How is star formation fed and quenched in massive galaxies at high redshift?

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Abstract

Observations of the location and kinematics of the atomic gas (HI) and the continuum radio emission from high redshift galaxies would mean a huge step forward in our understanding of galaxy evolution. We now have a secure global picture of the stellar content of massive galaxies and their precursors up to z∼4. But we still have to understand why star formation in these systems started early and quenched some time after, a scenario known as downsizing which, at face value, conflicts with the predictions from the current hierarchical galaxy formation paradigm. SKA will provide the missing piece to solve the puzzle: information about the amounts of gas falling into galaxies to form stars, as well as data to measure when and how the star formation turns off as the gas stops cooling due to still to be understood feedback mechanisms, such as (radio mode) obscured nuclear activity.

1 Introduction

Looking at early-type galaxies (ETGs), as well as at the bulges/halos of spiral galaxies such as the Milky Way, we are able to find some of the oldest stars known. These stars can be over 14 Gyr old, so they formed when the Universe was very young. In fact, ETGs not only typically harbor the oldest stellar populations, but they also present a variety of metallicities (from very low to quite high) and α-element enhancement, pointing out to early and also rapid starburst events that formed a significant fraction of their stellar mass (see, e.g., [54, 25, 39]).

The most probable progenitors of nearby ETGs and bulges of spirals have been identified in the last 15 years out to redshifts of z∼4 (12 Gyr ago). Indeed, based on optical and especially near-infrared surveys of galaxies, we have detected a numerous population of distant massive galaxies [65, 24, 17, 47, 10]. A good fraction of them (about half) are already dead at z∼2 [48, 23], but also many are experiencing very intense bursts of star formation, with SFRs of hundreds or even thousands of solar masses per year, and large amounts of dust [56]. In fact, about half of the stars that we see today were formed in the first 6 Gyr of cosmic time, and a fair fraction of the most massive galaxies ($M>10^{11}$ $M_{\odot}$) were already in place and evolving passively (with some further merging events, mostly dry) by z$\sim$1, with the bulk of the star formation in the Universe progressing to less massive systems as we move to lower redshifts [51, 41, 44, 37]. The epoch when the most massive galaxies were forming the bulk of their stellar content is then z=1–4. This is a formation scenario known as *downsizing* [15, 33, 28, 5, 50, 2, 51].

The observational evidence for early and rapid assembly of stars in ETGs is now very compelling. But the theoretical explanation of this behavior is not well understood, and modelers have difficulties reproducing the number density and the properties of high redshift (dead and alive) massive galaxies [41, 31]. This is also an observational problem: we do not have data to characterize in detail and with certainty relevant properties of this early assembly such as the timescale of the star formation and the amount of gas available to transform into stars, as well as its physical properties (i.e., whether the fuel can actually feed star formation), as a function of time. Very remarkably, the current paradigm of galaxy formation is hierarchical, with baryons following the behavior of the CDM halos, which merge and evolve from the smallest to the largest scales as we advance in cosmic time ([63]; see also [6, 61, 11, 62, 55]). The downsizing formation scenario is, in some way, antihierarchical (large galaxies assemble first), and that is nowadays a major problem in our understanding of galaxy formation.

The difficulty found to simulate the formation of galaxies, especially in the case of the most massive systems, is twofold. First, the physics governing the collapse, recombination, and cooling of ionized and atomic gas (the main form of baryonic matter in the early Universe) to form molecular gas and then turn this into stars is still poorly constrained. And second, the fuel consumption while forming stars must stop for some reason (still to be fully understood), i.e., there must be some negative feedback mechanism(s), given that we see massive galaxies stop forming stars and start evolving passively at high redshift, but we know that there are still large amounts of gas available in the intergalactic medium.

The most advanced simulations for the formation of galaxies now typically introduce (more or less *ad hoc*) some kind of feedback mechanism to regulate star formation (see, e.g., [45, 36]). For the most massive galaxies, the main suspects for the job are Active Galactic Nuclei (AGN). Moreover, many simulations now identify a *radio mode* as the most probable form of nuclear activity responsible for the quenching of the star formation, as well as for the dissemination of metals far into the inter-galactic medium, tens or hundreds of kpc away, the typical size of radio jets [57, 16]. Indeed, from the observational point of view, we have identified several evidences of this interplay between nuclear activity and star formation in galactic scales, e.g.: the intra-cluster medium in the local Universe seems to be shocked and heated by AGN radio jets [22]; the AGN activity peaks in the same epoch when the Universe was forming stars most efficiently [50, 34, 32]; AGN evolution models reproducing, among other observables, the X-ray background, predict many more obscured AGN than we have actually detected [27]; and, last but not least, many massive galaxies at high redshift present X-ray emission and/or dust properties compatible with the presence of intense heating sources such as dust-enshrouded AGN [20, 21, 18].

