape velocities

Testing galactic winds in different gas disks

Initial conditions:

- Baryonic mass: $M_b = 10^7, 10^8, 10^9 \, M_\odot$
- Stellar disk by Myamoto-Nagai potential
  \[ \psi(R, z) = -\frac{GM_b}{\sqrt{R^2 + (a + \sqrt{z^2 + b^2})^2}} \]
- Isothermal gas disk with flattening $b/a = 0.2, 1.0, 5.0$
- Gas fraction: 60% (L), 90% (H)
- Spherical DM halo with $M_{DM} = 10 \, M_b$
- SFR $\propto \rho^2$
Testing galactic winds in different gas disks

Blow-away of total gas almost impossible:
Only in lowest-mass DGs and flat, light gas disks, but then all metals are lost.
Gas disk, mixing, turbulence, external halo gas, and embedded clouds hamper outflow.

Oxygen ejection:
Only lowest-mass DGs with lower gas fraction lose large O fractions.
Thick gas disk and massive DGs retain their supernova elements.
Numerical Simulations of DG evolution

Star-formation self-regulation by Stellar feedback

$M_{\text{gas},i} = 1.4 \times 10^8 \, M_\odot$ ; $M_{\text{s},i} = 0$
$M_{\text{DM}} = 8.4 \times 10^8 \, M_\odot$
$v_{\text{rot}} = 30 \, \text{km/s}$

$M_{\text{gas},i} = 2 \times 10^9 \, M_\odot$ ; $M_{\text{s},i} = 0$
$M_{\text{DM}} = 9.4 \times 10^9 \, M_\odot$
$v_{\text{rot}} = \sim 50 \, \text{km/s}$

SF as in Köppen, Theis, G.H. (1998, AA, 331)

$\Psi(c,T_c) = C \cdot c^m \exp(-T_c/10^4 \, K)$

AMR code FLASH Steyerleithner et al. (2017)
SPH code Kuehtreiber et al. (2017)

Low star-formation rate;
No galactic wind!
SF concentrated to the central part;
Structures form; giant gas holes

Star formation is self-regulated!

What triggers Starbursts?
Gas Infall confirmed!

see Muehle et al. (2005)

Stil & Israel (2002)

**Gas infall triggers Starburst**

The case of NGC 1569:

- HI clouds (each ~10^9 M\(_\odot\)) fall towards in from a disk.
- 2 huge super star clusters are formed.

Muehle et al. (2005, AJ, 130)
NGC 4449
a triggered starburst

(Hunter et al. 1995)

II Zw 40

(van Zee et al. 1997)
**I Zw 18 - a perturbed dIrr with gas infall?**

(Östlin & Kunth 2000)

"Youthful-looking Galaxy May Be an Adult"

**NGC 1705**

- Single SSC formed:
  - age ≈ 10 Myrs, $M_{vir} ≈ 10^5 M_\odot$
- SSC embedded in HI disk: $M_{HI} ≈ 10^8 M_\odot$
- X-ray maxima surrounded by Hα loops, representing tips of a superbubble, expanding vertically to the HI disk, but confined

But: super star cluster is not formed in the center!!

X-ray contours overlaid on Hα

(Hensler et al. 1998)

Meurer et al. (1998)
How are dwarf elliptical galaxies formed?

- dlrrs do not lose their gas completely by galactic winds!
- Are all dEs formed morphologically separately?
- How much environmental effects?
- How would dlrrs without gas look like?
**dE Galaxies dominate in clusters**

Binggeli et al. (1987)

Sandage et al. (1984)

- **X-ray Gas in Galaxy Clusters**
  - $T_{\text{IGM}} \approx 10^7 \text{ K}$
  - $n_{\text{IGM}} \approx 10^{-4}$ cm$^{-3}$
  - $Z_{\text{IGM}} \approx 0.2 \ldots 0.4 Z_\odot$

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The Virgo Cluster, a merging complex
The vol. density of dIrrs fraction in clusters is the same as in the field.

- dEs dominate the morphology in clusters!

What makes dIrrs \( \rightarrow \) dEs?

- Which process drives gas loss?

1. Galactic winds, gas expulsion
2. Tidal stripping
3. Ram-pressure stripping
dEs in Virgo show a variety of shapes and properties that seem to correlate with the radial cluster distribution.

