Star formation and nuclear activity in dense environments through cosmic time

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The standard ΛCDM cosmological model predicts a hierarchical scenario for the formation and evolution of large-scale structures in an expanding Universe. In this scenario, the first structures to form in the Universe are halos of dark matter that, through merging with virialized, smaller halos, and accretion of diffuse matter, form increasingly massive, gravitationally bound structures such as groups and clusters of galaxies. The baryonic matter also falls into the potential wells of these dark matter halos, where it undergoes cooling and reaches high density, forming stars and galaxies and feeding super massive black holes (SMBHs).

In a simplified framework, galaxies can be classified in a bimodal scheme with red passive *early-type* galaxies being typically more massive and lacking star formation and gas, and blue *late-type* galaxies, which have newborn stars and greater reservoir of gas. The observed bimodality implies that galaxies rapidly evolve through a 'transition' region, called *green valley*, consisting in a rapid quenching of the star formation process. The quenching of star formation, and in general of any accretion process of diffuse baryons that can potentially feed new episodes of star formation and feeding of the SMBH, is an ensemble of complex physical processes that depends on the environment in a way that, at present, is not fully understood. At low redshift (z≤1.5) there is a strong anti-correlation between the star-formation rate and the environment density and mass. This means that the dense environments of local galaxy clusters are preferentially populated by massive early-type galaxies and show a pronounced morphology-density relation. This evidence can be understood as the result of the combined action of galaxy-galaxy mergers, harassment, strangulation, and ram-pressure stripping, that are enhanced in high-density environments and can directly affect the accretion of cold gas and, therefore, accelerate the evolution of galaxies from star-forming, gas rich, to red-and-dead galaxies.

However, increasing observational evidences show that this trend is completely reversed at high redshift ($z > 2$), when the densest regions in the Universe are also those with the strongest nuclear and star formation activity. We can roughly identify a transition epoch at $1.5 < z < 2.5$ when star formation and nuclear activity migrates from the densest, central regions of young clusters or protoclusters of galaxies, to the external regions of mature, virialized clusters. Therefore, the ideal approach to investigate the effects of the environment in galaxy evolution is to trace the galaxy population in well defined, dense environments through this redshift range. This approach is challenging from the observational point of view, since it requires deep, high angular-resolution observations on a broad wavelength range, to trace at the same time the cold, ionized and hot gas, stellar mass, star formation processes and nuclear activity, across the entire galaxy population.

A possible strategy is targeting specific objects and phenomena that are expected to play a major role in this framework. One of these is the origin and evolution of the Brightest Cluster Galaxy (BCG). BCGs are massive ($M \sim 10^{12} M_\odot$), luminous and giant elliptical galaxies at the center of evolved galaxy clusters. They constitute a special category of galaxies that still lacks a detailed understanding. Models and simulations predict that the mass of the BCG begins to assemble at z∼3-5 in several small distinct halos. At z∼2.5, thanks to the density increase of the environment and the formation of the so-called protoclusters, the progenitors of these giant galaxies are still actively forming stars while undergoing merging. At $z < 1.5$ BCG formation is almost complete in the Universe, and their star formation and nuclear activity are strongly reduced. Eventually, during their secular evolution, BCGs experience further mass growth due to merging with smaller satellite galaxies, and short episodes of star formation and nuclear activity triggered by intermittent cooling events in the cluster cores. Star-formation quenching, both after the major episodes associated to the formation of the BCG and after minor episodes, is thought to be regulated by the feedback phase of the Active Galactic Nucleus (AGN), in form of winds and outflows. However, many details of these processes are not clear yet, in particular: the coupling of the AGN jets and winds with the surrounding intergalactic and intracluster medium (IGM and ICM); the duty-cycle of feedback events; the competing role of merging with satellite galaxies and of accretion of pristine diffuse gas in triggering the activity. Therefore, tracing the co-evolution between star-formation, AGN, merger activity and growth of the environment in the range $z \sim 1-3$ (slightly wider than the epoch of maximum activity previously defined) is fundamental to understand the key steps in the evolutionary pathways of cluster galaxies, and, on a broader perspective, of the overall galaxy population.

I started to address these issues in my Master thesis project, studying the multi-wavelength properties of a dense region inside a galaxy cluster at $z \sim 1.6$ (`XDCP0044`). This cluster shows a clear inversion of the star-formation density relation and the presence of nuclear activity (at least five AGNs) in a dense environment. In the analyzed region, we found up to nine sources in two different complexes, a high level of star-formation rate, frequent nuclear activity and signs of ongoing mergers. Our analysis suggests that we are witnessing the mass assembly of the central massive galaxy in one of the densest region of a galaxy cluster at a lookback time of 9.5 Gyr. These results support a scenario in which AGN activity may be triggered by gas-rich galaxy mergers and that AGNs have a key role in the formation of red passive galaxies observed in local galaxy clusters.

In my PhD thesis project I plan to extend this approach to a broad mass and redshift range (protoclusters, clusters and groups of galaxies at $1 < z < 3$). For this project we will inevitably adopt a multi-wavelength approach including bands from X-ray to Infrared, and use imaging, photometric and spectroscopic data. We will make use of archival data when possible, and proprietary data obtained with proposals submitted to the major international observing facilities. The immediate goals of my research work consist in:

- analyzing X-ray spectra to investigate the presence of AGNs and, possibly, of hot diffuse baryons in high-density environment;
- performing optical spectroscopic analysis in order to investigate the presence of broad line AGNs, hence calculate the central black hole mass, Eddington luminosity and accretion rate;
- investigating emission/absorption lines from the extended optical emission to detect the presence of outflows/inflows;
- mapping emission lines and study the gas dynamics in the analyzed regions;
- performing photometric analysis in order to measure magnitudes and fluxes of the analyzed sources and examine color-color and/or color-magnitude diagrams, along with their spectral energy distributions;
- measuring the star-formation rate of the analyzed sources, along with their stellar mass.

Thanks to this multifaceted activity, I expect to return a strong impact in several topics related to the formation and evolution of the large scale structure of the Universe. In particular, I aim at:

- tracing the baryon energy budget in cluster cores (through gas entropy, nuclear activity and star-formation activity) through cosmic epochs;
- investigating the galaxy mass assembly, the formation of BCGs and the possible presence of cooling flows or cool cores;
- analyzing the AGN fraction in function of redshift, mass and distance;
- exploring how environment can influence nuclear activity and star-formation activity;
- confirming the AGN-galaxy co-evolution scenario.