Proposal for an ISSI International Team

COSWEB: The Cosmic Web and Galaxy Evolution

Coordinator: Gregory Rudnick

The Role of Environment in Galaxy Evolution

This work is an extension proposal for our previous ISSI team "The Effect of Dense Environments on Gas in Galaxies over 10 Billion Years of Cosmic Time." That team was very successful, producing papers, successful telescope proposals, and starting an unexpected new research project that has now become one of the major foci of our group. Below we describe our renewal proposal, where we discuss our new research areas, our continuing progress in previous research areas, and our team, which consists of a significant number of five new members.

Filaments as the place where galaxies begin to die? Galaxies in dense environments have lower average star-formation rates (SFRs) than field galaxies out to at least $z \sim 1$ (e.g. Poggianti et al. 1999; Lewis et al. 2002; Gómez et al. 2003; Postman et al. 2005). However, despite tremendous observational effort, it is still not clear whether the clusters actively alter the gas content of infalling galaxies or whether they are the final resting place of dead galaxies whose gas was depleted before entering the cluster environment.

Studies in the local Universe have found that the average SFR starts to decline at group densities, which are comparable to the density at $3-4$ times the cluster virial radius (Lewis et al. 2002; Gómez et al. 2003). More recent work at intermediate redshift shows that the suppression of star formation begins as galaxies enter the filaments of the cosmic web (Laigle et al. 2017; Rerat et al. in prep), which is consistent with simulations showing that ram pressure can be boosted by a factor of 10–100 inside a filament (Bahé et al. 2013). Indeed structure formation simulations show that most mass flow into massive halos occurs along filaments (Ramachandra & Shandarin 2015), implying that environmental galaxy processing starts far from the cluster core in the cosmic web of structure. In contrast, spiral galaxies in the Virgo cluster show evidence of cold gas stripping and truncated star forming disks (Koopmann & Kenney 1998, 2004; Dale et al. 2001; Crowl et al. 2005; Chung et al. 2007). This demonstrates that the cluster environment is actively altering the star-formation properties of infalling galaxies.

One reason for the continuing debate as to which environment dominates galaxy transformation is that most groups have focused on studying only one phase of the gas in galaxies (e.g. ionized vs. cold). To conclusively determine the cause for the end of star formation in dense environments it is important to study the fuel of star formation itself. In addition, because galaxies may be altered in the cosmic web well outside of the cluster core, it is crucial to probe not only the cluster itself, but also the filament and intermediate (i.e. group) environments through which galaxies pass on their way into the densest environments.

A revolution in our characterization of filaments: Until recently, filaments around clusters were hard to characterize because their moderate galaxy density contrast against the background makes them hard to distinguish from their lower density surroundings. For this reason, galaxy environment studies in the past 25 years have focused a simple trilogy of field, group, and cluster environments, with radial distance from the cluster being the best available proxy for density in the infall region (e.g. Lewis et al. 2002; Patel et al. 2009). Thanks to advances in analysis and technology, however, we can now characterize filaments of large scale structure out to loopback times of 6 billion years.

For example, Kim et al. (2016) has analyzed spectroscopy primarily from SDSS to identify seven well-defined filaments around the Virgo cluster (Fig. 1.) Only by combining uniform imaging and the massive investment of SDSS spectroscopy over $\sim$ 5000deg^2 was this possible. These physical associations of galaxies in our cosmic backyard are ideal for studying the effect of the environment on the stars, gas, and dust as the sources are far enough to efficiently observe in a single pointing of most instruments, but near enough to well resolve spatially with an array of ground and space-based facilities.

We have also made breakthroughs in our understanding of the filaments feeding distant galaxy clusters at $z > 0.4$. These advances have come thanks to the availability of 1 deg^2 field of view imagers on 4-

