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Galaxy evolution across the Cosmic Web: A review (Invited contribution)

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Abstract

From a galaxy's point of view, its environment has continued to evolve during its lifetime, going from lower to higher density regions as it moves across the cosmic web. This paper reviews our current understanding of the effect of environment on galaxy evolution, including the consequences of gravitational interactions between galaxies, and hydrodynamical interactions between galaxies and their host group or cluster. Some recent studies on galaxies caught in the act of transformation are highlighted, including the spectacular "jellyfish" galaxies which are in the process of gas stripping due to intense ram-pressure by the intracluster medium. We further discuss the current challenges in our understanding of galaxy evolution, including the complexity imposed by the hierarchical formation of structure which leads galaxies to be "pre-processed" in groups and filaments prior entering a massive cluster. Finally, we provide an overview of the ongoing and future observational efforts in the South America.

Resumen

Desde el punto de vista de una galaxia, su entorno evoluciona durante su vida, pasando de regiones de densidad baja a regiones de densidad alta a medida que atraviesa la red cósmica. Este artículo revisa nuestra comprensión actual del efecto del entorno en la evolución de las galaxias, incluidas las consecuencias de las interacciones gravitacionales entre galaxias y las interacciones hidrodinámicas entre galaxias y el grupo o cúmulo en el que habitan. Se destacan algunos estudios recientes sobre galaxias en pleno acto de transformación, incluidas las espectaculares galaxias "medusa" que están en proceso de barrido de gas debido a la intensa presión del medio intra cúmulo. Además, se discuten los desafíos actuales en nuestra comprensión de la evolución de las galaxias, incluida la complejidad impuesta por la formación jerárquica de estructuras que lleva a las galaxias a ser "pre-procesadas" en grupos y filamentos antes de ingresar a un cúmulo masivo. Finalmente, se destacan algunas campañas observacionales actuales en América del Sur.

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1. Introduction

In a hierarchical Universe clusters grow via the accretion of galaxies from the field, filaments, groups and even other clusters. As galaxies migrate from low to high density environments within the cosmic web, they can lose their gas reservoirs via different mechanisms, eventually quenching their star-formation and transforming morphologically. Evidence for this includes the increased fraction of early-type galaxies in dense environments at the expense of late-types (known as the morphology-density relation; Dressler, 1980); a bimodality of the colour-density relation (Hogg et al., 2003, 2004); the consistent decrease in the fraction of star forming galaxies in cluster cores (Lewis et al., 2002; Gómez et al., 2003; Bamford et al., 2009; von der Linden et al., 2010); as well as increasing gas deficiencies (e.g. Solanes et al., 2001; Jaffé et al., 2015).

It has now been established that galaxies are quenched by a combination of internal (e.g. AGN) and external processes (Peng et al., 2010).

This review focuses on external mechanisms which can be divided into two main types (see Boselli & Gavazzi, 2006; Boselli et al., 2022, for a review): **(i)** Gravitational or tidal mechanisms such as galaxy-galaxy interactions and mergers, interactions between galaxies and the gravitational potential of the host cluster, and the so-called "harassment", or cumulative high-speed encounters between galaxies. These kinds of interactions are expected to affect both the stellar and gaseous mass within galaxies. **(ii)** Hydrodynamical interactions between cluster galaxies' gaseous component and the hot intra-cluster medium (ICM) can result in gas stripping due to ram pressure thermal evaporation or turbulent/viscous stripping. All of these processes alter the gas content/consumption cycle of galaxies, altering their ability to form new stars and also their morphologies, and are thus fundamental to understand galaxy evolution. For example, galaxy mergers between two gas-rich star-forming spirals can result into a quiescent elliptical, and gas stripping of cluster spirals could potentially lead to form S0 galaxies (which where rarer in the higher redshift Universe; Desai et al., 2007).

In this (biased) review, I highlight a few recent efforts in understanding *how, when, and where* galaxies exhaust or loose their gas reservoirs, quench their star formation, and transform morphologically as a function of their environment.

2. Galaxy evolution in clusters

Galaxy clusters are one of the largest and densest concentrations of matter in the Universe and are known to accelerate galaxy evolution.

