Title: Large-Area Galactic and Extragalactic Research through an ATCA Legacy Experiment (LAGER ALE)

Point of contact: Shari Breen (Shari.Breen@csiro.au)

Scientific aims: "Our Galaxy, the Milky Way, is a benchmark for understanding disk galaxies. ...Galactic studies will continue to play a fundamental role far into the future because there are measurements that can only be made in the near field and much of contemporary astrophysics depends on such observations" (Bland-Hawthorn & Gerhard, 2016). Through an observational campaign targeting spectral lines and radio continuum at 7 and 15mm we will reveal the dense star-forming gas right across our Galaxy and extend our observations to a number of nearby galaxies, allowing us to probe size scales ranging from individual star forming clumps right through to star formation on galactic scales, and leave a legacy dataset to benefit a wide range of astrophysical challenges. Specifically, we will:

- Characterise the dense gas structure of our Galaxy through sensitive carbon monosulfide (CS) and ammonia (NH_3) observations, allowing us to detect molecular clouds out to the far side of the Galaxy. Combining these data with HI (from future ASKAP observations) and CO (from Mopra CO surveys) we will span the characteristic densities that the bulk of the interstellar gas exists in, from the atomic, through the diffuse molecular to the dense molecular. The transition of the gas through these scales and into new stars is at the heart of our galactic ecosystem. Key examples of specific science goals include:
  - Derive multiple physical parameters through observations of ammonia, including temperatures, densities, optical depths and the ortho-para ratio (providing a gas formation temperature).
  - Study the clump mass function within different Galactic environments and measure the column density PDFs to test the predictions of star formation theory.
  - Determinethe interplay between the less dense CO emission detected in large-scale surveys the ATNF has already made significant investment in, and the dense gas.
  - Compare the chemistry and kinematics of the detected sources with those found towards the Central Molecular Zone (CMZ) of our Galaxy in the SWAG survey (Survey of Water and Ammonia in the Galactic Center; Ott et al., C2927).
  - Gain unprecedented understanding of how gas and star formation parameters change with environment through comparisons of the chemistry, physical parameters and kinematics of objects in our Galactic plane (this work) and CMZ (from SWAG observations) with the CMZs of other galaxies. A number of our extra-galactic targets will be observed in higher-frequency spectral lines with ALMA, and the unique 15mm data collected with ATCA will be highly complementary – in particular the temperature tracer, ammonia, and the water maser line.

- Produce an essential dataset on CS clumps across the Galaxy that will underpin the Galactic plane survey in TeV (10^{12} eV) gamma-rays by the forthcoming multi-national Cherenkov Telescope Array (CTA) facility. In order to study the "cosmic accelerators" producing incident cosmic rays it is necessary to understand the gas distribution across all density scales from atomic to dense molecular (since the energy distribution of the gamma-rays that are produced depends on the density and distribution of the gas encountered).
  - The CS will complement ISM surveys of CO (from Mopra) and HI (from ASKAP) that the CTA will need to build a 3D picture of the ISM. CTA is the next generation gamma-ray facility ranked in Europe at the same level as the SKA. It is a multi-national project ($>$25 countries) with a $>$20 year lifetime ($>$250MEuro project). This CS survey will further solidify Australia's leading role in providing CTA with many of its much-needed ISM data.

- Determine the relative importance of turbulence and magnetic fields in star formation by comparing filament orientations to magnetic field direction measurements (from e.g. BLASTPol).

- Identify and characterise the enigmatic first signature of ionised hydrogen from young high-mass stars (hyper compact HII regions) by increasing the number of known regions by an order of magnitude and measuring their spectral indicies, which will tell us about their structure, as well as their gas and dust content.

- Characterise how class I methanol and water masers are related to star formation through the largest sensitive, untargetted surveys of these masers. In particular we will determine how these masers fit into the high-mass star formation time-line.

Number of objects, or area of sky: **7mm:** 85 degrees^2 of the Galactic plane allowing us to cover the entire 4th quadrant in $\pm$0.5 degrees (5 degrees^2 already covered by MALT45); **15mm Galactic:** 5 degrees^2 of the Galactic plane observed as a series of 1 degree^2 sections, spread to efficiently probe the structure of the Galaxy and different star formation environments; **15mm extragalactic:** single pointing, full synthesis observations towards $\sim$20 nearby galaxies.

