Formation and Evolution of Galaxies
Radio Futures Meeting WG Report

April 1, 2016

1 FIRST GALAXIES

Radio astronomy can provide a unique probe into the first stars and first galaxies that appeared during the epoch of re-ionization by utilizing the 21cm HI line and the redshifted λ 157 μm [C II] line, as well as synchrotron and free-free continuum emission as tracers. The comparison of the structures traced in 21cm HI line with those of dark matter simulations, as well as the locations of the first galaxies within these structures should provide insights into the importance of baryonic processes such as shocks, cooling, and feedback. The supermassive black holes associated with the quasars seen at $z = 6 - 7$ are thought to have formed at $z = 15 - 20$, and radio emission associated with their formation process and growth can yield important clues to their origin, as well as a light source to probe the gaseous environment along the line of sight.

1.1 Issues/Requirements/Goals

- What sensitivity is needed to detect the parent protogalactic clouds in 21cm HI line and the continuum associated with the first bursts of star formation?
- How quickly did metals form and significantly alter the cooling (and extinction) process? Would [C II] serve as an important tracer of the first galaxies?
- How do we recognize and study the highest redshift radio QSOs in the confusion limited nano-Jy radio sky?
- Is the origin of magnetic field primordial? Was magnetic field a key component regulating baryonic processes such as the collapse of gas clouds and filaments and driving turbulence?

2 BARYON CENSUS IN GALAXIES

2.1 Complete Cosmic Star Formation and Metal Production History

There is a clear discrepancy between the UV and IR derived cosmic star formation history (SFH), and star formation activity remains largely obscured by dust out to $z = 3$. The UV view of the cosmic SFH is currently being fleshed out to $z \sim 10$, and it should be extended to $z = 15 - 20$ when the JWST is launched. Completing the IR view of the cosmic SFH requires future surveys at submillimeter and millimeter wavelengths (dust peak of a $z = 3$ and $z = 15$ sources occur at λ 0.6 mm & 2.4 mm, respective), with sufficient depth and area to recover the bulk of the galaxies contributing to the cosmic IR SFH. Surveys large enough in size to allow detailed explorations of dependencies on other key parameters, such as stellar mass and environment, are necessary to obtain a deeper understanding on important physical processes (see below). The relative importance of the IR SFH compared the UV SFH might decrease with increasing redshift, but this depends on how rapidly metal production proceeds and how efficiently they are retained in galaxies. Future surveys will provide useful constraints on these key baryonic processes.

2.2 Survey of ISM Content and Phases over Time

Measuring stellar mass build up in forming and evolving DM halos is one of the key observational tests for the theory of structure formation and growth. However, determination of stellar mass and SFR requires making important assumptions on SFH, IMF, metallicity/extinction, etc., that are individually highly uncertainty. Star formation process is regulated ultimately by gas content, and mapping the ISM content evolution in galaxies is another fundamental way theoretical models of galaxy formation and evolution can be tested. The ISM in galaxies is multi-phased by nature, and the atomic (HI) and molecular (H_2) components dominate the total ISM mass. Theoretical studies on cold gas content and HI-to-H_2 ratio have produced disparate predictions with strong dependence on assumed baryonic physics. This in turn highlights the huge systematic uncertainties in the predicted cosmic SFH as well. The existing data are extremely limited and available only at $z \approx 0$ for now. Future surveys that can map the cosmic evolution the HI and H_2 (or dust) contents should serve as important observational tests and provide key constraints on these theoretical models. There is also growing evidence that cold gas content in galaxies is modulated by gas accretion, gas removal by stellar mass build-up, and gas outflows (see below), and future models should include a more sophisticated treatment of baryonic physics.

2.3 Issues/Requirements/Goals

- We need to fully resolve the cosmic IR background and recover the complete cosmic SFH to the first galaxies. Future surveys need to be large enough to probe the growth of the LSS, sensitive enough at high angular resolution to push past the confusion limit. How rapid was the metal build up? and at which point the dust obscured (IR) SF began to dominate the cosmic SFH?

- We need to trace the evolution of gas content and SF efficiency as a function of redshift and environment. How does the cold gas content of galaxies compare with the predicted gas accretion rate and measured cosmic SFH? Is the feedback sufficiently efficient to alter the balance between gas inflow and SFR?

- How reliable are CO and dust continuum as tracers of molecular gas content? What are the good tracers of gas content in the earliest epochs? Do we need a broader range of "cleaner" tracers to track ISM and SF?

3 BARYON CYCLE OVER COSMIC TIME

3.1 Sub-parsecs (Black hole growth) to Giga-parsecs (IGM, filaments)

A fundamental challenge in understanding galaxy formation and evolution is the huge range in the physical and time scales involved. Most of the relevant baryon processes (e.g., star formation, shocks, feedback) operate on sub-parsec scales, and obtaining deeper insights requires detailed investigations utilizing sensitive, high resolution observations of the local universe objects and zoom-in simulations with high time and spatial resolutions. On the other hand, the initial conditions for these details studies are set by Giga-parsec scale structures that formed and evolved over the cosmic time, and this requires large area surveys spanning the full range of cosmic history. Obtaining a comprehensive understanding of the baryon cycle requires both surveys including large volume as well as high resolution surveys covering a wide range of physical parameters in local galaxies.

3.2 Detail Understanding of Infall & Outflow from Large to Small Scales

While the accretion of gas onto Mpc scale DM structures is reasonably well understood, the baryonic processes that direct and concentrate gas onto kpc scale structures and fuel SF are still poorly understood. There is also growing evidence that one or more feedback processes are operating to directly affect this gas accretion and resulting SF, and yet neither the nature of these feedback processes nor the relevant spatial or time scales are well established. Are winds and shocks associated with energetic young stars sufficient to account for most of the feedback required? AGN feedback seems energetically favorable, but how well can AGN activities operating on parsec scales couple efficiently to influence gas infall associated with 10s to 100s of kpc scale structures? Does the large scale environment also play a role in modulating the gas accretion (e.g., ram pressure, harrassment)?

3.3 Role of Magnetic Fields

Magnetic field is shown to play a key role in star formation for angular momentum transport as well as a source of pressure on parsec to kpc scales in galaxies. Presence of magnetic fields at Mpc scales has been demonstrated by RM and synchrotron processes, but how important is its role in shaping the baryonic cycle? How frequent and how ordered are large scale magnetic fields?

3.4 Large Statistical Sample of Resolved Sources

Advances in computational techniques are beginning to yield new insight into complex and nonlinear astrophysical phenomena with increasing sophistication. However, fundamental assumptions built into these models (on size and time scales as well as the importance of physical parameters such as magnetic field) need to be guided and verified with accurate and robust observational data. For example, determining whether and how different feedback processes (star formation, AGN activities, cosmic ray) operate and over what scales require detailed studies of each phenomenon in carefully selected local laboratories with sufficient resolution and sensitivity. Different physical effects are often operating simultaneously, and studies of samples large enough to explore full ranges of parameter spaces are needed. The advent of big surveys such as SDSS and LSST should begin to allow systematic explorations of new physical parameters, such as chemical evolution and local density environment, and radio astronomy should be able to provide matching spatially resolved atomic/molecular gas and dust distribution, gas kinematics, and magnetic field that can lead to a more comprehensive understanding of galaxy mass build-up and disk evolution.

3.5 Issues/Requirements/Goals

- We want to be able to probe cold gas distribution, physical conditions, and kinematics to better than 10s of parsec scales out to $z \geq 10$ and explore how gas shapes the SF and AGN activities. We need to determine the nature and spatial extent of the feedback processes that have shaped galaxies over the cosmic history.
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