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LPR 2010 WHITE PAPER: GALAXY EVOLUTION AND CLUSTERING

H.K.C. Yee[1], R.G. Abraham[1], A. Babul[2], M. Balogh[3], M. Sawicki[4], and T.M.A. Webb[5]

1. INTRODUCTION

In the last decade tremendous progress has been made in the investigations of galaxy evolution and the large scale structure in which galaxies reside. Canadians have made fundamental contributions in these fields. In this white paper we will examine, with an emphasis on the Canadian perspective, the main advances in the past decade and future prospects in these areas.

2. GALAXY EVOLUTION

2.1. *The Evolution of Field Galaxies*

As the result of a number of galaxy surveys in recent years covering a redshift range from the local universe to over 2, a broad picture has emerged: star formation in the universe ramps up fairly quickly from reionization (at $z > 6$), peaks within $z = 1 - 3$, and then continues to decline to $z = 0$ (Fig. 1). Two new paradigms for describing galaxies are now widely accepted. The main paradigm emerging from the low-redshift surveys, such as the SDSS and the 2dF, is the bimodality in the nearby galaxy population – galaxies can be broadly categorized as belonging to the "blue cloud", or to the "red sequence". Much work has gone into trying to understand how systems wind up in these categories within a hierarchical framework in which galaxy growth is dominated by merging of dark matter halos. The observational impetus for understanding this has turned into a major focus for surveys in the past few years which attempt to characterize the changing galaxy populations to just beyond $z \sim 1$. At these higher redshifts, the dominant paradigm that has emerged is that of "downsizing", which posits that the most massive galaxies form their stars first, and as the universe evolves, stars begin to form in less massive systems.

The epoch between $z = 1$ and 3 contains the peak of both the rates of cosmic star formation and central black hole growth. In the past decade, the first challenge has been to reliably identify samples of galaxies for study at this epoch. A number of selection techniques have been developed, (e.g., LBGs, BzKs, DRGs, LAEs, along with full-blown photometric redshifts), which allow us, while with different selection biases, to locate galaxies at various $z \gtrsim 1$ epochs of interest.

The challenge now is to understand what causes this evolution and how the various types of high-z galaxy populations are related to each other and to the galaxies in the present-day universe. Some of the big questions are: What regulates star formation in galaxies and causes the observed difference in the star formation histories of galaxies of different masses or types? How do galaxies grow in size? How does the red sequence of quiescent galaxies form? What role do galaxy-galaxy interactions play? And what is the role of environment in all this?

Canadian astronomers have made seminal contributions in this effort, from some of the first determinations of the global cosmic star formation history (e.g., Lilly et al. 1996 with the CFRS; Sawicki et al. 1997 using the HDF) to studies of spectroscopically-confirmed mass-selected samples at $z \lesssim 1$ (GDDS: e.g., Abraham et al. 2004; ROLES: e.g., Gilbank et al. 2010) and the faint-end luminosity function at high redshift (Sawicki & Thompson, 2006). The GDDS showed that massive galaxies are far more common at $z \sim 1.5$ than originally expected, and that many of these systems are surprisingly old. Similar results emerged from a number of surveys, lending considerable impetus into making downsizing such a dominant paradigm.

Accommodating the new observations in the framework of hierarchical growth led to considerable revisions in models, and in particular highlighted the need for additional physics (such as the growth of black holes and the important role played by AGN feedback). While numerical simulations have grown more sophisticated over the years, the complex processes that regulate gas infall, cooling, star formation, and energetic feedback will remain challenging to simulate convincingly for some time yet, and the field will likely continue be driven by observations. To make further progress, we need robust observational tracers that can link galaxy populations over time, and provide information on processes such as gas consumption and energetic feedback. Here, it will be critical to survey large areas (to minimize "cosmic variance" and to probe a range of environments) with greater sensitivity (to probe down to low-mass systems). Multi-wavelength coverage from X-rays to rest-frame UV to radio wavelengths is essential to probe the range of relevant physical processes.

2.2. *Dusty Starburst Galaxies*

Despite the immense progress in our understanding of galaxy evolution through extensive optical spectroscopic surveys in the past decade, it was clear even a decade ago that the picture outlined by these data was incomplete. The measurement of the diffuse cosmic infrared background (CIB) provided by COBE indicated that approximately half the energy produced by objects in the universe was emitted at infrared wavelengths. The resolution of the CIB, with Canadian SCUBA surveys (e.g., Webb et al. 2003) on JCMT playing the dominant role, revealed populations of luminous infrared galaxies at $z>1$ with prodigious star formation rates and concurrent AGN activity, at levels far above that seen previously in the optical.