LST range(s): The bulk of the observations for this project target the Galactic plane so the LST range is constrained to ∼10 to ∼21 LST. The extragalactic targets will be selected to fall within the complementary LST range.

Frequency(/ies): 20-25 GHz and 42-50 GHz, covering a number of spectral lines (e.g. CS, SiO, class I methanol masers, ammonia, water masers, just to name a few) and allowing optimal radio continuum observations.

CABB mode(s): The best mode for the 15mm observations would be CFB 16M-8k, if developed, and CFB 64M-32k otherwise. For the 7mm observations we will require CFB 64M-32k.

Array Configuration(s): Any array without shadowing issues (7mm), H214 and H75 (15mm extragalactic) and H168 (15mm Galactic).

Observing strategy: On-the-fly mosaic in auto-correlation mode (7mm), single point full synthesis (15mm extragalactic), traditional mosaic with a number of cuts using both cross- and auto-correlations (15mm Galactic). Observations will cover a multitude of spectral lines as well as sensitive radio continuum data.

Required Sensitivity: Ability to detect CS clouds of 400 $M_{\odot}$ out to 15 kpc (equivalent to 44 mK in a single spectral channel), matching mass sensitivity in ammonia (equivalent to a 250 mJy detection limit for water masers, e.g.). 60 mK sensitivity to ammonia in extragalactic observations.

Approximate number of hours in total, and per semester: 3880 hours total, ∼500 per semester. (Breakdown: 2380 hours for 7mm 85 degree^2 coverage, 1000 hours 5 x 1 degree^2 coverage for 15mm Galactic and and 500 hours to observe ∼20 nearby galaxies at 15mm.)

Indicative resources/Representative team members & skills available: We have identified a core team to lead this project through to successful completion. We intend the project to be highly collaborative and will actively pursue other members who have a willingness to contribute to its success. For the purposes of this document we will focus only on the core team members; Shari Breen [1], Andrew Walsh [2], Chris Jordan [3], Gavin Rowell [4], Juergen Ott [5], Simon Ellingsen [6], Maxim Voronkov [7], Maria Cunningham [8], Paul Jones [9], Yanett Contreras [10], James Green [11], Peter Barnes [12], Michael Burton [13], Joanne Dawson [14], Christoph Federrath [15], James Jackson [16], Steven Longmore [17], Phoebe de Wilt [18], Balthasar Indermuehle [19], Lisa Harvey-Smith [20]. Between us we have all the skills, experience and resources necessary to the successful completion of the project:

- Almost all of the core team have been key members of successful large surveys in the past, both in the role of leaders and active members (e.g. MMB, HOPS, SPLASH, MOPRA CO, ThrUMMS).
- We have many members who are highly experienced with high-frequency radio data [1,2,3,5,6,7,8,9,10,12, 13,14,16].
- We have championed the usage of the ATCA auto-correlation data mode [1,2,3,6,7] with MALT45 (which surveyed a 5 degree^2 region of the Galaxy). The current proposal will use the same observing mode, and we will also use existing MALT45 and SWAG pipelines to reduce the Galactic data.
- We have a broad range of science experience, ranging from masers [1,2,3,6,7,11,13,16,19,20], dense gas [1,2,3,4,5,8,9,10,12,13,15,16,17,18], star formation [all], high-energy astrophysics [2,4,13,18], extragalactic studies [1,4,5,6,11,14,15,16] and star formation theory [15].
- Members [1,2,4] have submitted a Discovery Proposal to the ARC to support aspects of this work.
- We have access to theory and supercomputer simulations support (for e.g., understanding density PDFs, star formation regions, dense gas fractions, star formation laws, the initial mass function, etc.).
- Our team includes the Australian lead on CTA [4] and has experience merging gamma-ray and ISM data [4,13,18].

Specific team expertise not yet identified or non-standard ATCA capability required: This project will use the auto-correlation data from the ATCA, a non-standard mode, but a mode that we have extensively tested and that we are the experts in. We have also shown that, in this mode, we can observe outside the traditional mm season.
This project would be best completed with a combination of CABB modes CFB 16M-8k and CFB 64M-32k and so would require the CFB 16M-8k mode to be implemented.