Mapping the Cold Molecular Medium around giant galaxies at high-z: a low-surface-brightness CO Legacy Survey with ATCA

Expression of Interest

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SCIENTIFIC JUSTIFCATION:

There is a growing consensus that the formation of massive galaxies must be a two-phase process, with a late phase that is dominated by galaxy mergers and an early phase that is driven by gas-accretion.[1] Models and observations have predicted the existence of large (several 100 kpc) metal-enriched reservoirs of cool gas around high-z massive galaxies, which may have been deposited by long-sought cool flows of gas from the Cosmic Web.[2,3,4] However, neither observations nor simulations have been able to trace such widespread gas at temperatures below the ~10^4 K regime of Lyα-cooling.[5] Thus, a direct connection between gas-accretion processes and the stellar growth of distant massive galaxies is critically missing, until we identify the ultimate gas reservoir at the lowest temperatures (10-100K), which has enough mass to fuel star formation at scales of galaxy-halos.

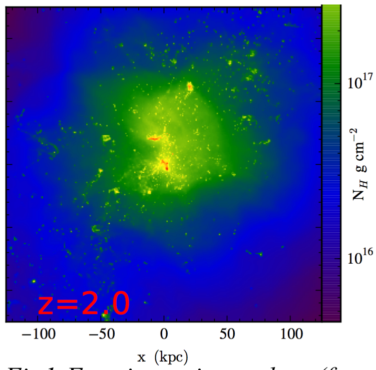

Fig 1. Forming a giant galaxy (from Narayanan+ '15). Simulated star formation from widespread, metal enriched gas on ~200 kpc scales.

Using ATCA, we recently obtained the first evidence for large (~100 kpc) reservoirs of very cold molecular gas in the halo-environments of massive, proto-cluster radio-galaxies at z~2 (Emonts+ '14, '15, '16).[6,7,8] We discovered that this cold molecular medium is related to a variety of processes, from jet-induced feedback to gas accretion and galaxy merging. These results indicate that we have to study the cold molecular phase of the inter-galactic and intra-cluster medium (IGM/ICM) to understand the early evolution of massive galaxies.

Interestingly, these observations also revealed that the ATCA is a uniquely suited instrument for investigating the cold molecular medium in and around high-z massive galaxies. The reasons are that:

1. ATCA is the only southern instrument that can trace CO(1-0) and CO(2-1) at z≥2. These lowest CO transitions are the most robust tracers of the cold molecular gas content of galaxies and their environments, including widespread and sub-thermally excited gas. ALMA can only target CO(3-2) and up, tracing denser gas in starburst/AGN regions. ATCA is thus an excellent complement to ALMA.
2. The ATCA has five antennas that can be placed closely together. This makes it very suited for detecting *low-surface-brightness* emission. It does so more efficiently than the VLA, which would require substantial tapering (e.g.uniformly spread CO(1-0) on scales ≥30 kpc can only be detected on baselines ≤750m).

We propose to exploit these two unique ATCA capabilities in a Legacy Project that addresses the question: ***"What is the role of the cold molecular medium in the early evolution of massive galaxies and clusters"***

We believe that this is important to the community, because our knowledge on the molecular gas content of the Early Universe is heavily biased -by the above mentioned technical limitations- towards dense molecular gas in starburst/AGN regions. We simply lack insight into the baryonic mass that is locked-up in the coldest gas phase outside of galaxies. We also believe that with this Legacy Project, the ATCA can highlight its capability to trace low-surface-brightness CO emission, and distinguish itself from ALMA and the VLA.

To reach our science goals, this proposed mm Legacy Project will have three requirements:

1. Observations should target the most massive galaxies in the Universe, preferably in high-z proto-clusters
2. Observing time should be a minimum of 100 hours on-source to reach the required sensitivity
3. Compact array configurations (≤1 km baselines) are needed to detect low-surface-brightness CO-emission

Our main science goals do not a-priori depend on specific targets. Our sample will likely consist of various types of massive systems at *z*~2-3 (perhaps also *z*~4-6), so that we can compare the cold molecular medium in different environments. These will include high-z radio galaxies, quasars and submm galaxies, preferably in rich proto-clusters. Essentially, this will start giving the community a low-order CO census of the molecular medium in and around high-z massive galaxies and clusters during the ALMA era. We defer the sample-selection to the proposal stage to explore commensality with other EoIs and involve the wider community.

TECHNICAL JUSTIFICATION:

Number of objects: With a *minimum* requested observing time per pointing and per frequency-tuning of ~200h (100h on-source + 100h overheads), we will request a ***maximum* of ~15 targets**. Our targets will be massive high-z galaxies in proto-clusters. Targets should have deep ancillary data, known line-detections at mm wavelengths and preferably other line-emitters (e.g., Lyα or Hα) within the primary beam. To remain flexible and involve the wider community, we defer the final sample selection to the proposal stage.

