RD9R section 4.3

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Background

The basic prevailing theoretical framework governing how galaxies form and evolve is the Hierarchical Model. Coming about as a consequence of a broader cosmological model, the ΛCDM (CDM meaning Cold Dark Matter and Λ representing a cosmological constant giving the Universe its observed accelerated expansion), which states that structure forms hierarchically in a bottom-up fashion, beginning with small primordial density fluctuations in dark matter. These then get amplified by gravitational instability and grow into self-similar, ellipsoidal collapsed objects called dark matter halos on a range of scales [1, 2]. Baryonic matter interacts with dark matter gravitationally and, since matter content is dominated by dark matter ($\sim$90% of the mass), gas follows the structure dictated by it [3]. The gas then cools via radiative processes and eventually settles at the centre of the potential well forming a rotationally supported disk galaxy [4, 5].

Galaxies don't spend their lives in isolation, however, as gravitational interactions between different galaxies (and their DM halos) cause them to form self-contained, gravitationally bound groups and clusters. Over time, haloes grow by collisionless accretion and mergers with one, most massive, halo being established as the central host [6]. The close proximity and frequent interaction of neighbouring galaxies give rise to several processes resulting in changes of morphology, mass, or altered star formation rate (SFR). One significant observation is that galaxies in denser regions tend to have attenuated star formation rates when compared to their counterparts in the less dense environments [7]. A similar trend is observed for galaxy morphologies, with more elliptical galaxies in dense environments [8].

Star formation may be quenched in one of several ways or, more likely, a combination of several:
Ram pressure stripping: galaxy clusters are filled with hot, X-ray emitting gas (the intra-cluster medium, ICM). As galaxies move within the clusters they move through the ICM and experience a resistive force like a wind. If the shock front is strong enough it can exert sufficient force on the cold gas in a galaxy for it to overcome the gravitational potential and be stripped. The cold gas becomes part of the intra-cluster medium and is no longer available for star formation, which results in a rapid form of quenching on timescales less than 500 Myr in massive clusters (M $> 10^{12}$ solar masses) [9, 10]. Whether it is as effective or, indeed, at all possible for lower mass clusters remains to be seen.
Turbulent viscous stripping: in addition to ram pressure stripping, as the galaxy moves through the ICM it will lose cold gas continuously due to viscosity and turbulence. Nulsen [11] found this mode can remove more gas than ram pressure alone, allowing for an even quicker quenching.

Collisions and mergers: within a densely populated cluster, mergers are inevitable. While merging can trigger a star burst in a galaxy immediately after a collision, on long timescales of more than a Gyr it has the effect of scattering and disrupting the gas available for star formation in a galaxy's disk [12].
Strangulation / starvation: a more gradual process involving the loss of gas accretion onto a galaxy. Disruptions from neighbouring galaxies can halt the process of ICM cooling and fuelling new star formation by accreting onto the disk [13]. The timescale is expected to be over 1 Gyr, however, the exact process is still under active research. It is unclear whether galaxies react to the halting of accretion immediately or if there is a delay, during which star formation goes on as normal.
Harassment: galaxies interact gravitationally with each other. High speed, nearby encounters can tidally disrupt and heat satellites, again, removing cold gas available for star formation [14]. This is a gradual process and is expected to take over a Gyr to have a significant effect.
Tidal compression / truncation: as satellites orbit and accrete onto the host halo, they experience significant tidal forces which can cause the disruption of the disk and a ceasing of star formation [15, 16].

A significant amount of work has been done in attempting to identify which of these processes are the most dominant, more specifically, how galaxy properties change with their environment. In addition to earlier type (elliptical) galaxies being more strongly clustered than the late type (spiral), it has been observed that colour also correlates with local density. Blue, star forming galaxies are observed predominantly in low density environments while red, inactive galaxies are common in clusters. Furthermore, a persistent bimodality in satellite galaxy colour is observed regardless of the nature of their host, there is no variation in the intermediate stage (the green valley), suggesting that quenching occurs rapidly. Satellites experience no significant effects until they come to within the virial radius of their host halo and, once they do so, star formation continues for several Gyrs, but then quenches rapidly [10, 17, 18], suggesting that ram pressure stripping and/or strangulation are involved. There is also evidence that satellites can be stripped and then ejected from the halo before falling back in, which complicates the picture as up to 40 percent of satellites can be of this kind [19]. More recent studies, however, present evidence that gas stripping externally may not be the dominant means of quenching. The suggestion is that 'overconsumption', the exhaustion of a gas reservoir through star formation and expulsion via modest outflows in the absence of cosmological accretion [20, 21] is what ultimately causes star formation to stop.

Proposed project

The overall aim of this project is to use recently available, galaxy independent observations to better characterise galaxy environments in clusters and groups. This will then be followed up with simulations in order to better understand the precise physical conditions.

Currently, in order to understand the environment of galaxies from redshift surveys alone, it is necessary to identify all galaxies in the immediate neighbourhood of the chosen target. This is done in one of three ways:

- Galaxies are assigned to groups or clusters and with sufficient number of galaxies its velocity dispersion can be computed. Velocity dispersion corresponds directly with the mass and, hence, density of a virialised dark matter halo.

- A local density can be assigned for each galaxy observed in the sample and density can be estimated using the projected distance to nth nearest neighbour.
- Given a fixed metric aperture, galaxy counts within it can be used to infer the density [22].