In particular, large spectroscopic surveys covering galaxy clusters have established that the quenching of the star formation occurs as galaxies "virialize" into the host cluster (see e.g. Haines et al., 2013; Pasquali et al., 2019).

There is mounting evidence that ram-pressure stripping (RPS) is among the most effective mechanisms removing gas from galaxies and subsequently quenching them in cluster environments (Cortese et al., 2021). The most striking observations of RPS at play come from measurements of the abundance and distribution of Neutral Hydrogen (HI) in infalling cluster galaxies (see Cortese et al., 2021, and references therein) which have revealed how cold gas is removed from the galaxies without altering the underlying stellar populations. Furthermore, Optical and Ultra-Violet (UV) observations have revealed the presence of young stars in the stripped tails of some cluster galaxies (e.g. Kenney & Koopmann, 1999; Cortese et al., 2007; Owers et al., 2007; Yoshida et al., 2008; Kenney et al., 2014; Gullieuszik et al., 2023). The most striking examples have been referred to as "Jellyfish" galaxies (Fig. 1).

Examples of "Jellyfish" galaxies started to appear increasingly more frequently in cluster studies in the past couple of decades in a variety of wavelengths, and more recently, large samples of jellyfish have become available (Poggianti et al., 2016; McPartland et al., 2016; Roberts et al., 2021), allowing for statistical studies of these galaxies undergoing intense transformations. With these samples and the use of phase-space diagrams to infer the orbital histories of galaxies it has been established that RSP is very effective on first infall into the cluster and is favoured in

Figure 1. Example "jellyfish" galaxy (JO206) from the GASP survey (Poggianti et al., 2017a). The stars in the disk (white) are largely unperturbed, while the gas (H_α emission in pink) is clearly disturbed. The direction of the tails is assumed to be opposite to the direction of movement within the cluster. Image credits: GASP-ESO.

radial orbits (Jaffé et al., 2015, 2018; Roberts et al., 2021). The tail directions of the jellyfish galaxies can be used to further constrain the duration of the visible RPS features (Smith et al., 2022), which seem to appear close to the virial radius during first infall and disappear 650 Myr after pericentric passage (Salinas et al. *submitted*).

The details of how the stripping happens and its consequences on galaxy evolution are revealed by dedicated surveys such as VESTIGE (Virgo Environmental Survey Tracing Ionised Gas Emission; PI. A. Boselli) and GASP (the Gas Stripping Phenomena Survey; PI. B. Poggianti). In particular, GASP obtained MUSE/VLT (and follow-up multi-wavelength) observations for over 100 jellyfish galaxies revealing how gas is stripped from the outside-in in the galaxy disks as they fall deeper into the potential well of clusters. This process can lead to enhanced star formation in the disk, extra-planar star formation, and even unwinding of the spiral arm structure or activation of the central black hole (Poggianti et al., 2017a,b; Bellhouse et al., 2021).

3. Pre-processing in groups and filaments

Where do cluster galaxies come from?

The mass assembly of galaxy clusters, aside from the initial filamentary collapse, is primarily driven by accretion of smaller scale haloes such as the collapse of galaxy groups into a galaxy cluster. Cosmological simulations predict that massive ($\sim 10^{15} M_\odot$) clusters at $z = 0$ have accreted $\sim 40\%$ of their galaxies from groups (McGee et al., 2009).

The accretion histories of clusters, together with observational evidence for quenching of galaxies in group-sized haloes have led to the concept of pre-processing (Zabludoff et al., 1996). Recent observations have confirmed that significant pre-processing must be at play, since even at large cluster-centric radii well beyond the maximal rebound radius of backsplash galaxies ($2\lambda 3\times R_{200}$), the star-forming galaxy fraction falls well short of that seen in the coeval field (Haines et al., 2015; Lopes et al., 2024).