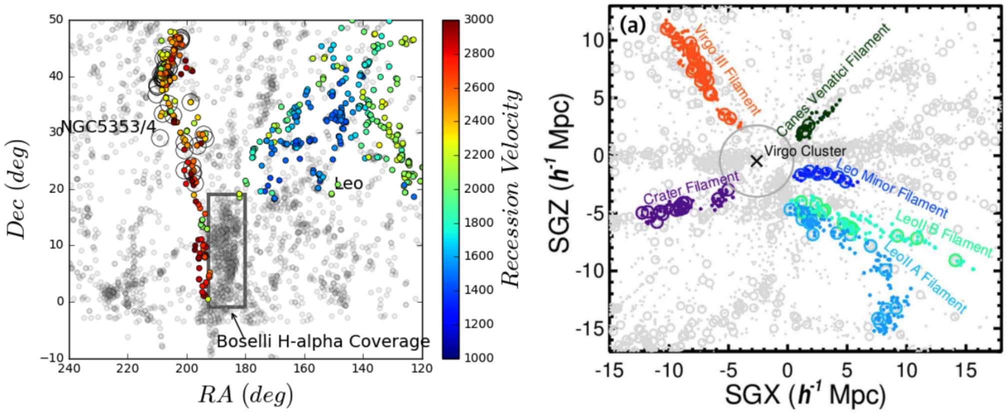

Figure 1: This is a placeholder caption about the Virgo filaments and SEEDisCS filaments.

meter telescopes that have enabled distant filaments to be identified via accurate photometric redshifts and subsequently be confirmed with multi-object spectroscopy on 6–8-meter class telescopes (Fig. 1; Rerat et al. in prep). It has taken years to amass this data but we now have the first ability to study highly pure samples of filament galaxies many virial radii away from clusters, in the regions where they may experience environmental affects for the first time.

The importance of understanding the gas: Through decades of work it has become clear that local supply of cold (mostly molecular) gas determines the SFR of galaxies (Kennicutt 1998; Bigiel et al. 2008; Leroy et al. 2008). Therefore, to truly understand how the SFRs of galaxies are altered it is necessary to directly probe the content and spatial distribution of the gas.

Different phases of the gas yield complementary information. The content and distribution of ionized gas traces the star formation that is relatively unobscured by dust while the mid-infrared emission tells us about the obscured star formation. Likewise, observations of the molecular gas constrain the fuel of star formation and its physical conditions, i.e. temperature, density, and filling factor. Although the mass of molecular gas is dominated by H_2, which has little accessible emission due to its lack of a permanent dipole moment and is only visible in shocked gas, we can use well-calibrated proxies, such as rotationally excited CO.

It is important to study the amount of gas and its spatial distribution with respect to that of the stars. A key difference between the studies of the Virgo core and other local SDSS results mentioned previously is that the Virgo studies are based on spatially resolved Hα, CO, or HI maps while the others are insensitive to processes that preferentially affect the outer radii of galaxies. This is an important distinction as the most common mechanisms proposed for depleting gas make different predictions for the size and symmetry of the gas and stars disks.

In addition, studying spatially-resolved gas and stellar disks *in filaments as well as in groups and clusters* can help constrain the relative importance of physical processes such as ram-pressure stripping, starvation, or tidal effects, because their effectiveness varies with the density of the intra-cluster, intra-group medium, or intra-filament gas and the velocity of galaxies relative to each other and that gas. For example, the removal of cold disk gas through ram-pressure stripping is expected to be most effective in the cluster core, whereas galaxy-galaxy interactions, which exhaust the gas supply through a burst of star-formation, are most effective in groups or cluster outskirts. However, galaxies can still experience a 10–100 factor boost in ram pressure stripping in filament environments as they move through the filament gas (Bahé et al. 2013).

In a preliminary study, we have found potential signed of gas stripping in that star-forming galaxies in clusters appear to have had some of their molecular gas stripped while leaving their SFRs - fueled by the densest gas - unaffected for a time (Jablonka et al. 2013). While suggestive, these conclusions are based primarily on local samples, which have numerous problems. Locally we can spatially resolve the gas to look for stripping effects. At intermediate redshift we can also effectively look for environmental effects because galaxies are still actively evolving. Despite this early progress, the number of CO measurements in dense environments at intermediate redshift and in filaments at all redshifts is very small and our efforts at enlarging them have just started.

A revolution in our knowledge of the gas: We are entering a new age of possibility in our ability to study how gas is affected by dense environments thanks to space-based (*Spitzer*, *Herschel*, WISE, HST, JWST) and ground-based (ALMA, IRAM, NOEMA, JVLA, VLT, Nancay) observatories. With slitless spectroscopy observations with HST we are obtaining detailed spatial maps of star formation in clusters and their infall regions for systems at $z < 0.6$. HST grism spectroscopy is allowing us to probe the ionized gas and stellar populations of a sample of the most distant clusters at redshifts $z > 1.5$. *Spitzer*, WISE, and *Herschel* have also given us views of the obscured star formation of galaxies back to the early epochs of time. Locally they allow us to map the relative spatial distribution of the dust and the stars, thus tracing the stripping of the cold gas. Millimeter observations at the JVLA, IRAM, NOEMA, and ALMA are enabling us to directly measure the content of molecular gas in filament galaxies and we can access HI with JVLA and the Nancay telescope. Finally, the fully commissioned ALMA and NOEMA are giving us the ability to measure the spatial distribution of molecular gas in galaxies, thus directly probing the physical conditions of star formation as they interact with dense environments.