The issue with all of these methods is that all redshift surveys are magnitude limited. This presents limitations in either assigning galaxies to groups and clusters or estimating halo mass. Ultimately, models have to be invoked to perform corrections which have the potential of introducing severe systematic errors.

This project proposes a way to characterise galaxy environment without the need to assign them to groups or clusters. The proposed mechanisms for environmental transformation are usually either gravitational (such as tidal interactions) or hydrodynamical in nature (ram pressure stripping, strangulation, etc.). Gravitational interactions are largely determined by the dark matter, while hydrodynamical interactions are determined by the local (hot) gas properties. To date, environmental studies have mainly been looking at the evolution of optical galaxy properties without the benefit of knowing what the local DM and hot gas conditions are. However, there has been a revolution recently in our ability to directly constrain the local DM and hot gas properties, via gravitational lensing (which measures the total overdensity, including DM) and thermal Sunyaev-Zel'dovich (integrated hot gas pressure along the line of sight) and X-ray (gas density) surveys. These new lensing/SZ/X-ray studies have been focussed almost entirely on cosmology [23, 24], but here the same data will be used in environmental work. By cross-correlating galaxy properties with these new data sets, it will be possible to directly map the response of galaxies to these quantities and try to directly determine the dominant environmental processes at play. This will be the very first time this has been done!

In order to perform the cross-correlations, a number of publicly available data sets will be called upon. For lensing, the following optical surveys, each covering a different area of the sky and having a different redshift range, will be used:

- *CFHTLenS*: the Canada France Hawaii Lensing Survey, a 154 square degree optical survey with a median redshift depth of 0.75.
- *RCSLenS*: the Red Cluster Sequence Lensing Survey, a 700 square degree multi-colour optical survey out to redshift of ~ 1.
- *KiDS*: the Kilo-Degree Survey, a 750 square degree optical survey with redshift range of up to ~ 0.3.
- *DES*: the Dark Energy Survey, a 5000 square degree survey of the southern sky out to z$\sim$1.

The Planck all-sky Sunyaev-Zel'dovich effect maps are adequately suitable for this purpose and are publicly available. If the Atacama Cosmology Telescope (ACT) and South Pole Telescope (SPT) data become available over the course of this study, it will be possible to take advantage of their increased resolution (1 arcmin vs. 5 arcmin for Planck) in areas of the sky they cover.

For X-ray data, the publicly-available ROSAT All-Sky Survey (RASS) is sufficient, however, the XMM-Newton XXL survey can also be used to supplement it in select regions of the sky due to its superior redshift range (5.0 vs. 0.7 for RASS).

It is expected that correlations will be found between galaxy properties and all three environmental indicators (SZ, X-ray, and lensing). Advanced statistical techniques (such as Principal Component Analysis) will be applied in order to determine which local conditions are more important for galaxy evolution. This then will allow us to determine which processes (tidal, ram pressure, etc.) are most relevant.

In order to gain a more accurate understanding of the exact physical conditions, taking into account the evolution of galaxy properties with time, simple hierarchical-based, dark matter-only models (similar to those employed by Wetzel et al.) will be constructed in Year 2. These will provide an insight into cluster dynamics and mass distribution without the overly complex interactions of hydrodynamic fluids, making it easier to analyse and understand.

In addition to the dark matter-only models, like-for-like comparisons of the cross-correlation measurements will be made with state-of-the art hydrodynamical simulations like EAGLE and Illustris. Synthetic observations of X-ray, SZ, and lensing will be computed and then cross-correlated with the simulated galaxy population. This will assess the realism of the simulations, particularly with regards to their treatment of environment processes.

Anticipating there to be some successes but also some deficiencies in the simulations, in Year 3 a programming project will be undertaken to improve the realism of physics in the EAGLE simulation code. For example, the EAGLE code does not model radiative processes (such as photoionisation/photoheating) and does not consider thermal conduction, both of which could be important for the question of environment. Alternatively (or perhaps in addition to), an improved model of the cold ISM component of the galaxies (which is treated in a subgrid way in EAGLE) may be deemed necessary to accurately describe the ram pressure stripping of galaxies. Finally, it may be that an improved model of galactic feedback is needed, since the efficacy of environmental processes depends on the internal properties of the galaxies as well (not just on the local environmental properties), which we know is sensitive to how feedback is modelled.

Timescale

- First year (2016 - 2017):

  - October - January: Read the relevant literature and familiarise with existing catalogs.

  - February - April: Compute the relevant maps in a useable format. Compute the cross-correlations between different maps (galaxy properties, lensing, X-ray, SZ).

  - May - August: Perform statistical analysis to interpret the results and determine the dominant processes.

- September - October: Write and submit the transfer report.

- Second year (2017 - 2018):
  - October - January: Construct hierarchical dark matter-only models.
  - February - April: Analyse the synthetic observations and compare the cross-correlation signals with true observations.
  - May - August: Attend at least one major conference/workshop in a related field of study.
  - September - October: Compute synthetic observations from hydrodynamic simulations and contrast with those already obtained.

- Third year year (2018 - 2019):
  - October - April: Modify EAGLE/Illustris code to take into account environmental effects.
  - May - June: Demonstrate the effectiveness of changes made to the simulations by obtaining matching signals.
  - September - October: Prepare, write, and submit thesis.

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