In this context, SKA will be a key facility to understand how gas feeds star formation in massive galaxies as well as why the job is abruptly stopped. It will provide two of the key pieces, probably the most relevant, to solve the puzzle of galaxy evolution: how much atomic gas (HI) falls into the center of the DM halos to form stars and the dynamics of this accretion, and why that cooling is stopped in spite of the availability of more gas in the IGM.

In this white paper we discuss an experiment to understand the earliest phases in the formation of massive galaxies by studying the amounts of atomic gas in the outskirts of high-z massive galaxies, as well as its dynamics, in a sample of massive galaxies in various stages of star formation (and probably nuclear) activity at $1<z<4$, when they formed the bulk of their stars. We also present a scientific case for the study of feedback mechanisms linked to the activity of obscured AGN presenting intense (and even not so intense) radio emission.

2 Atomic hydrogen at z>1

SKA will provide excellent data to understand the formation of massive galaxies from the earliest stages of their evolution. In Figure 1 we show how SKA1-MID and SKA2 surveys will be able to detect Damped Lyman-α systems up to $z\sim3$. These observations would tell us how much gas is falling into galaxies at the peak of their star formation history, z=1–3, when the Universe was most efficient forming stars. SKA would also allow to study the kinematics of the gas, so we can understand how gas stops collapsing into the center of the dark matter halo, eventually resulting in the quenching of the star formation. We want to emphasize that these observations would provide direct measurements of the effects of (supernova and/or AGN) feedback. We still have very limited understanding about feedback since, up to now, we have only been able to study its effects for nearby systems (mostly in clusters) and a few high redshift sources, based mainly on the study of the kinematics of ionized gas, as well as on the X-ray emission from hot gas in clusters. SKA will allow us to characterize the dynamics of the main component of intergalactic gas feeding star formation in galaxies.

In Figure 1 we also show the expected HI column densities for the compact star-forming galaxies (also called *nuggets*) in [3]. These galaxies have been identified as the progenitors of the compact quiescent massive galaxies at $z\sim2$, which are believed to be the cores of nearby elliptical galaxies [35]. The compact star-forming nuggets exhibit large SFRs, very compact sizes, and many of them have X-ray emitting AGN, being in the way of quenching their star formation and starting evolving passively [4, 49]. Even if their HI content were relatively small and similar to nearby quenching early-type galaxies, $M(HI)=2\text{–}40\times10^{8}\ M_{\odot}$ (a very conservative assumption, since they are forming the bulk of their stars and probably have larger gas contents than nearby galaxies), they would be readily detectable by SKA in just 100 hours.

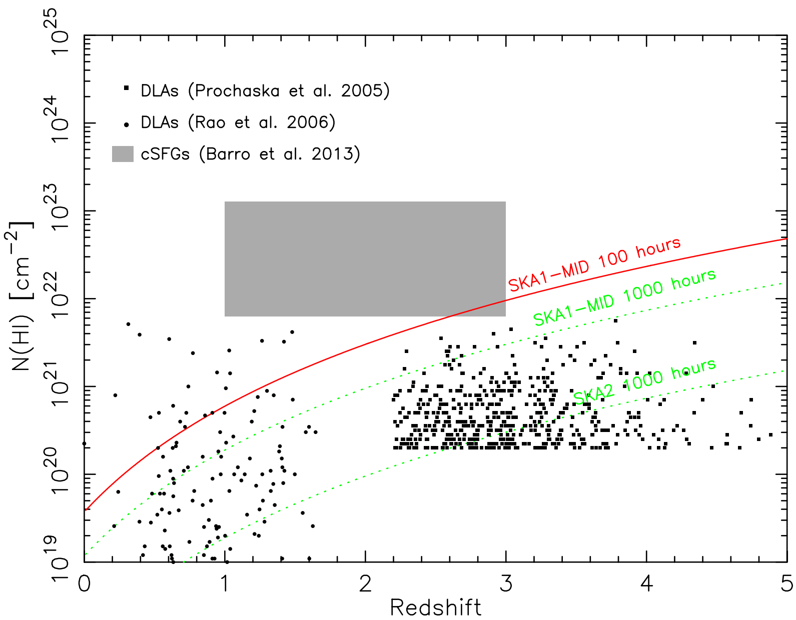

Figure 1: Sensitivity of the SKA in terms of the detection of neutral hydrogen at high redshift. We depict detection limits for HI 21 cm line surveys integrating for 100 and 1000 hours in the SKA1-MID configuration, and 100 hours with SKA2. We plot the column densities for the z>2 DLAs in [52], as well as for the z<1.65 DLAs in [53]. The shaded gray region corresponds to the HI column density expectations for the 1<z<3 compact star-forming nuggets in [3]. We have assumed that their typical size is 2 kpc, they would present HI masses similar to those for quenching nearby early-type galaxies in [64], and the density would be constant throughout their optical extent. Given that the high-z star-forming nuggets are forming the bulk of their stars and they are quite massive, probably they will present larger HI contents and the SKA observations will reveal HI gas far beyond the zone dominated by stellar emission, allowing the most detailed characterization of the gas in-fall to feed star formation in high-z galaxies.