How to distinguish between cluster-born dEs vs. fallen-in, ram-pressure stripped, and harassed former dIrrs?

Infalling field dEs not to be discussed!
**DGs**

**Distribution of Virgo dE ages** (all dEs; Hielscher, Janz et al.), with X-ray contours overplotted. **Red** = older, slower; **blue** = younger, faster.

- dEs as products of infalling RPS dIrrs are expected to:
  - be at higher ICM densities
  - be at large cluster-centric distances,
  - to be flatter,
  - to have smaller Z,
  - move faster, eccentr. orbits


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**Dwarf Galaxies are expected to lose gas at cluster infall already by the low-density ICM ram pressure**

How much gas loss? Ram-pressure effects on star formation:
- In the DG body? In the RPS gas tail?

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**Figure 1.** Left: Archival HST/ACS image of the ESO475s fiber (PID 11616, PI Meng Stein), with superposed, the MUSE field of view at the two locations targeted by our observations. In this figure, north is up and east is to the left. The coordinate system is centered at the 2000 position of ESO475s, 001 (α = 16h13m21.1 s = 46h45.51). Right: RGB color image obtained combining images extracted from the MUSE datacube in three wavelength intervals (λ = 5000 – 6000 Å for the B channel, λ = 6000 – 7000 Å for the G channel, and λ = 7000 – 8000 Å for the R channel). A map of the Hβ line is overlaid in red using a logarithmic scale, revealing the extended gas tail that originates from the high-velocity source of ESO475s, 001 with the intercluster medium.
Star formation in the RPS blobs with rates of $\sim 10^{-1} \ldots 10^{-3} \, M_\odot/yr$

The detection of ESO 137-001

The case of VCC1217

Transformation by RPS

RGB

UV,U,B,V

Ha-off

Ha-on

not nec. SF!
Gas Loss of DGs by strong RPS

Mori & Burkert (2000)

Transformation of dIrrs by RPS should be visible already in a dilute environment, if $v_{\text{rel}}$ is sufficiently large. Consequences for their abundances? Star formation?
Metal-Poor cometary BCDs

HST V image of SBS 1415+437

Fig. 2. Continuum-subtracted Hα image of SBS 1415+437 with superposed Hα continuum isophotes. Regions with nebular emission are labeled e1, e2 and e4. The faint region e3 with Hβ and Hα emission lines in its spectrum is not seen in the Hα image.

RPS acts more efficiently for Dwarf Galaxies, even already at low densities in the outskirts of clusters

Thorsten Lisker, priv. comm.
The complexity and variety of dEs in the Virgo Cluster

Stellar content, MAss and Kinematics of Cluster Early-type Dwarfs (SMAKCED): project of dEs in Virgo Cl.

http://www.smakced.net

Urich, L., Lisker, T., Janz, J., et al. (HENSLER, G.):
Young, metal-enriched cores in early-type dwarf galaxies in the Virgo cluster based on colour gradients, 2017, Astron. Astrophys., 606, A135


Stellar Kinematics and structural Properties of Virgo Cluster Dwarf early-type Galaxies from the SMAKCED Project. III. Trends as a Function of projected Distance from the Cluster Center. 2015, ApJ., 799, 172


Janz, J., Laurikainen, E., Lisker, T., et al. (HENSLER, G.):
A Near-Infrared Census of the Multi-Component Stellar Structure of Early-Type Dwarf Galaxies in the Virgo Cluster, 2014, Apj, 786, 105

Toloba, E., Guhathakurta, P., van de Ven, G., et al. (HENSLER, G.):
Stellar Kinematics and structural Properties of Virgo Cluster Dwarf Early-type Galaxies from the SMAKCED Project. I. Kinematically Decoupled Cores and Implications for Infallen Groups in Clusters, 2014, Apj, 783, 120

Janz, J., Lisker, T., van den Anen, E., et al. (HENSLER, G.):

DGs
Modelling RPS DGs

- $M_{\text{gas},i} = 1.4 \times 10^8 M_\odot$; $M_{s,i} = 0$
- $M_{\text{DM}} = 8.4 \times 10^9 M_\odot$
- $v_{\text{rot}} = 30 \text{ km/s}$
- $v_{\text{rel}} = 290 \text{ km/s}$, $n_{\text{ICM}} = 10^{-4} \text{ cm}^{-3}$

