An ATCA 4–10 GHz Legacy Survey of the Magellanic Clouds

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Significance: Two neighbouring galaxies – the Small & Large Magellanic Clouds (MCs) – are the subject of a large number of astronomical studies, due to their location far away from the problematic Galactic plane region, their close proximity and well known distance. Studies & observations of MCs are important for our understanding of the structure and evolution of galaxies, since there are many observable objects that have a significant impact on the MCs. For example – Supernovae and their Remnants (SNRs) are together one of the most influential and energetic events that influence the evolution of galaxies, making it crucial to understand how these objects themselves evolve and interact with the surrounding medium. Other objects influencing the structure and growth of galaxies include H II regions, (super)bubbles, Young Stellar Objects (YSO) and Planetary Nebulae (PNe), all of which allow us to probe the physical conditions in which they reside. We propose to study these objects at high resolution to enable the structure and environment of the entire MC regions to be traced on small spatial scales, which hasn't been done before. As a bonus, our observations will provide a deep survey of background objects, most of which will be Active Galactic Nuclei (AGN).

Legacy Value: This survey will be the widest, deepest and highest-resolution radio survey of the MCs to date, which will bridge a crucial gap between previous shallow, low-resolution surveys of the MCs and the upcoming all-sky surveys such as ASKAP, MWA, eROSITA and the CTA. The ATCA is currently the only suitable telescope that will allow us to obtain a well-sampled field in both the *uv* and spatial domains at 5 and 9 GHz. This fact combined with our science goals makes our legacy proposal of *lasting use and importance*.

Goals: Here, we propose a deep survey of the MCs at 5 and 9 GHz with an RMS of <40 μJy/beam. This field has been chosen due to its extensive multi-frequency coverage from deep surveys over the last few decades, which provide a wealth of data on the structure and composition of the MCs. The scientific goals for this ATCA legacy project are: (1) to comprehensively survey the MCs at high resolution & over large bandwidth, augmenting existing surveys − this will allow us to observe how SNRs, PNe and star forming regions evolve and expand, enabling us to understand the effect of these objects on the surrounding interstellar medium. At the same time, we will construct the first complete radio sample of SNRs (over 120) and PNe (over 400) in any external galaxy; (2) create a comprehensive catalogue of radio sources behind the MCs (e.g. AGN & SFGs). In particular, providing excellent spectral coverage of Gigahertz Peak Spectrum (GPS) sources and High Frequency Peakers (HFPs) − with a simultaneous frequency coverage between 4 − 10 GHz. (3) study the strength and direction of the magnetic fields present within the MCs − this will be achieved both directly with the use of polarimetry measurements of gas clouds and indirectly by utilising the upcoming ASKAP & MWA catalogues in a Faraday de-rotation process.

Motivation: The MCs are the ideal laboratories as they are two nearby, face-on galaxies with well known distances and circumpolar visibility (>90% of time). This ideal location has allowed the MCs to be extensively studied over the last 30 years, including all types of galactic and inter-galactic objects (e.g. Magellanic Bridge). The current best ATCA interferometric surveys of the Large Magellanic Cloud (LMC) at 5 and 9 GHz (Dickel *et al.*, 2005) achieved an RMS of ∼280 μJy (Fig. 1) and ∼500 μJy, respectively. However, these surveys only cover the central region of the LMC and omit short spacing data. Similarly-restricted surveys of the Small Magellanic Cloud (SMC) have been conducted by Filipović *et al.* (2002) at 4.8 and 8.64 GHz (respective RMS of 800 & 400 μJy). Our survey aims to address both limitations by improving the RMS to < 40 μJy/beam and combining short and long baselines, enabling a large range of spatial scales to be probed at faint levels, particularly at high resolution. This is an order of magnitude of improvement compared to previous MC radio continuum surveys.

