Proposal for an ISSI International Team

The Effect of Dense Environments on Gas in Galaxies over 10 Billion Years of Cosmic Time

Coordinator: Gregory Rudnick

One of the main quests of modern astrophysical research is to understand how galaxies evolve throughout cosmic time. Since the 1930's, astronomers began to suspect that the places in which galaxies live played an important role in their evolution. It was observed that galaxies residing within groups and clusters of galaxies are systematically different than those residing in more sparsely populated regions of the universe. In particular, they have a higher fraction of old stars, and tend not to produce many new stars. However, despite tremendous effort, it is still not clear by what mechanisms galaxies are altered by their surroundings. What has become clear is that solving this problem requires a direct measure of the gas, which is the fuel of star formation. We need to know how much gas is in galaxies, its physical state, its spatial distribution, and how these change both over time and in different environments. By understanding how the fuel supply is regulated we will therefore be able to understand the observed changes in the star formation rates. Recent advances in instrumentation are now giving us, for the first time, the ability to study the physical conditions of the gas over the relevant scales in environment and cosmic time.

We propose to form a new research team to capitalize on these emergent observational resources, synthesize the results from existing studies, form a comprehensive picture of how gas is altered in dense environments, and plan for the exploitation of future facilities. Our team is composed of 12 individuals from 6 countries whose research expertise are as follows:

- *Molecular tracers of star-forming gas:* F. Walter (D), F. Combes (F), P. Jablonka (CH), G. Rudnick (USA), T. Rawle (ES)
- *Ionized tracers of star-forming gas:* A. Aragón-Salamanca (UK), B. Weiner (USA), B. Poggianti (IT), R. Finn (USA)
- *Dust-obscured star formation:* R. Finn (USA), V. Desai (USA), G. Rudnick (USA), T. Rawle (ES)
- *Galaxy environment:* D. Zaritsky (USA), B. Poggianti (IT), V. Desai (USA), P. Jablonka (CH), A. Aragón-Salamanca (UK)
- *Very distant galaxy clusters:* G. Rudnick (USA), B. Weiner (USA), F. Walter (D)
- *Theoretical modeling:* G. De Lucia (IT)

These individuals are using the largest ground-based telescopes, the best space facilities, and the largest and newest radio interferometers on the planet. Together they account for much of the data on gas in dense environments, and they are studying galaxies over extremely large baselines in cosmic time.

This ISSI project will bring together the work of these individuals to form a coherent picture of how gas is affected by the environment. Our immediate goals are to:

- Determine the response of the ionized gas to the environments by combining results of HST spectroscopic observations of intermediate redshift galaxy clusters with Gran-TeCan 10-meter Telescope (GTC) tunable filter observations of local galaxy clusters.
- Determine how the star formation rate and dust content are affected by environment through the use of *Spitzer* observations of dust emission and millimeter-wave interferometric observations of the molecular gas and dust continuum in galaxy clusters spanning 10 Gyr of cosmic time.
- Compare the state of the gas to that of the stars to constrain the transformative mechanism.
- Initiate new observational programs to measure the physical state (temperature and density) and spatial distribution of the molecular gas and compare it to the state of the ionized gas.
- Make powerful new constraints on the implementation of gas depletion in galaxy formation models.

The Role of Environment in Galaxy Evolution

Galaxy Clusters as Executioners? Galaxies in dense environments have lower average star-formation rates (SFRs) than field galaxies out to at least $z \sim 1$ (e.g. **????**). 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 (**??**). This implies that processing prior to accretion into the cluster is important. In contrast, spiral galaxies in the Virgo cluster show evidence of cold gas stripping and truncated star forming disks (**?????**). This demonstrates that the cluster environment is actively altering the star-formation properties of infalling galaxies.

One reason for the continuing ambiguity 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 well outside of the cluster core, it is crucial to probe intermediate (i.e. group) environments through which galaxies pass on their way into the cluster.

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 (**???**). 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, 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 Virgo and other local results mentioned above is that the Virgo studies are based on spatially resolved $\mathrm{H}\alpha$ 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 both groups and clusters* can help constrain the relative importance of these physical processes because their effectiveness varies with the density of the intra-cluster or intra-group medium and the velocity of galaxies relative to each other and the intra-cluster medium (ICM). 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.