The last decade has seen an immense effort to build up larger samples of these systems (such as SHADES [Coppin et al. 2006], in which Canadians played a key role) and elucidate their nature through multiwavelength follow-up. Facilities such as the Spitzer Space Telescope

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[1] Dept. of Astronomy & Astrophysics, University of Toronto
[2] Dept. of Physics & Astronomy, University of Victoria
[3] Dept. of Physics & Astronomy, University of Waterloo
[4] Dept. of Astronomy & Physics, Saint Mary's University
[5] Dept. of Physics & Astronomy, McGill University

have pushed to lower star formation rates (down to tens of $M_{\odot}$/year) over wide areas, confirming the increasing importance of the IR-luminous population with redshift to $z \sim 2$. However, even with this, the bulk of the CIB has yet to be resolved; thus, the majority of the systems responsible for the CIB energy budget remain unknown.

While our modeling of galaxy formation has improved to match observations, we still lack a detailed understanding of the physical processes responsible for the triggering and shutting off of the intense star-burst activity and often concurrent AGN activity prevalent at high redshift. Indeed, the data themselves require substantial improvement before they can be properly guide the models. Small sample sizes so far have precluded robust measurements of clustering for the most IR-luminous galaxies, which is crucial for placing them within a theoretical context. Currently, we also have no comprehensive study of the connections between star-burst activity with environment. The way forward requires high quality observational constraints and inputs for galaxy formation models. IR surveys of wide areas and faint limiting depths are required, but must also be coupled with multiwavelength data and high spatial-resolution observations.

3. GALAXY GROUPS AND CLUSTERS

3.1. *Evolution of Galaxies in Groups and Clusters*

The rate and mode of galaxy evolution clearly depends on environment: galaxies in clusters today differ markedly from the average in most respects (e.g., star formation rate, gas content, morphology). Simple CDM theory predicts that this is at least partly due to the fact that the most massive galaxies form in the densest environments and galaxies get a head-start in clusters. However, the group/cluster environment also dramatically alters the course of evolution through more complex processes such as tidal and hydrodynamic interactions. Because of the growth of large-scale structure with time, and the nonlinear scale-dependence of these effects, such physics must play a large role in the general evolution of galaxies, but remains poorly understood.

Thanks to large spectroscopic surveys such as the SDSS, combined with multi-wavelength photometric data (e.g., GALEX, 2MASS, Spitzer), the environmental dependence of galaxies at z=0 is now well characterized (e.g., Balogh et al. 2004). We have also begun to study how the rate of galaxy evolution depends on environment, from studies of groups and clusters at different redshifts. Canada has played an important role here, starting with the CNOC surveys (Yee et al. 1996, 2000) and continuing with surveys such as the RCS, CFHTLS, and GEEC (Balogh et al 2009). Combined with efforts from other international groups (most notably zCOSMOS), we have established that galaxy evolution has been more rapid in dense environments, and that this is most noticeable in the low-mass systems.

Theoretical work has shown that many properties of the galaxy population can be reproduced in simple “halo models”, in which the dark matter halo mass determines everything about the constituent galaxies, with a distinction made only between the “central” galaxy in the halo and its “satellites”. Such models can explain the colour-dependent correlation functions, and the environmental dependence of the stellar mass function.

The key unanswered question is *why* satellite galaxies have a different evolutionary history from central galaxies, or, indeed, if such a simplified distinction is even adequate. Numerical simulations currently do not have the resolution necessary to reliably follow the key hydrodynamic processes in galaxies together with their motion through growing large scale structure. While progress needs to be made on both sides, ultimately more observations on the star formation and gas consumption timescales as a function of stellar and halo mass are required to constrain theoretical models.

To uncover the mechanisms that have shut down star formation in satellite galaxies we have to observe them when they *first* become incorporated in larger structures, at a time when they were still vigorously forming stars. Much research has focused on galaxies in clusters – but most galaxies become satellites long before they are accreted in large clusters (McGee et al. 2009). The key therefore lies in observations of low-mass galaxies within small groups, up to $z \sim 1$. This will be challenging, as it requires deep, highly complete spectroscopy over large areas and IR/submm follow-up observations to elucidate the nature of the star formation.

3.2. *Cluster Physics*

As one of the main reservoirs of baryons in the universe, galaxy groups and clusters also offer a unique setting to study the impact of galaxies on their environments. These baryons, in the form of hot diffuse gas, bear the imprint of both the gravitational potential of the halos in which they reside, as well as the sequence of thermodynamic processes to which they have been subjected. Models for the formation and evolution of these systems have typically treated non-gravitational processes as minor perturbations. Accumulating observations, however, all indicate that the intracluster gas (ICM) has been profoundly affected by non-gravitation processes. At present, a detailed understanding of the processes responsible for the non-gravitational heating remains elusive.