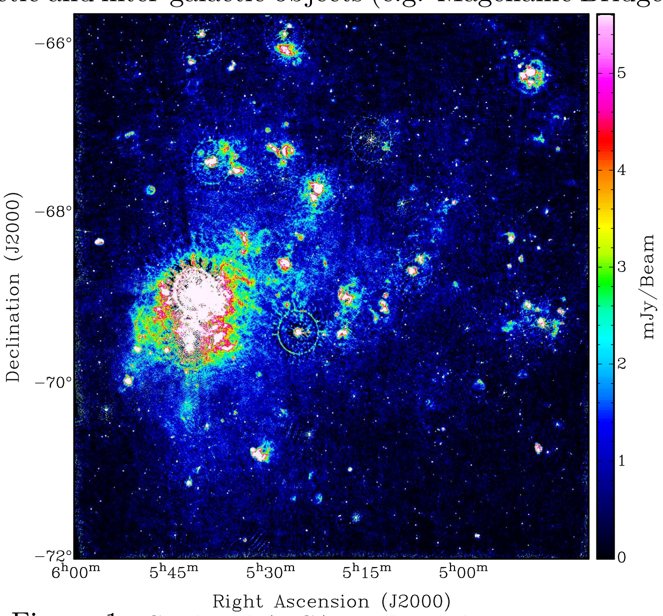

Figure 1: Combined ATCA+Parkes radio continuum image of the LMC at 4.8 GHz (θ_{FHWM}=40″; RMS ∼280 μJy).

Additionally, highly sensitive and detailed polarisation studies can be carried out, shedding light on the physical conditions of the ISM. Moreover, RM synthesis will allow us to study the overall magnetic field structure of MCs in great detail, with significantly less confusion than similar studies in the plane of the Milky Way. This may provide new insights into how magnetic fields are distributed in galaxies and the importance of turbulent (small scale) magnetic fields compared to those generated by large-scale galactic motions.

Scientific Aims: We propose to undertake a deep radio continuum survey of the MCs at 5 and 9 GHz, to fully sample the MCs in the frequency and *uv* domains. Our key science aims for this project are:

(1) To observe the small and large-scale kinematics of the MCs through the detection of H II regions, SNRs and PNe. We expect to detect over 120 SNRs, 400+ PNe and hundreds of various types/sizes of H II regions. We will establish the first complete sample of these objects which will allow us to increase our understanding of how they evolve in the rarefied environment of the MCs. We aim to accurately measure the shock fronts and the surrounding turbulence using high resolution observations ($< 1''$ at 9 GHz). This, in conjunction with sensitive polarimetric data, will constrain the physical parameters of the expanding material. These are some examples of research questions that we aim to answer with this proposed survey:

1. To what degree the recently discovered 15 evolved Fe-rich type Ia SNRs in the MCs (Maggi *et al.*, 2016) differ (if at all) from other type Ia remnants in the radio-continuum. Do double degenerate systems expand faster then Single Degenerate ones as theoretically predicted by Chakraborti *et al.*, (2016)?
2. To establish the bright end of the radio PN luminosity function from significant (400+) new samples in MCs. How all differences in the multi-wavelength characteristics of Galactic and MCs PNe relate to PN age and luminosity and hence: How we can use PNe as cosmological radio 'standard candles' via a new radio luminosity function we will establish in this project?

(2) To detect the large scale, low surface brightness structures within the MCs. Coupled with the background source catalogue (aim #3) it will facilitate the measurement and analysis of large scale magnetic fields present in the MCs. Gaensler *et al.* (2005) and Mao *et al.* (2008) used 1.4 GHz to derive the overall magnetic field of the MCs, but on large spacial scales. This Legacy Survey ($< 2''$ at 5 GHz), in combination with Gaensler *et al.* (2005), Mao *et al.* (2008) and the upcoming ASKAP-POSSUM Survey ($\sim 6''$ at 1.8 GHz), will provide an unprecedented opportunity to study the MCs magnetic fields at all scales. Assuming that at 5 GHz Faraday rotation is low, our survey may prove as an ideal test bed to study the whole Magellanic System peculiar structure including a giant magnetic loop emerging out of the plane of LMC noted by Klein *et al.* (1993).

