Strangulation of cluster galaxies as seen by their chemical enrichment and HI gas content and quenching timescales

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Environmental effects: more dominant at $z<0.5$

- Environmental effects gain importance as large scale structures in the Universe develop with time, and become the dominant mechanism for quenching $M_{\text{stellar}} < 2-3 \times 10^{10} M_{\odot}$ galaxies at $z<0.5$

- Clusters of galaxies at $z<0.5$: sites where environmental effects more pronounced and more easily observed with present-day telescopes

Peng, Lilly, ... Maier et al. (2010)
Short advert: mass-quenching using zCOSMOS $M_{\text{stellar}}/M_{\text{tot}}$

- Master thesis of N. Lampichler under my supervision: use zCOSMOS VIMOS tilted-slits to get $v_{\text{max}}$, study Tully-Fisher relation and derive $M_{\text{total}}$

- compare $M_{\text{stellar}}/M_{\text{tot}}$ with MZR at $z<1$ & bathtub to constrain halo-quenching

Maier, Lampichler et al., in prep.

Maier, Ziegler, Lilly et al. (2015)
Strangulation/starvation/suffocation: slow process

In humans: death by strangulation is a slow process, about 4 minutes - victim uses up oxygen in the lungs but keeps producing carbon dioxide, which remains trapped in the body - high levels of carbon dioxide in the blood of a corpse suggest suffocation

In galaxies: strangulation is a slow process, ends the formation of stars in galaxies in ~4 Gyrs (Peng et al. 2015, Maier et al. 2016) - the supply of cold gas onto the galaxy disk is halted, but star formation can continue, using the gas available in the disk until it is completely used up - instead of building carbon dioxide, the strangled galaxies accumulate metals produced by massive stars - higher metallicities: evidence for galactic “suffocation”
Environmental effects on Z(M,SFR) and quenching

Heterogeneous results in literature on the role of environment, by enhancing/lowering metallicities in cluster galaxies compared to field: e.g., Mouhcine et al. (2006), Cooper et al. (2006), Ellison et al. (2009), Kulas et al. (2013), Valentino et al. (2015), Kacprzak et al. (2015)

Aim of this work:

Use large samples of emission line galaxies in clusters, with reliable gas metallicities O/H based on Hβ, [OIII], Hα, [NII], and SFRs from Hα - to study the influence of cluster environment on the mass-metallicity relation Z(M) and on the Z(M,SFR) relation and constrain quenching in:

LoCUSS clusters at z~0.2 (Maier et al. 2017, in prep)

MACJ0416.1-2403 CLASH cluster galaxies at z~0.4 (Maier et al. 2016, A&A, 590, A108)
CLASH-VLT

Cluster Lensing and Supernova survey with Hubble, Postman et al. (2012)
HST Multi-CycleTreasury Program (530 orbits) – PI: M. Postman

CLASH-VLT (PI : P. Rosati):
- 200 hours of VLT-VIMOS (LR-Blue and MR grisms) spectroscopy
- 13 massive relaxed clusters at z=0.3-0.6 from CLASH

dynamical analysis up to $\sim 3R_{\text{vir}}$

$\sim 500$ members per cluster

HST area $3.3 \times 3.3 \text{ arcmin}^2$

VIMOS spectra over 30x30 arcmin$^2$ field
Subaru Suprime Cam
different environments D1-D4

Cluster MACSJ0416 at $z \sim 0.39$
BPT diagram of CLASH MAC0416 cluster galaxies at z~0.4

Star-forming sequence is O3N2 metallicity sequence (between dashed lines)

Field and cluster SF galaxies at z~0.4 are not dominated by type-2 AGNs


Maier et al., 2015, A&A, 577, A14
The specific SFR vs. mass relation

- SFRs from extinction corrected Hα (both for cluster and field galaxies)
- oblique solid thick line shows the main sequence (MS) at z~0.4 and its dispersion (gray area), the dashed red line depicts the local SDSS MS
- comparable distribution (median values and scatter) of field and cluster galaxies, especially at intermediate masses $9.2 < \log(M/M_{\odot}) < 10.2$

Maier et al. (2016)
Caution note: high SFR threshold selection effects

- a higher SFR threshold (above red solid line), like in some studies with SFRs derived from infrared observations, would result in higher mean sSFRs of field compared to cluster galaxies:

