The GASKAP-OH Survey

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1 Project Summary

GASKAP-OH will probe the beginning and end points of stellar life, by observing the four 18-cm transitions of ground-state hydroxyl (OH) in the Milky Way and Large Magellanic Cloud (LMC) at unprecedented sensitivity and resolution. The flow of matter and energy between stars and the interstellar medium (ISM) is at the heart of galaxy evolution. GASKAP-OH will reveal the formation and early evolution of molecular clouds and young stars, and the end-of-life activities of old massive stars in the galactic context, at a level of detail that can only be achieved through observations of our own Galaxy and Magellanic System.

GASKAP-OH will quantify the birth and evolution of molecular clouds, by producing the largest and most sensitive interferometric maps of quasi-thermal OH absorption ever created. Together with GASKAP-HI observations of cold atomic gas, we will measure the thermal and physical state of the ISM at multiple points along the evolutionary timeline from atomic gas to dense, star-forming clouds, and characterise statistically how these change with Galactic environment. To pinpoint sites of active star formation, GASKAP-OH will undertake the deepest ever unbiased census of OH star formation masers in the Southern Milky Way, discovering many hundreds of new sources. Characterising the full population of OH maser sources and their properties, in conjunction with maser pumping models, will inform the physical conditions in the star-forming gas, and the evolutionary stage of young stars in throughout our Galaxy.

GASKAP-OH will undertake a large-scale census of circumstellar OH masers around luminous dying stars. These stars return copious amounts of mass back to the interstellar medium; in the case of red supergiants this mass loss also determines the nature of the ensuing supernova demise. OH maser profiles will provide a vital parameter: wind speed. This is the key to understanding wind driving and allows determination of the dust-to-gas ratio. Studies across the Milky Way and Large Magellanic Cloud will allow to determine the most crucial and poorly known parameters in the mass-loss process: luminosity and metallicity. Moreover, GASKAP-OH will also be a deep, unbiased survey for supernova remnants. Maser observations of the shocked gas in SNRs will establish their evolutionary stage, their energy and chemical element impact on the ISM, and probe the impact of these enormously energetic end-of-life explosions on their natal clouds.

Finally, we will leverage all of these measurements to refine our understanding of the structure of the Milky Way Galaxy, which has long been better determined in the Northern sky than the South.

Synopsis of the 2009 Science Case & Changes in Scope: The original GASKAP team was formed in 2008 by combining several Expressions of Interest, all focused on the ISM, star formation and evolved stars in the Milky Way and Magellanic System. At that stage, ASKAP was to have a 'split band' mode, allowing simultaneous observation of HI and multiple OH lines. The 2009 science case linked the evolution of gas from the warm, diffuse atomic medium, through to cold atomic gas, then finally into molecular gas, star formation, and mass-return to the ISM, as traced by OH absorption and OH masers. GASKAP thus leveraged the commensality of the HI and OH observations to address in a comprehensive and connected way some of the key bottlenecks in our understanding of how galaxies evolve.

In 2021 with the prospect of split-band observing uncertain, GASKAP has divided into GASKAP-HI, and GASKAP-OH. These twin surveys remain tightly connected scientifically, and are managed at a high level by the GASKAP leadership team. In GASKAP-OH we have carefully constructed a science programme that balances the additional time burden of split surveys, while maximising the science returns and ensuring that we can achieve our core goals. While our time request is modest (1232 hours), we will significantly outperform all similar surveys to-date. We note that the time request in the 2009 GASKAP proposal was 8945 hours, and that GASKAP-HI requests 6840 hours, making the revised total requested by the GASKAP project smaller, at 8072 hours.

2 Overview of SSP activities and achievements 2009–2021

Early Data & Publications: GASKAP as a whole has been actively publishing science from HI Early Science and Pilot Phase I data (McClure-Griffiths et al., 2018; Di Teodoro et al., 2019b,a; Murray et al., 2019; Szotkowski et al., 2019). However, GASKAP-OH only received its first potentially science-quality test data in September 2021[1]: a single 8-hour closepack-36 observation (three interleaves) of the 1665 and 1667-MHz lines, taken in 32× zoom mode ($\Delta v \sim 0.1$ km s^{-1}), centred on a Galactic longitude of $\ell = 340°$ (we refer to this as the G340 test field). We have worked quickly to assess these test data, and have been able to validate aspects of the data quality[2], proposed survey strategy, science goals and analysis tools in the short time available. As shown in Fig. 1, we have so far confirmed 37 maser detections at 1665 MHz, 26 of which are new discoveries, within just a fraction of the ASKAP footprint (approximately 1/6 of the overall field). In addition we have identified at least 70 distinct absorption component detections (shown in Fig. 3 across the entirety of the test field. These numbers confirm that GASKAP-OH will be *significantly* better than any work that has come before, both due to the sensitivity and the complete coverage.