Each of our proposed ISSI team members is leading 1–2 of the efforts described above. We will bring together these resources to address the following questions: In what environment moving from the field, into filaments, through groups, and into cluster cores is the gas of galaxies first affected? How are the content, distribution, density, and temperature of the gas altered? Over what timescales does the depletion occur? What are the responsible mechanisms for the gas removal and do they operate differently in different environments?

Our proposed activities

We have spent significant observational efforts characterizing the extended environments around galaxy clusters over the past 10 Gyr of cosmic time. For example, we have well-defined filament catalogs of galaxies in the vicinity of Virgo identified from SDSS and have also expended significant observational effort finding filaments and their member galaxies when the Universe was 5 Gyr younger than its present age (Fig. 1). Going even further, to 10 Gyr in the past, we have characterized a set of forming clusters that are progenitors of our lower redshift systems.

Now that the environments of our galaxies have been largely characterized, our immediate work is to study specific phases of the gas. The analysis of individual datasets, which usually focus on an individual environment, redshift, or gas phase, will be primarily done by the PIs of those programs. Collectively our team members are studying the both densest environments over 10 Gyr of cosmic time and also the extended cosmic web that feeds those dense environments. However, until we try to bring all of the results together it will be impossible to form coherent and broad-reaching conclusions with the data that have been provided by the revolutionary new facilities. Performing this synthesis is one of the main goals of our proposed ISSI team.

Ionized gas: The effect of environment on the dense ionized gas will be determined by combining an HST/WFC3 grism Cycle 20 program (PI: Rudnick) on the infall regions of 4 intermediate redshift clusters with a narrow-band imaging survey of Virgo filament galaxies (PI: Finn). With these programs we will distinguish between different methods of gas depletion by determining relative structure of the star-forming and stellar disks. For example, ram-pressure stripping makes the prediction that the gas disks will be asymmetric (e.g. Quilis et al. 2000; Crowl et al. 2005) with respect to the stars and that the SFRs in the inner parts of the galaxy should be the same as or even enhanced with respect to field galaxies (Koopmann & Kenney 2004; Weinmann et al. 2010). Galaxy-galaxy interactions, however, will result in both the gas and stars being asymmetric. Finally, starvation, which describes a weaker version of ram-pressure stripping (e.g. Larson et al. 1980), may only affect the relative sizes of the gas and stellar disks. By comparing the Hα properties of the filament galaxies to those in clusters and infalling groups, we will be able to determine if the filament and group environments are hosting processes that are important in altering star-forming galaxies and how how that role has evolved over the last 5 Gyr.

Obscured star formation: Infrared observations from *Spitzer*, WISE, and *Herschel* probe the emission by dust grains that have been heated by star formation and can by used to infer the total infrared luminosity L_{IR} and SFR. Using measurements for clusters at $z < 2$ it is clear that the total SFR in cluster galaxies has declined faster than the field (Finn et al. 2010; Saintonge et al. 2008; Tran et al. 2010; Alberts et al. 2014). This could be because of “accelerated evolution” in clusters (Papovich et al. 2012) or because the cluster environment speeds up the depletion of gas at late times. To break this degeneracy it is necessary to look in a more detailed way at the properties of the gas itself.

To address this we will use completed wide-field *Spitzer* 24μm observations around 11 clusters at $0.6 < z < 0.8$ (PI Rudnick) to measure whether there is a location at which the fraction of vigorously star-forming galaxies drops. We will also use *Spitzer* 24μm observations of 9 local groups and clusters (PI Finn; Finn et al. 2017) and WISE 12 and 22μm observations of Virgo filament galaxies (PI Finn) to compare the spatial distribution of the dust emission in galaxies to that of their stars . Active stripping of the dust, which is usually co-spatial with the cold gas, will result in a spatial offset of the dust emission from the stellar light, while a mere decoupling of the galaxy from its gas supply will result in a lower mean intensity and smaller dust emission size. The ISSI team will combine these two approaches to determine what the spatial distribution of the dust is at the same density or clustercentric radius where a suppression of star formation is seen.