A preliminary study has found that 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 (**?**). While suggestive, these conclusions are based primarily on local samples, which have numerous problems. Intermediate redshift is the place to look for environmental effects because galaxies are still actively evolving. However, the number of CO measurements at these 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-interferometer, JVLA, GTC, VLT) observatories. With tunable filter and slitless spectroscopy observations with the GTC and 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 it allows 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, and ALMA are enabling us to directly measure the content of molecular gas in cluster galaxies. Finally, the fully commissioned ALMA promises us the ability to measure the spatially resolved gas excitation 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 adress the following questions: In what environment moving from the field, 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

The first step will be to study specific phases of the gas. The analysis of individual datasets, which usually focus on an indidvual environment, redshift, or gas phase, will be primarily done by the PIs of those programs. Collectively our team members are studying the densest environments over 10 Gyr of cosmic time. 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. **??**) 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 (**??**). 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. **?**), may only affect the relative sizes of the gas and stellar disks. By comparing the Hα 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.

Obscured star formation: Infrared observations from *Spitzer* 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 (**????**). This could be because of “accelerated evolution” in clusters (**?**) 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 10 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 to compare the spatial distribution of the dust emission in galaxies to that of their stars (PI Finn). Active stripping of the cold gas will result in a spatial offset of the 24μm 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 24μm 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 gas, or at least the best tracer possible, which is CO. Thanks to dramatic technological advances in millimetric interferometry with JVLA, IRAM, and ALMA we are now able to study CO over the full redshift range in which clusters are growing. As described above, we have already started on this rode by starting to increase the number of CO detections in intermediate redshift cluster galaxies (**?**). Such measurements are crucial as they have less systematics then lower-redshift measurments and are being made when the evolutionary rates and gas contents of galaxies were much higher. Our ISSI team will use these facilities to build large samples of galaxies at intermediate redshift. As the result of a new large JVLA program, team members have now detected CO in 5 galaxies that reside in a well characterized $z = 1.62$ cluster (Rudnick et al. in prep). Taken together with the intermediate redshift measurements, these programs comprise most of the CO detections in cluster 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. 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 (**??**). 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, will provide us an unprecedented opportunity to study the gas contents of galaxies as a function of environment. ALMA will open the door to spatially resolved studies of the gas excitation and JWST will allow the high spatial resolution of the ionized gas. Our ISSI team will build large programs on these facilities to tackle the main questions of this proposal. A timely effort in the design of these programs is crucial, as JWST has a limited mission lifetime. Likewise, as ALMA ramps up to full sensitivity over the next few years, our ISSI team will be in a perfect position to propose large programs to study the cold gas. As more distant clusters become confirmed, a priority of the team will be observing these with HST, ALMA, and eventually JWST.

Why is our project powerful? Collectively, our team has access to the ideal data to address the questions outlined in our proposal. Our cluster sample spans ~ 10 Gyr of cosmic time and includes the highest redshift cluster with both extremely deep HST grism data and JVLA data. Importantly, our 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).

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. 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 12 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. Walter (D), F. Combes (F), P. Jablonka (CH), G. Rudnick (USA), T. Rawle (ES) • *Ionized tracers of star-forming gas:* A. Aragón-Salamanca (UK), B. Weiner (USA), B. Poggianti (IT), R. Finn (USA) • *Dust-obscured star formation:* R. Finn (USA), V. Desai (USA), G. Rudnick (USA), T. Rawle (ES) • *Galaxy environment:* D. Zaritsky (USA), B. Poggianti (IT), V. Desai (USA), P. Jablonka (CH), A. Aragón-Salamanca (UK) • *Very distant clusters:* G. Rudnick (USA), B. Weiner (USA), F. Walter (D) • *Theoretical modeling:* G. De Lucia (IT)

The value of ISSI. Historically, studies of the cold gas have been carried out independently from those that study the effects of environment. 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 to share our results in the context of a larger picture of how gas in galaxies behaves. Extended face-to-face meetings are critical for such undertakings and the ISSI funds make this possible as none of the collaborators has the necessary funds from other sources.

Outcomes. Our collaboration will result in mutiple high impact papers describing the results above. 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, PdBI, HST, and eventually JWST to characterize the gas in much larger samples than is currently possible.

Schedule. We propose to hold an initial full team (12 members) meeting of five days to kick off the project during the summer of 2015. This would be followed by a final 5 day full team meeting in the summer of 2016.

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.

Alberts, S. et al. 2014, MNRAS, 437, 437; 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; De Lucia, G. et al. 2012, MNRAS, 423, 1277; Finn, R. A. et al. 2010, ApJ, 720, 87; 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; Koopmann, R. A. et al. 1998, ApJ, 497, L75; —. 2004, ApJ, 613, 866; 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; McGee, S. L. et al. 2011, MNRAS, 413, 996; Papovich, C. et al. 2012, ApJ, 750, 93; 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; Saintonge, A. et al. 2008, ApJ, 685, L113; Tran, K.-V. H. et al. 2010, ApJ, 719, L126; Weinmann, S. M. et al. 2010, MNRAS, 406, 2249