Measuring Thermal Emission of Star Forming Galaxies at High Redshift

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EXECUTIVE SUMMARY: We propose a deep (RMS $\sim 1.5\,\mu$Jy) 10 GHz radio-continuum survey targeting the thermal emission of distant ($z \sim 3.5$) Star Forming Galaxies (SFGs) in the Extended *Chandra* Deep Field South (ECDFS). The ECDFS is an extensively studied field and offers a wealth of excellent multi-wavelength surveys that would only compliment this proposed legacy project and enable complex modelling to be crafted and tested. Therefore our key science goals are to: (1) use thermal radio-continuum emission, which offers a *direct* and *unbiased* measure of *current* star formation rates free from the effects of dust attenuation, to characterise star formation in the early Universe and improve current star formation rates (SFR) measures for the Square Kilometre Array (SKA) era, (2) develop and calibrate new techniques to derive photometric redshifts of dusty starburst galaxies from radio-continuum and IR data alone, (3) investigate source counts of flat spectrum active galaxy nuclei (AGN) with increasing redshifts, and (4) identify AGN through cosmic time by searching for their variability.

MOTIVATION: Radio emission from galaxies is a superb tracer of SFR as it is not affected by dust attentuation. Deep radio surveys from the SKA and its pathfinders will be dominated by distant star forming galaxies and hence will perform the most detailed measurements of the star formation history of the Universe yet. The far infrared to radio correlation (FRC) is the key relationship used to infer the star formation rates of distant galaxies detected at radio wavelengths.

In the context of radio-continuum surveys, this method usually relies on the 1.4 GHz mono-chromatic luminosity of an object to estimate its SFR. At this frequency the spectrum is comprised predominantly of non-thermal synchrotron radiation (see Condon 1992; fig. 1). This radiation, caused by ultra-relativistic electrons accelerated by supernovae, may be used as a non-instantaneous tracer of star formation and, because of its relatively steep spectra, is easily detectable (Seymour et al. 2008, Padovani et al. 2011). However, due to inverse-Compton losses that begin to suppress the non-thermal emission in proportion to $(1+z)^4$ and the changing composition of the radio-continuum as a function of frequency, it is increasingly more difficult to use this type of emission as the basis of reliable radio SFR indicators at high redshifts.

Thermal free-free emission originating from HII regions makes up a small fraction ($\sim 10\%$) of rest frame 1 GHz radio-continuum. Although it is a direct, instantaneous measure of the Lyman photons which trace star formation, there have been few studies (Price and Duric 1992 and Clemens et. al 2008 being the most notable) that have successfully isolated its flat spectra ($\alpha = -0.1$), primarily due to the having to model the radio-continuum over a modest frequency range. High frequency observations ($\nu \sim 10\,$GHz) offer a superb window into the thermal emission of distant galaxies (Murphy 2009 and Murphy et. al 2011). It is this regime, where thermal emission begins to dominate over the non-thermal emission processes, where we can calibrate far more accurate SFR indicators.

SCIENTIFIC AIMS: (1) *Characterising the SFR of distant galaxies at high redshifts.* Current measures of SFR in the radio regime primarily use the 1.4 GHz luminosity of galaxies, a frequency that is predominantly non-thermal in nature. Although calibrated well against local galaxies ($z < 0.5$), increasing redshifts will begin to suppress the main emission mechanism. Thermal emission originating from HII regions are a direct tracer of the *current* SFR of galaxies and a deep high frequency survey offers an excellent window into this process. With accurate redshifts from auxiliary projects (e.g. OzDES), we will be able to construct measures of SFR through cosmic time which could correct current SFR calibrations based on 1.4 GHz luminosities - something critically important for future surveys from the next generation of radio telescopes.

(2) *Improve methods to derive photometric-z measurements from the radio-continuum.* Yun & Carilli 2002 showed that photometric redshifts of dusty starburst galaxies could be obtained by using information associated with the entire radio to far-IR. By constructing an SED template encoding theoretical expectations of thermal dust, thermal and non-thermal radio-continuum emission, a photometric redshift could be obtained with only a few measurements in the radio and IR domains. Initially, we plan to use the ATLAS (Franzen et. al 2015), 5.5 GHz ECDFS (Huynh et. al 2015) and *Spitzer* SWIRE (Lonsdale et. al 2003) radio and far-IR surveys to refine this technique, using spectroscopy redshifts from OzDES as the training set. This method of obtaining photometric redshifts will be immediately useful for upcoming surveys from SKA pathfinders.

(3) *Investigate flat spectrum AGN counts at high redshift.* The AT20G survey (Murphy et. al 2009), with a flux density limit of 40 mJy, revealed a larger than expected sample of flat-spectrum AGN when compared to expected counts extrapolated from lower frequency surveys with assumed typical spectral indices. This project will be able to further explore this population of sources and investigate their source counts with increasing redshifts.