Development & Testing of Analysis Tools for GASKAP-OH:

- **Maser source finding:** Source finding on large spectral datacubes is a major technical and computational challenge. We have worked closely with M. Whiting (CSIRO) to optimise the ASKAPSOFT source finding package SELAVY for integration into the ASKAPSOFT workflow.
- **Absorption pipeline:** We have adapted and optimised the HI absorption pipeline developed as part of the GASKAP-HI tools (Dempsey et al 2021, in prep), to work on GASKAP-OH image cubes. The pipeline uses the automatically generated SELAVY continuum source component list, and produces a catalogue of science-ready optical depth spectra and associated statistics.
- **Automated spectral fitting:** Gaussian decomposition of OH optical depth spectra is crucial to the OH absorption science. The AMOEBA package (Petzler et al., 2021) can automatically decompose sets of OH optical depth spectra using a fully Bayesian framework, by exploiting the unique set of constraints that governs the four-line system.
- **Non-LTE modelling toolkit:** The thermal and physical state of quasi-thermal OH may be constrained by non-LTE excitation modelling of the four-line system. We have been developing and testing modelling code for use specifically in this regime, applying it successfully to interpret peculiar patterns of satellite line excitation in gas associated with HII regions (Petzler et al., 2020).
- **Maser theory:** Key to interpreting maser observations, maser theory has progressed dramatically in the past decade (see e.g. book by GASKAP-OH team member; Gray, 2012).

Complementary & Pathfinder Surveys: In the last 12 years, the GASKAP-OH team has driven considerable advances in all science areas of this proposal, including leadership of major surveys. Here we list those of most immediate relevance; many are led by GASKAP-OH members:

- **SPLASH** (PI J. Dawson+; Dawson et al. 2014, 2021 in prep) observed all four OH lines at high sensitivity and low resolution ($\sim 15'$) between $\ell = 332°$ and $\ell = 10°$, $|b| < 2.5°$ with the Parkes telescope. SPLASH was designed as a precursor and complement to GASKAP. The two surveys probe distinct and complementary regimes. The interferometric component to SPLASH (Qiao et al., 2016, 2018, 2020) observed all maser candidates, confirming and localising over 400 new maser sites. GASKAP-OH will more than double this point-source sensitivity, at comparable resolution, over a much larger area.
- **MAGMO** (PI J. Green) made polarimetric ATCA observations of OH masers towards hundreds of sites of high-mass star formation (Green et al., 2012; Ogbodo et al., 2020), aiming to measure magnetic field strength and orientation in regions of star formation spread across the Galaxy.
- **THOR** observed HI and OH in the Northern Galactic Plane (ℓ=15–65°, $|b| < 1.25°$) with the Very Large Array, at 20–30″and ~ 1.5 km s^{-1} resolution (Beuther et al., 2016), with a recent extension

[1] All GASKAP-OH tests prior to this point were affected by critical technical issues. This includes a problem with ASKAP fringe rotation

[2] There are some remaining concerns with these data, specifically in the LSR correction and flux density calibration.

to $\ell = -5.75°$. THOR provides a preview of what we can expect to obtain (Rugel et al., 2018), but GASKAP-OH will be a major step up in all respects, covering in the Southern Galactic Plane a distinct and much larger region, with higher latitude coverage, better sensitivity, 15 times the velocity resolution (critical for masers), and twice the positional accuracy.

- **StarFISH** (PI S. Breen) is an ongoing ATCA Legacy survey of a host of spectral lines near 7mm spanning the range $\ell = 270°$ (through the GC) to $\ell = 5°$. StarFISH will provide complementary CS and SiO and methanol maser data for GASKAP-OH.
- **The MMB survey** provided a complete census of 6.7-GHz methanol and 6035-MHz excited-state OH masers in the Southern Galaxy (see e.g. Green et al., 2009). The excited-state OH masers provide complementary diagnostic information to the ground-state OH lines.
- **Goldman et al. (2017)** targeted evolved stars in the LMC with Parkes and the ATCA, more than doubling the number of known 1612 and 1665 MHz circumstellar OH masers. They confirmed expected flux densities and maser peak velocity separations in the metal-poor LMC.
- **BAaDE:** (PI L. Sjouwerman+) provides a valuable complementary SiO maser dataset for GASKAP-OH circumstellar masers, enhancing the science outcomes of the Bulge observations.

