Proposal for an ISSI International Team

# COSWEB: The Cosmic Web and Galaxy Evolution

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## 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 $\sim 5000\text{deg}^2$ 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 $\text{deg}^2$ field of view imagers on 4-

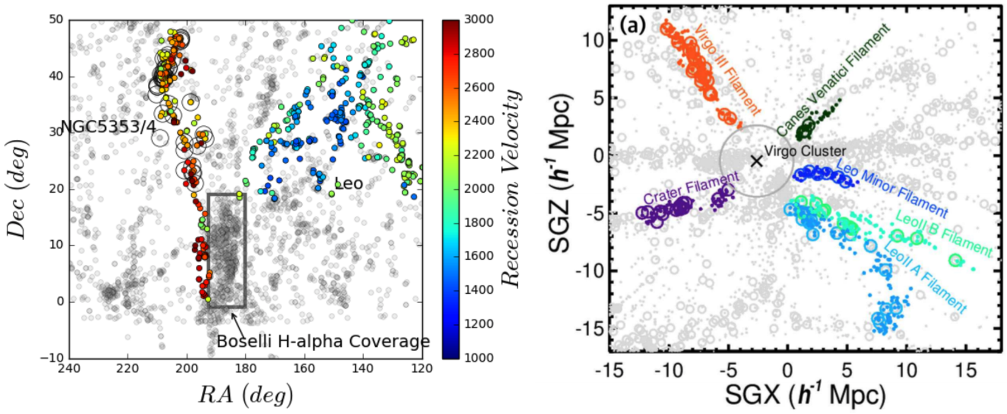


Figure 1: This is a placeholder caption about the Virgo filaments and SEEDisCS filaments.

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 $\mathrm{H}\alpha$, 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*, 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* 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 ESO Large Programe with the GTC (PI: Aragón-Salamanca) on a z=0.2 supercluster. 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 H$\alpha$ properties of the cluster galaxies and those in infalling groups, we will be able to determine if the cluster environment plays an important role in altering star-forming galaxies and how how that role has evolved over the last 5 Gyr.

**Why is our project powerful?**

**Our proposed team:**

**The value of ISSI.**

**Outcomes.**

**Schedule.**

**Financial Support.**

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

## References


Bahé, Y. M. et al. 2013, MNRAS, 430, 3017

Bigiel, F. et al. 2008, AJ, 136, 2846

Chung, A. et al. 2007, ApJ, 659, L115

Crowl, H. H. et al. 2005, AJ, 130, 65

Dale, D. A. et al. 2001, AJ, 121, 1886

Gómez, P. L. et al. 2003, ApJ, 584, 210

Jablonka, P. et al. 2013, A&A, 557, A103

Kennicutt, Jr., R. C. 1998, ApJ, 498, 541

Kim, S. et al. 2016, ArXiv e-prints

Koopmann, R. A. et al. 1998, ApJ, 497, L75

—. 2004, ApJ, 613, 866

Laigle, C. et al. 2017, ArXiv e-prints

Larson, R. B. et al. 1980, ApJ, 237, 692

Leroy, A. K. et al. 2008, AJ, 136, 2782

Lewis, I. et al. 2002, MNRAS, 334, 673

Patel, S. G. et al. 2009, ApJ, 694, 1349

Poggianti, B. M. et al. 1999, ApJ, 518, 576

Postman, M. et al. 2005, ApJ, 623, 721

Quilis, V. et al. 2000, Science, 288, 1617

Ramachandra, N. S. et al. 2015, MNRAS, 452, 1643

Rerat, F. et al. in prep

Weinmann, S. M. et al. 2010, MNRAS, 406, 2249