- due to larger scatter of sSFRs in the field compared to cluster, and because of missing lower sSFR galaxies
The mass-metallicity relation (MZR)

- gas metallicities using O3N2-method, 4 emission lines Hβ, [OIII], Hα, [NII]
- cluster galaxies have similar metallicities as field galaxies (polynomial fits and median values), lower by ~0.1 dex compared to SDSS (at a given mass)

Maier et al. (2016)
Morphological dependence of offsets to local MZR

- median offsets of cluster galaxies to the local MZR (shaded: 1σ scatter)
- Bulge-dominated (smooth) and compact cluster galaxies have lower sSFRs and higher O/Hs than disk-dominated and peculiar objects (FMR)
- the location of galaxies in projected phase-space provides valuable information on their accretion history: on average, infalling galaxies are separated from virialized/accreted galaxies.

- simulations of mass assembly around clusters (massive clusters in the Millenium simulation) demonstrate how galaxies of different accretion histories populate different areas in a characteristic trumpet shaped caustic (isodensity) profile.

Simulations, Haines et al. (2012)
Phase-space diagram MAC0416 & strangulation

- dashed magenta line: caustic from Balestra et al. (2016) dividing infalling objects (above) from accreted objects (below)
- galaxies with $9.2 < \log(M/M_{\odot}) < 10.2$: only 28% infalling objects with higher O/Hs, while 63% of accreted galaxies with higher O/Hs (red symbols)
- plausible scenario: strangulation: metallicity increases because the reservoir of pristine gas is depleted when the galaxies enter the cluster

Maier et al. (2016)
The bathtub model and $Z(M_{\text{star}}, \text{SFR})$

$$Z_{eq} = Z_0 + \frac{y}{1 + \lambda(1 - R)^{-1} + \varepsilon^{-1} \cdot \left(\text{sSFR} + (1 - R)^{-1} \frac{d\ln \mu}{dt}\right)}$$

- The only knowledge of the history of the system is in $d\ln \mu/dt$ term, which reflects changes in the $\text{sSFR}/\varepsilon = \mu$ product (variable $M_{\text{gas}}/M_{\text{star}}$)
- “Ideal” regulator: $d\ln \mu/dt = 0$

$Z_0$: metallicity of the infalling gas
$Z_{eq}$: equilibrium value for metallicity
$y$: yield: mass of metals returned to ISM per unit mass locked up in long lived stars
$\varepsilon = \text{SFR}/M_{\text{gas}}$: star formation efficiency
$\lambda$: mass-loading factor (mass loss is $\lambda \times \text{SFR}$) of any wind that drives gas out of the system

Lilly et al. (2013)
Strangulation indicated by \(Z(M, SFR)\) comparison

- Measured O/Hs of field and infalling cluster galaxies quite agree with the FMR predictions of Lilly et al. (2013), while accreted cluster galaxies (intermediate masses) have a distribution shifted to higher O/Hs than predicted.

Maier et al. (2016)
Strangulation indicated by Z(M,SFR) comparison

\[ Z_{\text{eq}}(m_{\text{star}}, \rho) = Z_0(m_{\text{star}}, \rho) + y(m_{\text{star}}) \frac{SFR(m_{\text{star}})}{\Phi(m_{\text{star}}, \rho)} \]

Peng & Maiolino (2014)

- low-mass galaxies have 2-3 times higher O/Hs than predictions with inflowing pristine gas (open circles): strangulation may have stopped gas inflow and increased their metallicities (cf. Peng & Maiolino 2014, Peng et al. 2015)

Φ: gas inflow rate
Z_0: metallicity of the infalling gas

Surpressed Φ or enhanced Z_0 in dense regions (cluster environment) can enhance metallicities

\( \Phi, Z_0 \): gas inflow rate, metallicity of the infalling gas

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Surpressed Φ or enhanced Z_0 in dense regions (cluster environment) can enhance metallicities
Strangulation indicated by model galaxies

- Offsets to MS and local MZR and paths of model galaxies with constant or exponentially declining SFRs and with or without starvation
- To reach higher O/Hs of SDSS galaxies, strangulation is needed