LST ranges: For flexible scheduling, targets will be spread across LST, but will preferably avoid LST~4-8h, because those will be night-time in mid-summer and thus suffer most from the weather.

Frequency: All observations will be done in the sensitive part of the 7mm band (30-45 GHz). This frequency range can capture the CO(1-0) transition at ~1.5 < z < 2.8, or the CO(2-1) transition at 4.1 < z < 6.7. If desired, we can consider targeting the CO(1-0) line in the 15mm band for 3.6 < z < 6.2.

CABB modes: Standard low-resolution spectral-line mode: 2×2 GHz bands with 2048 channels of 1 MHz. This gives a velocity coverage of ~17,000 km/s per 2 GHz band with ~8 km/s resolution for a target at z~2.

Array configurations: To image the CO, but remain sensitive to low-surface-brightness emission, observations will be done with baselines up to ~1km: **H75 (essential), H168, H214, 750m (1.5k possibly)**.

Observing strategy: This project requires night-time observations as much as possible. To minimize overheads and optimize uv-coverage, the ideal scheduling would consist of 8h blocks in the hybrid and 12h blocks in the east-west configurations. Observations will be single pointing, single frequency, with perhaps room for a redundancy in IFs (both 2 GHz bands placed at the CO-line) to insure against spurious correlator problems. Bandpass, phase and pointing calibration need to be done each run, but flux calibration has to be done only occasionally. From experience, we envisage that *the bulk of the observations could be performed in a non-interactive mode,* where the observing schedule can loop automatically for the full duration of the run. The ATCA provides sufficient information to manually flag periods of bad weather during the reduction stage. To further ease this process, our team is also developing an automated flagger routine based on the water-vapor-radiometer output. Our program would benefit from poor-weather/RFI swap with a cm project.

Required sensivity: Our goal is to reach a reliable 4σ limit to the H_2 mass of $M_{H2} \sim 1 \times 10^{10}\ M_{\odot}$ at z=2, assuming a galaxy with a typical $FWHM_{CO} \sim 500$ km/s and $X_{CO} = M_{H2}/L'_{CO} \sim 0.8$. This corresponds to a 1σ rms limit of $L'_{CO} \sim 1 \times 10^9$ K km/s pc^2 per 50 km/s channel, or $\sigma = 0.1$ mJy/beam per 50 km/s channel. From our extensive experience with various ATCA mm projects (C2052, C2717, C2815, C3003, C3026, C3096) we know that we will reach this noise level after 100h on-source time at 30-40 GHz in natural weighting.

Approximate time request: We conservatively aim for 3000h total observing time, which implies ~1500h on-source time, with the possibility to reduce this request after selecting the final sample. This request assumes a "swap-model" in which observations are only scheduled when weather predictions appear favorable. Considering that calibration and frequent slewing will take ~40% of the time, and that ~10% of the data will need to be flagged due to "in-run" changes in weather conditions, we assume that 50% of our overall time request is lost to overheads. We do not limit the number of semesters, but we may ask ATNF to prioritize the completion of individual targets, e.g. within the time-frame of PhD projects.

Team members, skills & resources: Our team consists of experts in mm observing and data reduction with the ATCA. Emonts, Norris, Huynh, Mao, Sadler, Heywood, Allison, Mahony, Ekers, Seymour, Dannerbauer et al did >>1000h of hands-on observing with the mm system, and published a dozen refereed papers on high-z CO studies with ATCA. B. Indermuehle implemented the ATCA water-vapor radiometers and is testing potential applications for Legacy Projects (see below). Data rates are manageable, given that no zoom capabilities are needed, with an expected raw data volume of ~ 3-4 Tb over 3000h observing time.

Non-standard ATCA capabilities: Our project could hugely benefit from the water-vapor radiometers (WVRs). The WVR-expert within our team, Balthasar Indermuehle, has done experimental tests regarding the application of the WVR phase-corrections to the data, as well as an automated "bad-weather-flagger". If ATNF resources allow, further development of these WVR-applications would be highly valuable.

References: *(1). Oser+ 2010, ApJ, 725, 23; (2). Dekel+ 2009, Nature 457, 451; (3). Prochaska+ 2014, ApJ, 796; (4). Narayanan+ 2015, Nature. 525, 496; (5). Ceverino+ 2010, MNRAS, 404, 2151; (6). Emonts+ 2014, MNRAS, 438, 2898; (7) Emonts+ 2015, MNRAS, 451, 1025; (8) Emonts+ 2016, submitted (pre-print available upon request)*