- No enhanced SF
- No total gas evacuation

RPS for very low-mass DGs

- $M_{\text{gas},i} = 6.3 \times 10^6 M_\odot$; $M_{s,i} = 0$
- $M_{\text{DM}} = 1.2 \times 10^3 M_\odot$
- $v_{\text{rot}} = 2 \text{ km/s}$
- Moderate infall: $v_{\text{rel}} = 290 \text{ km/s}$, $n_{\text{ICM}} = 10^{-4} \text{ cm}^{-3}$
- SF enhanced when $v_{\text{rel}}$ reaches max.
- No SF in RPS gas tails
- Gas almost totally lost, but condensed clouds survive with varying SFRs

Steyrleithner et al., 2018, in prep.
fast RPS DGs

- $M_{gas,i} = 6.3 \times 10^8 M_\odot$; $M_{s,i} = 0$
- $M_{DM} = 1.2 \times 10^9 M_\odot$
- $v_{rot} = 2 \text{ km/s}$
- fast infall: $v_{rel} = 1000 \text{ km/s}$,
- $n_{ICM} = 10^{-4} \text{ cm}^{-3}$

Steyrleithner et al. in prep.

- Critical velocity for enhanced SF is reached earlier not when $v_{rel}$ max.
- Gas almost totally lost, but condensed clouds survive
- When these condensed clumps get RP stripped at later stages, they bear SF

Galaxy Cluster DGs:

- DGs are RP stripped in low-density inter-galactic medium!

Star formation enhanced due to ram pressure!

SF in stripped clumps: Under which conditions? Where observable?

Steyrleithner et al. (GH) 2018, MN, to be submitted

Gas loss + harassment! Smith et al. (GH) 2015, MN

How do transformed dEs look like? See SMAKCED publs
Virgo dEs with kinematically decoupled cores

VCC 1183

So far only known in Es and caused by gas/galaxy accretion! Yet no plausible explanation for dEs!


The KDCs of VCC1183 and VCC1453 are younger than the main body. Unsolved problem of the KDC formation:

Figures 2, 3: Spectral index-index diagrams used to estimate the stellar populations of galaxies. The gray dashed lines represent the grid of models by Vazdekis et al. (2000) in the system LIS-5 A based on the MILES stellar library (Sánchez-Blázquez et al. 2006; Casini et al. 2007; Falvani-Baruffo et al. 2001) with a Kroupa initial mass function (Kroupa 2001). Nearly horizontal lines indicate constant ages, values in Gyr printed at the right end of those lines, and nearly vertical lines show constant metallicity, labeled in the lower part of the grid. Following the color code from Figures 1 and 2, the open dark blue squares correspond to the KDC, and the light blue dots represent the main body of the galaxy. The solid dark blue square and light blue circle are the resulting spectral indices after the co-addition of the spectra inside and outside of the KDC region.
7. Star-formation history in Virgo dEs


Star formation histories in dEs

Light fractions of each burst for all the galaxies. Each galaxy is represented with a different colour indicated in the frame. Each star formation phase position is its age and height its light contribution to the total spectrum.

Summing up Dwarf Galaxies:

- DGs' evolution is highly complex!
  Gas outflows and infall, transformation
- DGs morphology results from their environment!
  Starbursts by gas infall vs. numerical tricks?
  As satellites of mature galaxies!
- Morphological transformations are possible:
  Cluster dEs of different origin; cl.-born vs. infall!
- Starbursts by gas accretion (or stochastically?)
- DGs as probes of astrophysical processes and numerical prescriptions:
  star-formation recipes, ISM phases
- TDGs are a potential reservoir of replacing destroyed DGs.
- DGs are challenging CDM cosmology
THANK YOU
for your attention!!!
- Glad to be here and
to seeing you for
discussions and collaborations

Summing up Dwarf Galaxies:

- DGs’ evolution is highly complex!
  Gas outflows and infall, transformation
- DGs are results of their environment!
  Cluster dEs of different origin!
  Starbursts by gas accretion (or stochastically?)
- DGs’ CDM formation questionable: Continues
  production-transformation-mass loss/accretion cycle?
- TDGs survive without DM: DG fraction?
- What does their distribution in the local
  Universe teach us?
  More observational and modelling details requested!
- Present-day gas accumulation:
  HI-dominated LSB DGs