- Evolution of model galaxies according to predicted $Z(M,SFR)$

Maier et al. (2016)
- At \( \log(M/M_{\odot})<10.2 \) in SDSS (Salpeter IMF used for CLASH, Peng+ 2015 uses Chabrier IMF): stellar metallicity enhancement of satellites is larger than for centrals implying an **environmental origin of strangulation** at \( \log(M/M_{\odot})<10.2 \), with low-mass satellites suffering more from strangulation than centrals.
LoCuSS (Local Cluster Substructure Survey)

- LoCuSS: a multi-wavelength survey of ~80 X-ray luminous galaxy clusters at 0.15<z<0.3 (Smith et al. 2010)
- Imaging: optical, NIR, Spitzer, X-ray

- Arizona Cluster Redshift Survey (ACReS): large spectroscopic survey using Hectospec/MMT of 30 LoCuSS clusters: FoV~1 degree diameter, reaching into infall regions of the clusters, up to ~3R\textsubscript{vir}
- target selection based on J and K NIR imaging: unbiased, stellar-mass selected sample of cluster galaxies
- spectra cover [OII], H\textbeta, [OIII], H\alpha, [NII] emission lines: measure reliable O/Hs and SFRs

- cluster A963: BUDHIES HI survey (Jaffe et al. 2015) detected HI down to 2x10\textsuperscript{9}M\textsubscript{sun} HI masses
LoCuSS HI gas masses in A963 (work in progress)
- Cluster galaxies with HI gas masses measured (red) compared to a local ALFALFA sample with HI measured
- At $\log(M/M_\odot)>10.1$ (above dashed line) almost all cluster galaxies are in gas-depleted region ($\log(M_{\text{st}}/M_\text{H})>0.6$), while almost all local galaxies with $\log(M/M_\odot)>10.65$ are in the gas-depleted region.
Quenching Timescales from fraction of SF objects $f_{SF}$

- Comparison of observed radial population gradients with predictions from cosmological simulations, assuming that 75 clusters form.

- Millenium simulations have the same $f_{SF}$ of field galaxies before galaxies are accreted to the cluster.

- Red/magenta points are for IR and UV SFR>3.4Msun/yr IMF Salpeter (SFR>2Msun/yr IMF Chabrier).

- Timescale for quenching of about 2Gyrs (yellow curves).

Haines et al. (2015)
Quenching Timescales (work in progress) from $f_{\text{SF}}$

- Now LoCuSS clusters galaxies with SFR$>$1Msun/yr (Salpeter IMF) from Hα: more complete sample (see diagram below)
- $f_{\text{SF}}$ consistent with 3-4 Gyrs quenching timescales (orange curves)

New fractions based on fraction of SF galaxies with Hα in emission
Summary

Gas metallicities based on 4 emission lines (H\(\beta\), [OIII], H\(\alpha\), [NII]) and SFRs from extinction corrected H\(\alpha\), in cluster and field galaxies at z~0.2 (LoCuSS/ACReS) and at z~0.4 (CLASH-VLT)

A plausible strangulation scenario for log(M/M\(_{\text{sun}}\))<10.2 cluster galaxies (cf. Peng, Maiolino & Cochrane 2015) indicated by three observing facts:
- higher fraction of accreted (inside caustic) cluster galaxies with high O/Hs compared to infalling objects
- higher metallicities of lower mass cluster accreted galaxies compared to FMR predictions
- chemical evolutionary paths of model galaxies without inflow of gas are needed to explain the higher metallicities of accreted galaxies

Quenching timescales of 3-4 Gyrs in clusters at z~0.2 are found comparing f\(_{\text{SF}}\) (in seven LoCuSS clusters) as a function of clustercentric radius with Millenium simulations
Selection of MAC0416 objects

- Color-luminosity and color-mass diagrams of the sample of 76 galaxies with O/Hs measured compared to parent sample of blue spectroscopic cluster members.
Morphological dependence of offsets to main sequence

- Offset of cluster galaxies from the MS at $z \sim 0.4$ (shaded area: $1\sigma$ scatter)
- Bulge-dominated (smooth) and compact cluster galaxies have lower sSFRs than disk-dominated and peculiar objects (dashed line: median value)