Non-gravitational heating, and particularly heating of the diffuse gas during the early phases of cluster formation, is the leading explanation for the recent X-ray observations showing that clusters can be characterized as cool core and non-cool core. Canadians have played an instrumental role in uncovering this dichotomy, and in explaining the various cluster scaling relations, and the structure in the associated scatter, as imprints of this dichotomy (e.g., Babul et al. 2002; Balogh et al. 2006; McCarthy et al. 2008). In recent years, Canadians have taken a leadership role in two major multi-wavelength cluster surveys, the CCCP (Mahdavi et al. 2007) and the LoCuSS (Zhang et al. 2010). These surveys are uncovering a wealth of correlations between AGN and star formation activity in central galaxies, about the physics of the ICM (Bildfell et al. 2008; Pipino et al. 2009) and about the interactions between the ICM and the infalling galaxies.

Additionally, X-ray spectra of the gas in cool core clusters shows that it is not cooling as efficiently as expected. Somehow, the radiative losses are being (nearly) offset. High-resolution X-ray images, in conjunction with radio data, indicate that jets and outflows from supermassive black holes in galaxies at cluster centers are interacting with the ICM, inflating “bubbles” (e.g., Fig. 2), and may be responsible for heating the ICM and tempering the cooling flows. A number of Canadians are at the forefront of associated theoretical and observational investigations (e.g., McNamara & Nulsen 2007; Benson & Babul, 2009; Rafferty et al 2010).

In spite of all the progress, a complete picture is still lacking: The precise mechanisms through which AGN outflows heat the ICM remain unresolved, as is the origin of the dichotomy between cool core and non-cool core clusters. A common speculation asserts that the latter are cool core systems transformed by either major mergers or powerful AGN outbursts. However, theoretical and simulation studies pose powerful challenges to both these scenarios. Are the seeds for the dichotomy established earlier, on the group scale perhaps? Groups, which are the building blocks of clusters, have yet to be systematically studied. Finally, there is growing realization that ICM physics is much richer than previously imagined and numerical simulation studies of the phenomenon are still in their infancy.

3.3. *Galaxy Cluster Surveys and Cosmology*

Galaxy clusters and groups serve not only as laboratories for the study of the connections between environment and galaxy formation and evolution, their mass function is the only measurement which provides constraints on cosmological parameters via both the growth-of-structure and volume tests, and can be served as a large scale test of theories of gravity. Large and well-defined samples of clusters and groups at $z \gtrsim 1$ are vital in providing the redshift leverage needed for both galaxy evolution and cosmology.

In the past decade there have been many large efforts using different techniques to conduct surveys for high-redshift galaxy clusters and groups over large areas. Canadians have been in the forefront in these efforts, from being part of SZ surveys (such as ACT and Planck) to being the leading player in optical/IR surveys, thanks to the availability of premiere wide-field capabilities on CFHT. The Red-Sequence Cluster Survey, beginning with RCS1 (Gladders & Yee 2005) in the late 1990's and extending to the 1000 sq. deg RCS2 (Yee et al. 2007), developed the cluster red-sequence method to minimize contamination effect and optimize the discovery of clusters up to $z \sim 1$ (Fig. 3). To push to the $z > 1$ regime, the SpARCS survey (Muzzin et al. 2009) was carried out combining Spitzer SWIRE IR data with optical images (Fig. 4).

These surveys, along with work done using the CFHLS-Wide survey (e.g., Lu et al. 2009), provide samples of as large as 10^4 clusters and groups with $z \lesssim 1$, and hundreds of clusters with $1 \lesssim z \lesssim 2$, sufficient for answering many of the questions raised in this paper. Currently, we are still at the stage of fully exploiting these large photometric databases (e.g., Gladders et al. 2007, Gilbank et al. 2008); detailed follow-up observations of these samples will maximize the scientific returns. To fully utilize these surveys, whether for galaxy evolution, cluster physics, or cosmology, we require wide-field MOS instrumentation to obtain detailed spectroscopic and dynamical information on unprecedented large samples over a significant redshift range, along with high-quality multi-wavelength observations.

4. THE WAY FORWARD

In this white paper, we have summarized the current state and the leading questions in the study of galaxy evolution and their relation to the clustering properties of the universe. Canada has played very significant roles in the advances in this and related areas, especially on the observational side. Progress in the field in the coming years depends on detailed multi-wavelength studies of large samples of faint galaxies of different populations covering large ranges of redshift and mass, and in varied environments. To ensure Canada's continued international stature and competitiveness in this very broad field, we provide the following recommendations.