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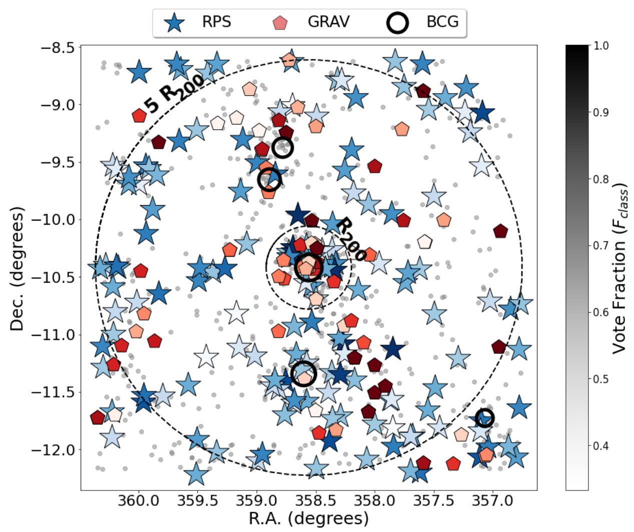

Figure 2. Distribution of interacting galaxies around the galaxy cluster A2670, split by type of interaction: Gravitational (red pentagons) and Hydrodynamical (RPS, blue stars). Both types are found in the cluster core and extend even out to $5 \times R_{200}$. The darkness of symbols correspond to the degree of confidence of the visual classification of the interacting galaxies. Grey dots correspond to other galaxies in the cluster and the open black circles mark the location of the 5 brightest ones. Adapted from Piraino-Cerda et al. 2023.

What remains unclear is what physical mechanisms drive galaxy evolution in those environments and how efficient they are in quenching and transforming galaxies.

In addition to groups, cosmic filaments are also key in understanding pre-processing as they contain 50% of the mass in the Universe even though they only make up 6% of the volume (Cautun et al., 2014). It has been found that, similarly to cluster environment, filaments can induce galaxy transformations, such as increased fractions of elliptical or red galaxies, quenching of star-formation processes, and increased stellar masses. However, the strength of these density relations are not as prominent as those found in within the galaxy cluster regions themselves and the transformation mechanisms in these environments remain vastly unknown.

4. Future Perspectives

To study pre-processing at play and understand the physical mechanisms transforming galaxies outside of clusters it is thus important to study galaxy clusters well beyond the virial radius and to study those galaxies that lie within large-scale filaments. This is only possible with large cosmological simulations and wide and deep photometric and spectroscopic surveys.

In the latin-american region, there are several large efforts including the The Souther Photometric Local Universe Survey (S-PLUS; PI. Mendes de Oliveira) is an ongoing multi-band optical survey designed to cover an area of 8,000 deg^2 down to i=21. S-PLUS is observing large areas around massive clusters at different redshifts in an efficient way, providing the means to obtain accurate photometric redshift, colour and stellar mass estimates for galaxies well beyond the virial radius.

Going to unprecedented depths, the upcoming LSST at the Vera Rubin Observatory will revolutionize our view of galaxy evolution by revealing the very low-surface brightness regime. With such sensitive data we will be able to characterize galaxy morphologies in a whole new way. The current trend is to utilize AI or parametric tools to classify and identify different kinds of galaxies and features (Bom et al., 2024). In addition to these efforts, there are a number of citizen science projects aiming at obtaining large samples of specific galaxy populations such as "jellyfish" galaxies[1].

On the spectroscopic side, the 4MOST facility will soon start operating in Chile, and will immensely increase the spectroscopic coverage of the southern sky. In particular, the 4MOST CHileAN Cluster galaxy Evolution Survey (CHANCES, PIs Haines & Jaffé) will study the evolution of over 300.000 galaxies in and around 100 clusters and superclusters over the last 4 Gyr of cosmic time (Haines et al., 2023), providing legacy support for the eROSITA X-ray mission. One of its unique aspects that it will push well beyond the virial radius of massive nearby clusters to cover the surrounding infall regions as far out as 5 times the virial radius from the cluster, permitting the effects of pre-processing on galaxies within infalling X-ray groups and filaments to be quantified in unprecedented detail down to the dwarph galaxy regime (r= 20.5).

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[1]See projects "Cosmological Jellyfish" and "Fishing for Jellyfish galaxies" in zooniverse.org

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