The fuel for star formation. To truly understand the modulation of star formation by reduction in the H_2 fuel supply requires that we observe the cold gas, or at least CO, which is the best tracer possible. Thanks to dramatic technological advances in millimetric interferometry with JVLA, NOEMA, and ALMA and the sensitivity if the IRAM 30m telescope we are now able to study CO over the full redshift range in which clusters are growing. As part of the new efforts initiated by our previous ISSI team we have embarked on an ambitious observational campaign to image Virgo filament galaxies in CO, both with the IRAM 30m dish and with the NOEMA interferometer, the best millimeter interferometer in the northern hemisphere. We are nearly complete with the IRAM program and are proposing for the NOEMA program in Spring 2017. We have also made excellent progress on increasing the number of CO detections in intermediate redshift clusters and their surrounding filaments using NOEMA (Jablonka et al. 2013) and ALMA observations (Jablonka in prep.) Such measurements are crucial as they have less systematics than lower-redshift measurements and are being made when the evolutionary rates and gas contents of galaxies were much higher. Our ISSI team will continue to use these facilities to build large samples of galaxies at intermediate redshift.

As the result of large JVLA and ALMA programs, team members have now detected CO in 13 galaxies that reside in 4 well characterized $z \sim 1.6$ proto-cluster (Rudnick et al. submitted to ApJ; Noble et al. in prep). Taken together with the intermediate redshift measurements, these programs comprise most of the CO detections in cluster and filament galaxies outside the nearby universe. Part of our ISSI program will be to combine these studies to measure how molecular gas and star formation relate in dense environments since $z < 2$. CO measurements for field galaxies at normal IR luminosities are rapidly increasing, promising a perfect field comparison sample. This is a particularly important part of our project as it gets to the heart of what is driving star formation and its cessation, namely the molecular gas and its depletion.

Providing crucial constraints for theoretical models. All of these observations will give us an unprecedented view of how gas is being altered in galaxies as they enter cluster environments. Our ISSI team will use them to to place very strong constraints on theoretical models of galaxy formation. In nearly all of these models, the gas supply to galaxies is cut off upon their entry to another more massive dark matter halo. The exact mechanism for this "satellite quenching" is unspecified in the models but is parameterized as a timescale for the cutoff of the gas supply. Our observational programs will directly constrain these models by revealing where the gas supply is cut off, i.e. filaments, the virial radius, cluster core, in groups, and how fast it is shut off. Current attempts at constraining these timescales have revolved around modeling the buildup of quiescent galaxies and result in uncomfortably long quenching timescales (McGee et al. 2011; De Lucia et al. 2012). The fundamental problem is that the models don't properly treat quenching because the mechanism is unknown. We will make crucial steps towards answering this long-standing question.

Elucidating measurements with revolutionary facilities: Future facilities like JWST and those nearing completion, like ALMA and NOEMA, will provide us an unprecedented opportunity to study the gas contents of galaxies as a function of environment. ALMA and NOEMA open the door to spatially resolved studies of the cold gas and JWST will allow the high spatial resolution of the ionized gas. Our ISSI team has been successful proposing for ALMA to and will build on these efforts with the submission of a proposal to make the first significant census of CO in clusters at $z \sim 1.6$. Thanks to its large wavelength range and 3D spectral capabilities, JWST will allow us to probe the ionized gas in our intermediate and high redshift samples, at wavelengths unencumbered by extinction (Paα, $\lambda = 1.875\mu$m). For our nearby galaxies it will also give us the capability to measure H_2 directly, and thus measure the bulk of the cold gas without relying on CO as a proxy. A timely effort in the design of these programs is crucial, as JWST has a limited mission lifetime and the first call for proposals is March 2018, right within the timeframe of this proposed team. Likewise, given ALMA's completion, our ISSI team is in a perfect position to propose large programs to study the cold gas. A priority of this team will be observing filament galaxies and distant clusters with HST, ALMA, and JWST.

Why is our project powerful? Collectively, our team has access to the ideal data to address the questions outlined in our proposal. Our filament sample spans ~ 5 Gyr of cosmic time while our cluster sample spans ~ 10 Gyr and includes the highest redshift cluster with both extremely deep HST grism data (Lee-Brown et al. 2017) and JVLA data (Rudnick et al. 2017), along with one of the largest sample of CO detections in distant clusters (Noble et al. in prep.) Importantly, our distant clusters are ideally suited for evolutionary studies as they are all typical progenitors of our local clusters (Milvang-Jensen et al. 2008; Rudnick et al. 2012). At intermediate redshift we probe far enough out in clustercentric radius to identify all of the members that will end up in the cluster at $z = 0$ (Just et al. 2014). At low redshift we use the proximity of Virgo and other local clusters to probe to low stellar masses where environmental quenching is thought to be dominant and we access HI, CO, Ionized gas, dust, and stellar mass in all of our target galaxies.