- **Near-Term Facilities:**

1) Continued support for Canadian participation in JWST and ALMA. JWST will give us very deep imaging at rest-frame optical and IR wavelengths that will allow studies of stellar populations and of galaxy morphologies. ALMA will provide capabilities to study molecular gas, gas kinematics, and dust emission of high-z galaxies. **2) Continued access to SCUBA2** and completion of the JCMT Cosmology Legacy Survey. As the premiere wide-field imaging submm survey instrument in the world, SCUBA2 has an extremely important role to play in the era of ALMA to provide proper samples for statistical analyses and detailed follow-up studies. **3) Continued access to wide-field imaging and MOS.** While Canada has been a leader in wide-field optical/IR imaging, in the era of Hyper-SuprimeCam, PanSTARRS, and LSST, Canada will require continued access to wide-field imaging and 8-m class MOS (IR and optical) follow-up capabilities to remain competitive.

- **Future Facilities:**

1) Access to a VLOT, such as the TMT. It will be vital for our field to have spectroscopic capabilities beyond what can be done with 8m-class telescopes: a well-instrumented VLOT with optical and NIR spectrographs, and both moderate-field MOS and IFU, will be critical for us to remain at the forefront. **2) Wide field multi-object spectroscopy**. Access to some powerful next-generation wide-field MOS (similar to the now-defunct WFMOS) is essential for us to fully exploit the large samples of galaxies, galaxy groups, and galaxy clusters that will soon become routinely available from wide-field imaging surveys. **3) Space missions**. Involvements in future wide-field imaging missions, in X-ray (such as WFXT; see Gallo et al. 2010) and optical (e.g., JDEM) will greatly enhance Canada's competitiveness in the studies of clusters and galaxy evolution.

- **Funding Postdoctoral Fellows.**

High calibre postdoctoral fellows are essential if Canada is to maintain a leadership role and maximize our scientific return from investments in these leading facilities and technologies. On the observational side, this will allow Canadian astronomers to make rapid progress with the large and complex data flows from facilities such as ALMA and JWST to retain our international competitiveness. On the theoretical front, as our field moves towards increasingly complex numerical simulation studies, we need programs and mechanisms for securing the necessary resources to recruit top postdocs and build world-class research groups at multiple sites across the country.

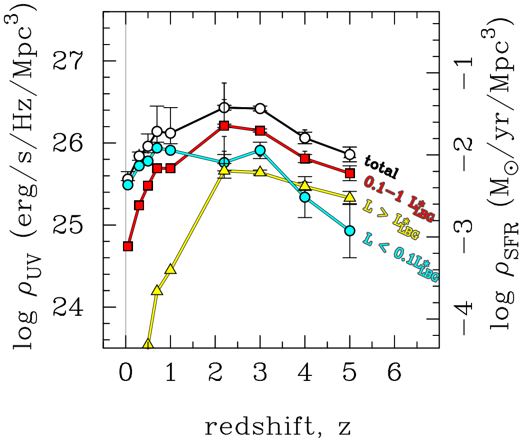

FIG. 1.— Evolution of the UV luminosity density with redshift. The right axis shows the evolution of the SFR density under the assumption of no light-absorbing dust. The overall picture is that of a rise from earliest epochs, a peak around $z \sim 2$ and then a decline to redshift $z = 0$. Within this picture, activity among the most luminous galaxies starts to decline first (yellow curve), while low-luminosity galaxies continue to form stars for quite some time, consistent with the down-sizing scenario of star formation. Figure from Sawicki & Thompson (2006).

