Formation of S0 galaxies in extreme environments: Clues from kinematics and stellar populations
- A pilot study -

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Formation scenarios of S0 galaxies

**Topic:** How environment (field/cluster) affects the formation of lenticular galaxies (S0s).

Several S0s formation scenarios have been proposed → different signatures on the galaxy properties (see e.g., Ricci et al. 2018 for a compilation of prediction w.r.t. j-M)

- **Mergers:** depending on the geometry and mass of progenitors, S0s can be formed (N-body sim. Bournaud+2005, Eliche-Moral+2012)
- **Ram pressure stripping:** spirals falling into clusters loose gas (Gunn&Gott 1972, Steinhauser+2012) and spiral structure (see also GASP survey, Poggianti et al. 2017).
- **Tidal interactions:** remove gas from a spiral (Merluzzi+2016).
- **Starvation, gas ejection by AGN:** faded spirals, exhausted their gas and lost spiral structure (van den Bergh 2004, Eliche-Moral+ 2012).

...
Formation scenarios of S0 galaxies

Two “macroscopic groups” of formation scenarios:
- Galaxy mergers → favors more “dynamically hot” systems.
- Change of gas content → favors more “dynamically cold” systems.

Different environments can contribute in different ways to these mechanisms →

How does environment affect the formation of S0s?

- elliptical, red;
- S0, blue;
- cD, green

Thomas et al. (2005)
Galaxy properties with environment

Properties depend on environment and for how long the galaxy has been exposed to that environment.

Study that I will present: S0s only, mainly kinematics, isolation vs cluster.

Pasquali et al. (2019)
See also talk by Gallazzi yesterday.
Formation scenarios of S0 galaxies

Two “macroscopic groups” of formation scenarios:
• Galaxy mergers $\rightarrow$ favors more “dynamically hot” systems.
• Change of gas content $\rightarrow$ favors more “dynamically cold” systems.

Different environments can contribute in different ways to these mechanisms $\rightarrow$ How does environment affect the formation of S0s?

To answer to this question, we will:
• Investigate whether or not S0s living in different environments (field/cluster) have different properties $\rightarrow$ signature of the environment in the S0s properties.
• Establish a link between these differences and the formation mechanisms.
• $\rightarrow$ Identify the dominant formation mechanism that acts in a given environment (dominant w.r.t. S0s, not in general).
How can we do it? A survey

~250 S0s from existing surveys plus dedicated observations in the nearby universe covering:

- from sparse fields to dense clusters;
- Various clustercentric distance and infall-time estimate;
- ~uniform mass distribution;
- ~uniform bulge/total light ratio distribution.

The planned analysis

Tully-Fisher relations, rotation curves, morphology, $V/\sigma$ and $\lambda$ profiles, stellar population separating the mutual contamination of bulge and disk via spectroscopic decomposition; analysis in bins of mass, environmental density, bulge/total light, luminosity...

...Unfortunately we do not have started survey yet. We have completed the analysis on a pilot sample of 21 S0s in opposite environments (field/cluster) → subject of this talk. (Coccato et al. 2019, submitted).
The pilot sample

FIELD sample: 12 galaxies.
• 4 S0s from the 2MASS catalogue of isolated galaxies (2MIG, Karachentseva et al. 2010), with our VLT-MUSE observations.
• 8 S0s from ATLAS3D (S0s in common with 2MIG + galaxies at the lowest 3D galaxy density bin).

CLUSTER sample: 9 galaxies.
• 4 S0s from the Centaurus Cluster, with our VLT-MUSE observations.
• 5 S0s from ATLAS3D (S0s in VIRGO in the highest 3D galaxy density bin of the cluster).

Morphology confirmed via visual inspection and bulge/disk photometric decomposition. No barred systems.
Data Quality of new observations

Coccato et al. (2019, submitted)
Vrot/σ and λ

Vrot/σ

Vrot: armonic decomposition of velocity field ("kinemetry", Krajnovic et al 2006)

\[ V(a, \psi) = A_0(a) + \sum_{n=1}^{N} A_n(a) \sin(n\psi) + B_n(a) \cos(n\psi), \]

\[ V(R, \psi) = V_0 + V_c(R) \sin i \cos \psi, \]

σ = azimuthal average along elliptical bins

λ

\[ \lambda_R = \frac{\sum_{i=1}^{N_p} F_i R_i |V_i|}{\sum_{i=1}^{N_p} F_i R_i \sqrt{V_i^2 + \sigma_i^2}}, \]

Emsellem et al. (2007)
Note:

- $\lambda(R)$ is a “cumulative” measurement, the value at large radii depends also on the properties of the inner region (global galaxy property, with possible dependency from bulge/disk ratio, but see next slide).
- $V_{\text{rot}}/\sigma$ is a “local” measurement, the value at large radii is independent from the properties in the inner regions.
Environment and Kinematics – $V_{\text{rot}}/\sigma$ and $\lambda$

Thick lines: MUSE sample.