Our proposed collaboration will also probe nearly all of the phases of the gas that are relevant for star formation, from the hot dense gas that traces active star formation to the cold molecular gas that is the fuel of star formation. We also probe all relevant densities in the cosmic web, from distant filaments to the bottom of deep cluster potential wells. By combining our measurements with theoretical models we will gain a greatly improved understanding of how star formation is regulated, and eventually quenched, in dense environments. This synergy of the appropriate data, in the appropriate sample, spanning a large range in redshift, and with accompanying theoretical modeling is unique.

Our proposed team: Our team is composed of 15 highly recognized experts in various areas of galaxy evolution studies and represents 6 countries. They are playing key roles or are leading projects in one or more of the areas mentioned above. • *Molecular tracers of star-forming gas:* F. Combes (F), P. Jablonka (CH), G. Rudnick (USA), A. Noble (USA), E. van Kampen (DE), J. Hodge (NL), C. Papovich (USA), M. Cooper (USA) • *Ionized tracers of star-forming gas:* B. Weiner (USA), G. Rudnick (USA) R. Finn (USA) • *Dust-obscured star formation:* R. Finn (USA), V. Desai (USA), Norman, D. (USA), G. Rudnick (USA), C. Papovich • *Galaxy environment:* D. Zaritsky (USA), G. Castigiani (F), V. Desai (USA), P. Jablonka (CH), M. Cooper (USA) • *Very distant clusters:* G. Rudnick (USA), B. Weiner (USA), A. Noble (USA), E. van Kampen (D), C. Papovich (USA) • *Theoretical modeling:* G. De Lucia (IT), M. Cooper (USA).

This group has five members not in our previous and these new members bring essential expertise to our collaboration. This group is larger than 12 but we expect that some members will self-fund to come to the workshop. Such a large group is necessary to ensure that we have the proper cross-section of expertise.

The value of ISSI: Historically, studies of the cold gas have been carried out independently from those that study the effects of environment. Even among those studying environment, those studying intermediate density environments like groups and filaments have often been disjoint from those studying the cluster cores. Likewise, the high redshift cluster community has, been focused on finding systems, with relatively little work having been done on the effect of environment on the physical properties of galaxies. Making significant progress requires a concerted and multi-wavelength approach that stretches across large swaths of cosmic time. This is a highly valued endeavor as understanding the gas in galaxies was highlighted in the Astro2010 Decadal report from the U.S. National Academy of Sciences. It is also a main focus of ALMA, the largest Europe-US-Japan project of the decade.

The funding from ISSI gives us a unique opportunity collaborate over an extended period at the same location. The value of these meetings are clear. During our first workshop as part of the previous proposal we organically decided on pursuing the Virgo filament studies, which now forms a backbone of this proposal. We have an active ISSI-hosted wiki that serves as an information repository, have already produced multiple papers together, and have been successful both in funding and telescope proposals[1]. Extended face-to-face meetings are critical for such undertakings and the ISSI funds make this possible as almost none of the collaborators has the necessary funds from other sources.

Outcomes: Our collaboration will result in multiple high impact papers. We will also write a paper that combines the different studies above into a summary and synthesis of all we know observationally about the gas in galaxies in dense environments. Another paper will combine those observational constraints with our theoretical modeling to constrain the timescales and physical mechanisms for the quenching of star formation.

We will submit multiple telescope proposals to ALMA, JVLA, NOEMA, HST, and most importantly JWST to characterize the gas in much larger samples than is currently possible.

Schedule: We propose to hold an initial full team meeting of five days to kick off the project during the summer of 2017. This would be followed by a final 5 day full team meeting in the summer of 2018.

Financial Support: We request the standard support provided by ISSI of a per diem for the living expenses of Team members while residing in Bern and for the travel expenses of the coordinator (Rudnick). We would also appreciate benefiting from the ISSI Young Scientist scheme for two young researchers.

Required Facilities. We require only meeting facilities and reasonably fast internet access.

[1] `http://www.issibern.ch/teams/gasingalaxies/`

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