(4) *Identify active galaxies by searching for variability.* A legacy project conducted over a number of years will offer a unique opportunity to track variability, in terms of flux density and polarisation, of sources in the ECDFS. The origin of such variability, which can be on timescales as short as weeks, is caused by the core of the galaxy interacting and ejecting nearby matter. When coupled with redshifts from auxiliary surveys we will be able to understand how such objects may evolve through time.

TECHNICAL JUSTIFICATION: The ATCA telescope is perfectly suited for this legacy project, as we require a robustly tested, well understood instrument capable of observing at 10 GHz reliably. Using the ATCA sensitivity calculator with a centred on 9.5 GHz (covering 8.5 - 10.5 GHz with the CABB filters), we find that a 3 μJy RMS sensitivity can be achieved using a 6A array configuration, a natural weight scheme and approximately 720 minutes of time on source. Assuming a primary beam FWHM of 289$''$ at a frequency of 10.5 GHz, the $30' \times 30'$ ECDFS field can be covered by 143 pointings using a hexagonal scheme separated by 0.5 increments of the primary beam. Thus, scaling the initial 720 minute per pointing across the entire field, and assuming 20% of time for overheads, we estimate the total time required is $\sim$2200 hours. Linear mosaicking the overlapping pointings together will improve the sensitivity by a factor of $\sim$2, giving us an estimated 1.5 μJy RMS. Referring to Fig. 1 (which has been taken from Murphy 2009), a 5σ RMS of 7.5 μJy will be able to detect sources out to a $z \sim 3.5$ for the most powerful starburst galaxies ($\mathrm{L_{IR}} = 10^{13}\,\mathrm{L_\odot}$, $B = 10\,\mu$G), and a $z \sim 0.5$ for more typical objects ($\mathrm{L_{IR}} > 10^{11}\,\mathrm{L_\odot}$). The sparsely distributed 6 km and 1.5 km arrays would be used together across the entire field to provide sufficient confusion limits (calculated to be in the sub-μJy regime for these configurations) without resolving structure from high redshift galaxies. Furthermore, this frequency range is virtually free from interference, enabling a superb observing window with no technical constraints. The ECDFS is observable from the ATCA for roughly 12 hours a day (LMST $\sim$ 21:30 - 09:30), facilitating straight forward scheduling. The second ATCA CABB IF will be configured with a central frequency of 7.5 GHz which will allow for polarisation and rotation measure studies across a wide contiguous bandwidth. Additional sensitivity could also be achieved be merging portions of the two IFs together and using sophisticated cleaning algorithms, such as MIRIAD's MFCLEAN and CASA's CLEAN, while imaging.

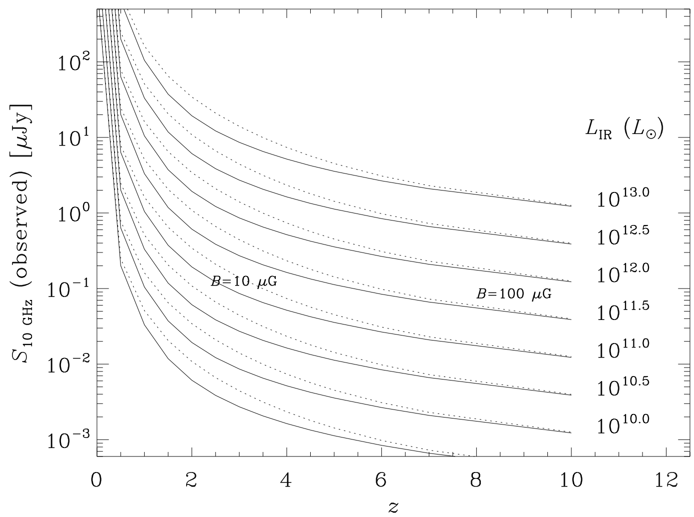

Figure 1: The observed 10 GHz sensitivities required to detect starburst galaxies at various redshifts (Murphy 2009; fig. 7). The solid and dotted lines represent magnetic field strengths of 10 μG and 100 μG respectively. Each track is labelled with its corresponding IR luminosity.

REPRESENTATIVE TEAM MEMBERS

Ray Norris (WSU/CSIRO): Lead investigator of the ATLAS and EMU projects, and has extensive expertise in all aspects of radio astronomy. ***Nick Seymour (Curtin University)***: An expert on high redshift surveys, and a member of OzDES spectroscopic programs. ***Eric Murphy (NRAO)***: Extensive work on star formation in the early Universe whose work this proposal is based on, ***Miroslav Filipović & Nick Tothill (WSU):*** They have a wealth of experience on a number of multi-wavelength projects. ***Minh Huynh (UWA)***: The project lead on a number of earlier ATCA mosaic surveys, including one targeting that ECDFS at 5.5 GHz. ***Josh Marvil (CSIRO)***: A key member of the upcoming EMU all sky-survey and ASKAP commissioning projects. ***Martin Bell (CSIRO/WSU)***: Has been heavily involved in transient studies involving SKA Pathfinder instruments.

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