Coccato et al. (2019, submitted)
S0s in a CLUSTER environment tend to have
- steeper Vrot/σ and λ profiles
- higher values of Vrot/σ and λ at given radius (Re or 1.5 Re)
than S0s in the FIELD. Differences at 1Re is at 1.5 sigma level.
Do we really see environment or do we have a biased from other parameters? 

Class separation by other parameters is not as significant as the separation by environment! → We see the signature of the environment in the kinematic properties of S0 galaxies.

Coccato et al. (2019, submitted)
S0s lie below their Spiral counterparts.

No difference between galaxies in FIELD and CLUSTER.
- noise too large?
- really no difference?

Mergers place the remnant at low V_{circ} for fixed luminosity.
- S0s formed via major mergers “were” off the present-day T-F, but “got back in line” after 4-7 Gyr of passive evolution (Tapia et. al 2017).

V_{circ} from Jeans Axisymmetric Models of the stellar kinematics.
Only “flat” stellar rotation curves are used.
Environment and stellar populations

No difference between **FIELD** and **CLUSTER**.

Hint of difference with mass (more massive \( \rightarrow \) older, metal richer, smaller formation time-scale) \( \rightarrow \) This is already know (e.g. M-Z relation).

2D maps, spectroscopic bulge/disk decomposition, composite stellar populations on the way (Johnston et al., in preparation)

Full spectral fitting, mass-weighted SSP parameters

Coccato et al. (2019, submitted)
Environment and stellar populations

Ellipticals + S0s

Strong dependency with MASS
Weak dependency with galaxy density

McDermid et al. (2015)
Environment and stellar populations

Fraser-McKelvie et al. (2015)

Clear mass bimodality in disk age/metallicity

No difference between field and isolated S0s, but:
- cluster galaxies are missing/rare.
- only bulge of S0s are.
Interpretation of the results

2 groups of S0s formation scenarios:

- **Galaxy interactions** (mergers, interactions). Products have smaller \( V/\sigma \) and \( \lambda \) than spiral counterparts. Consistent with properties of S0 in FIELD environment. For a given mass, \( V_{\text{circ}} \) is lower at formation time than what observed at \( z=0 \). Need 4-5 Gyr to get back to \( z=0 \) Tully-Fisher relation.

- **Change of gas content** (ram pressure stripping, starvation...). Products have kinematic properties not too far away from their progenitors, i.e., faded spirals will retain most of their \( V/\sigma \) and \( \lambda \). Consistent with properties of S0 in CLUSTER environment.

Interpretation. The most efficient formation scenarios for S0s are:

- Field environment \( \rightarrow \) mergers. 4-7 Gyr of passive evolution.
- Cluster environment \( \rightarrow \) gas stripping; “faded spiral” scenario(s). Contribution of minor mergers is not excluded (Cluster S0s are not as cold as spirals).
Summary

- Signature of environment (field/group) in kinematic properties \((V/\sigma, \lambda)\) of S0s at \(\sim 1.5\sigma\) significance level. **Field S0**: dynamically hotter. **Cluster S0** dynamically colder. No differences in the Tully-Fisher relation.

- Interpretation:
  - **Field S0s** are the end product of mergers that produce a component “dynamically hotter” than cluster S0s. Formation happened 4-7 Gyr ago, to leave merger remnant enough time to get back into the present-day Tully-Fisher relation.
  - **Cluster S0s** are formed via processes that involve the rapid consumption of gas that produce stellar components that are “dynamically colder” than field galaxies. Majority of Cluster S0 in our sample have little or no gas. Cluster S0 are “faded spirals”.

- Stellar populations (age, metallicity, star formation time-scale) depend more from MASS than from environment.

**Caveat**: Only 21 galaxies in this PILOT STUDY, do not over-interpret the results.

**Planning of a larger survey ongoing.**

**Warning**: be careful when comparing to results from other studies, as definition of environment, mass range, parameter space, and analysis are different.