3 AGN-star formation separation

The radio sky is dominated by extragalactic sources at metre to cm wavelengths. At flux densities above 1 mJy (at 1.4 GHz) most are AGNs while radio sources associated with starburst galaxies dominate the source counts below that flux [14, 26, 19]. However, results by Gruppioni et al. [29] indicate that early-type galaxies at $z > 1$ dominate at sub-mJy levels. It has also been suggested that the flattening of radio counts below 1 mJy may be caused by radio-quiet quasars and type 2 AGNs [59].

It is crucial to disentangle the star-forming galaxies from the AGNs, although the expected fraction of AGN vs. star-forming galaxies is expected to be $\sim 17\%$ at $z < 5$ below the 10μJy level, and $\sim 7\%$ at the 1μJy level [38]. A diagnostic tool to distinguish between AGN and star formation is the known correlation between FIR and radio continuum emission from star-forming galaxies (e.g. [12]). A criterion is that galaxies with radio to far-IR flux ratio more than three times higher than the mean for star-forming galaxies are classified as AGN [13], although Mauch and Salder have found a disagreement at the $\sim 10\%$ level between spectroscopic and radio/FIR classification [42].

Optical spectra can be used to identify the origin of the radio emission. However, optical AGN spectra do not always imply that the radio emission is of nuclear origin. In fact, there is evidence that nuclear activity and star formation are connected. The widespread detection of blueshifted rest-UV ionic absorption lines demonstrates that most star-forming galaxies (SFGs) at $z \sim 1-3$ exhibit nuclear AGN-driven gas outflows (e.g., [58]). Multiwavelength SED fitting (e.g. [1]) and X-ray and infrared information are useful to discriminate AGNs from star-forming galaxies. For instance, using three bands from WISE ($3.4, 4.6$, and 12μm) it is possible to separate AGNs from ULIRGS and normal galaxies [40]. Other methods are based on the finding that the NUV-NIR SEDs of galaxies are well correlated with line strengths and hence with their position on the BPT diagram [60].

Thermal and synchrotron self-absorbed spectra are expected to show different properties. Observations covering the range $\sim 1-10$ GHz will be useful to discriminate thermal and non-thermal radio emission. A flat spectrum up to high frequency is evidence of thermal emission, while a turnover around a GHz supports synchrotron radiation from an AGN. The broad-band radio spectrum may be combined with polarization information in order to study the nature of the radio emission from different regions. A jet structure is expected to show a polarised steep-spectrum, while a diffuse star-forming region should be highly depolarized (see [46]). With 3-4 measurements in the spectral range $1-10$ GHz at a resolution of ~ 100 MHz it should be possible to discriminate AGN from star-forming galaxies, reaching flux densities levels of around $10-20\mu$Jy in one hour. High resolution radio observations can be used to distinguish between compact AGN cores and inner jets from $\sim 1-10$ kpc-scale star-forming disks [43, 7, 30, 9]. Resolutions of at least 0.05 arcsec at 1.4 GHz (i.e. 1000 km baselines) are necessary to separate individual sources. However, to image sources with sufficient detail to determine if the emission comes from the disk, star formation, or an AGN will require higher resolutions.

Radio morphological identification can be also useful to reveal obscured AGN activity otherwise undetected at other wavelengths [8].

4 Synergies with other facilities

The observations put forward in the previous sections should be accompanied by observations in separate wavelengths taken at different facilities. The main thrust of the science here presented is the analysis of the neutral hydrogen component associated to moderate-to-high redshift normal galaxies, its dynamics and its relationship to the star formation and galaxy evolution processes.

In order to complete this objective it will be important to add other pieces of information. Many of them are treated in detail in other chapters of this work, but we will only mention here some of the most obvious:

- VLT, GTC: Optical/near infrared imaging and, specially, spectroscopy of the observed sources will be crucial to determine the properties of the galaxies being observed. Whereas we cannot realistically expect to study the same galactic components that will be measured by SKA, because their surface densities and emission levels will be too low, we can study the metallicities and star formation histories of the galaxies that are receiving (or, in the case of very strong winds or AGN activity, expelling) the HI flows that will be observed in the SKA data. VLT will be perfectly suited in terms of sky coverage, while GTC will be able to observe areas close to the celestial equator–there is still a significant areal overlap between both facilities.

- ALMA: Observations in other radio wavelengths in the millimeter range will allow for the analysis of abundances of other molecular species, unreachable to SKA. This study will contribute to our knowledge of the physical state of the neutral gas (in particular its temperature), and also to analyse its metallicity and, from a different point of view, its dynamics. A wider coverage of the radio spectrum should also become useful for the separation of the star formation and AGN components.

- Space: By the time SKA will be productive, we expect JWST to be the most important tool for the kind of science we are presenting here. In particular, observations with the MIRI instrument will cover the wavelength range 5-25 μm, both in imaging and spectroscopy. At the redshifts we intend to study, this will fully cover the rest-frame near infrared bands, allowing for detailed measurements of the stellar mass and adding critical data to analyse the past star formation history of the surveyed galaxies.

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