At the same time, our secondary aim is: **(3)** To detect and catalogue an estimated $\sim$14 000 background sources ($\geq 5\sigma$ at 5 GHz; Wall, 1994) from which we estimate $\sim$1 500 to be GPS and HFPs. These data will be invaluable when combined with exiting MWA and pre-CABB ATCA data (Wayth *et al.*, 2015; Dickel *et al.*, 2005; Murphy *et al.*, 2010). A high-frequency turnover is indicative of a young source that has not experienced significant electron ageing (e.g. Kardashev 1962; Callingham *et al.*, 2015). We aim to construct the large sample of low-luminosity HFPs, which will provide key insights into the earliest stages of AGN evolution. This data will also allow the detection of variable sources when compared with existing datasets.

Observing Strategy: In order to achieve the required sensitivity and *uv* coverage, we will require:

Array Configurations & CABB Mode: Two array configurations — a 6-km and a compact array such as EW352. Two observing bands will be used simultaneously, centered at 5 and 9 GHz, with 2048×1 MHz channels, giving a primary beam of $306''$ at 10 GHz.

Magellanic Clouds' Field: The LMC field of 144 deg^2 ($12^\circ \times 12^\circ$) would require $\sim$22 800 pointings, while the SMC field of 12 deg^2 ($4^\circ \times 3^\circ$) can be covered by $\sim$1 900 pointings when assuming a nyquist sampling rate.

Time per Field & Semester: An estimated 5.4 minutes on each pointing (using the ATCA sensitivity calculator) distributed equally between array configurations is sufficient to reach an RMS of $< 40\,\mu$Jy/beam at 9 GHz. This time will be further distributed between eight 20-second cuts (in each array configuration) to maximise *uv* coverage and reduce radial striping around strong sources when imaging. Therefore, by extrapolating the sensitivity and field size requirements, this project will require $\sim$2 670 hours when assuming 20% overheads – (22 800+1 900)×5.4min/60min×1.2=2 667 hours. We estimate some 300 hours per semester across a 4–5 year period (8–10 semesters) is required to achieve this project in a timely manner.

Non-Standard ATCA Capabilities: The overhead due to telescope slew time can be reduced significantly ($\sim$15%) with an "on-the-fly" observing regime because of the large amount of pointings required.

LST Range: Observing the MCs field is easily achieved as they are circumpolar.

Representative Team Members and Skills Available: *K. Grieve (WSU; PhD Student; AGN), J. Marvil (CSIRO; data processing), R. Norris (CSIRO/WSU; Cluster Physics & AGN), E. Crawford & T. Galvin & N. Tothill & J. Collier & A. O'Brien (WSU; AGN/PNe/SFG), D. Leahy (U. of Calgary; PNe/SNRs/Polarimetry), G. Rowell (U. of Adelaide; SNRs), L. Staveley-Smith (U. of Western Australia; Polarimetry & H I), M. Sasaki (U. of Tübingen; SNRs), P. Kavanagh (DIAS; SNRs), F. Haberl (MPE; SNRs), J. Dickel (U. of New Mexico; surveys/SNRs).*

References: Callingham *et al.*, 2015. ApJ, 809, 168♣ Chakraborti *et al.*, 2016. ApJ., 819, 37♣ Dickel *et al.*, 2005. AJ, 129, 790♣ Filipović *et al.*, 2002. MNRAS, 335, 1085♣ Gaensler *et al.*, 2005. Sci, 307, 1610♣ Kardashev 1962. SvA, 6, 317♣ Maggi *et al.*, 2016. A&A, 585, 162♣ Mao *et al.*, 2008, ApJ, 688, 1029♣ Murphy *et al.*, 2010. MNRAS, 402, 2403♣ Wall, 1994. AuJPh, 47, 625♣ Wayth *et al.*, 2015. PASA, 32, 25♣ Klein *et al.*, 1993. A&A, 271, 402