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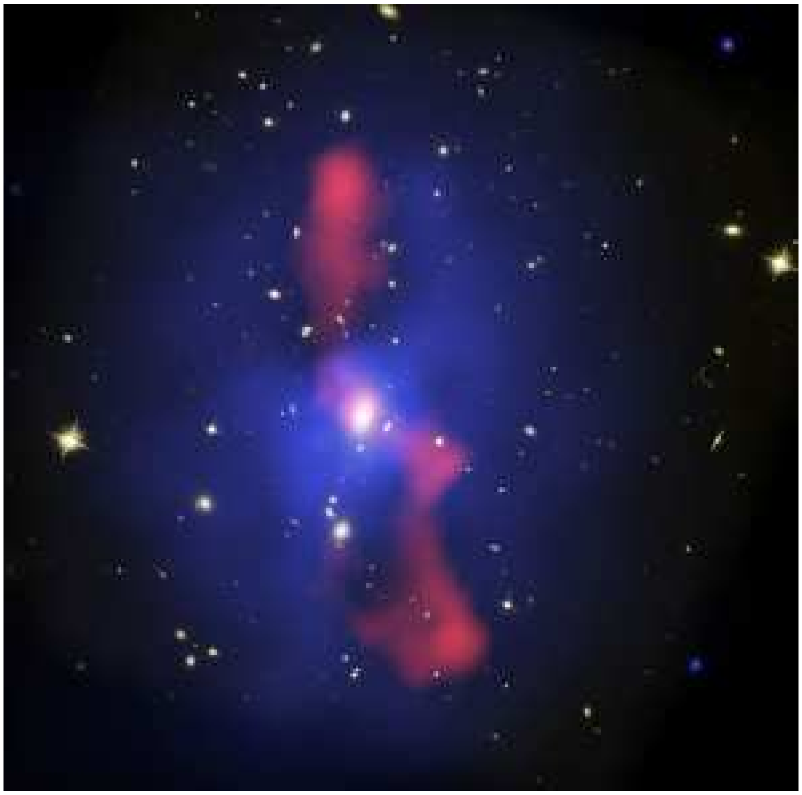

FIG. 2.— Composite image showing optical (HST/ACS), X-ray (blue; Chandra) and radio (red; VLA) image of MS0735.6+7421 (from McNamara et al. 2005). The image show radio jets from a $\sim 5 \times 10^9\ M_\odot$ supermassive black hole in nucleus of the central cluster galaxy displacing more than $10^{12}\ M_\odot$ of the intracluster gas, and inflating gigantic cavities. Estimates place the energy associated with the outburst at 10^{62} ergs (McNamara et al. 2009). ‘

FIG. 3.— The richest galaxy cluster found in the RCS2 survey. This $z = 0.70$ cluster is one of the most massive clusters known with a velocity dispersion of 1400km/s and an X-ray temperature of 10.3 keV, or a mass of about $2 \times 10^{15}\mathrm{M}_\odot$. The image is $\sim 2'$ in size. Note the blue arc to the upper left, 45” away from the cluster center, making it the largest Einstein radius found associated with an intermediate/high-redshift cluster. Figure from Gladders et al. (2010, in preparation).

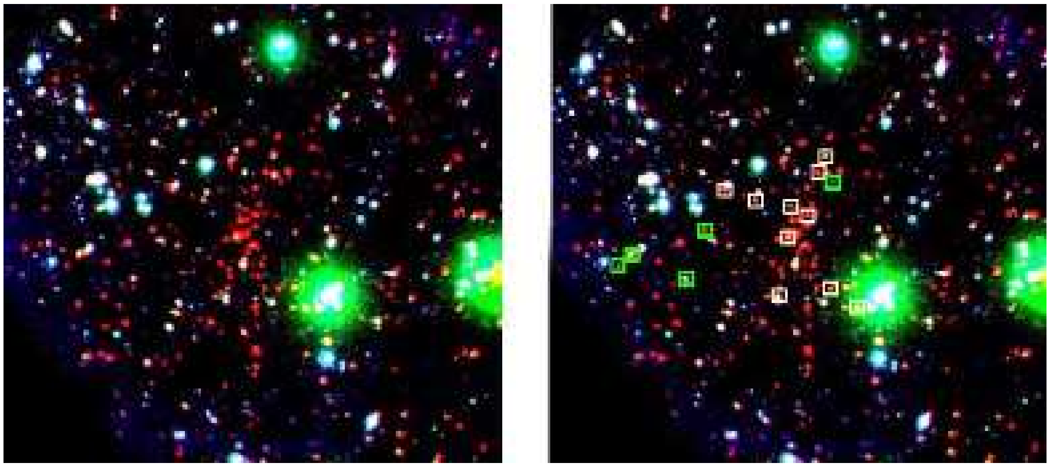

FIG. 4.— SpARCS J003550-431224, at (spectroscopic) $z = 1.335$. The SpARCS survey is a 42 sq. deg survey optimized to find galaxy clusters at $1 \lesssim z \lesssim 1.7$ using a combination of the publicly available SWIRE IRAC 3.6μm images and deep z'-band images from CFHT MegaCam and CTIO MosaicCam. The survey finds ~ 200 $z > 1$ cluster candidates. The false-colour image covers the central 1.5 Mpc of the cluster and illustrates the power of the red-sequence method – the red early-type galaxies in the core of the cluster show up prominently. The white squares on the right panel mark the spectroscopically confirmed members using GMOS on Gemini-S. A band nod-and-shuffle technique is used to maximize the coverage of galaxies in the high density core. Figure from Wilson et al. (2009).