3 Full updated Project Science Case

The 18-cm transitions OH are an extremely versatile probe of a host of astrophysical phenomena, ranging from molecular cloud evolution and star formation, to late-stage stellar evolution and stellar feedback. The four lines (consisting of main lines at 1665.402 and 1667.359 MHz and satellite lines at 1612.231 and 1720.530 MHz) all exhibit maser emission whose diverse pumping mechanisms and physical requirements set strong constraints on the types of environments that can produce them.

Like the original GASKAP SSP, GASKAP-OH combines many surveys in one. These are distinct but complementary, and together form a coherent project that is greater than the sum of its parts. With OH absorption measurements (together with GASKAP-HI observations of the cold neutral medium), we will capture the coalescence of molecular clouds from the atomic ISM, and model the thermal and physical state of the transitioning gas. Star formation masers will provide a deep, unbiased census of active high-mass star formation sites in the Southern Milky Way, while circumstellar and supernova remnant masers pick up the story again as stars die, returning their enriched material to the ISM. Results from all of these tracers will be combined to provide new insight into the structure and evolution of our Milky Way Galaxy.

3.1 Molecular Cloud Evolution via OH Absorption

The formation of dense molecular clouds from the diffuse atomic ISM is at the heart of galaxy evolution. As the ISM cools and condenses, it undergoes several phase transitions, from warm to cool atomic gas, through to cold, dense and highly-structured molecular clouds. These phase transitions set fundamental boundaries on star formation rates, and go hand-in-hand with the formation of structure, including the ubiquitous self-gravitating filaments seen in all star forming regions (André et al., 2014; Ballesteros-Paredes et al., 2020).

Studies of the Milky Way are essential to determine the key physical processes driving molecular cloud formation and evolution. GASKAP-OH, in combination with GASKAP-HI, will provide something unique: a statistical census of the atomic and molecular gas along hundreds of sightlines throughout the Disk. The key is *matched pairs* of OH and HI absorption spectra, seen against (almost) identical resolved continuum sources. Together these will probe the cold ISM pre- and post-transition to the molecular phase, with the common background source and high resolution greatly reducing confusion, and allowing us to assess the degree of mixing of the two phases. We expect to detect OH absorption towards ~ 4 sources/deg^2 in the Plane (many with multiple components), and to produce *resolved maps* of OH optical depth towards the brightest continuum complexes, enabling us to track small-scale variations in gas properties at a resolution of $\sim 10''$ (~ 0.1 pc at 3kpc).

The four OH lines exhibit non-LTE OH excitation almost everywhere in the ISM (Dawson et al., 2014; Li et al., 2018), even in the quasi-thermal gas observed in absorption. The line ratios (particularly in the 1612 and 1720-MHz satellite lines) are sensitively dependent on temperature, density, radiation field and column density (e.g. Guibert et al., 1978). Combining HI temperature measurements from GASKAP-HI with non-LTE excitation models (Ebisawa et al., 2019; Petzler et al., 2020), and drawing on single-dish data from SPLASH (which constrains excitation temperatures; Dawson et al., 2014), we will constrain the temperature, density and mass of both the molecular and atomic gas, and statistically track how these vary with Galactic environment, building up a comprehensive database of physical properties against which evolutionary models (e.g. Goldsmith et al., 2007; Seifried et al., 2020) can be thoroughly tested. To-date, no study has had the large library of sensitive optical depth measurements needed for such systematic modelling of OH in the Milky Way.

Dark Molecular Gas: A major advantage of OH is that it can *trace molecular gas throughout its lifecycle*, from diffuse CO-dark H_2 ('dark molecular gas', DMG), through to dense star-forming clouds. DMG is a diffuse, low-extinction molecular phase that may account for as much as $\sim 50\%$ of the Milky Way's molecular gas (e.g. Grenier et al., 2005; Pineda et al., 2013; Busch et al., 2021), and is missed by traditional CO surveys. Regions dominated by DMG may mark the earliest stages of molecular cloud formation, but DMG also exists in the envelopes of CO-bright clouds (e.g. Remy et al., 2018), and may even be well-mixed with warm HI (Busch et al., 2021). While GASKAP-OH may only expects to detect completely CO-dark velocity components (typically $\tau \lesssim 0.05$) towards the brightest background sources (see Section 4), we expect to be able to recover the *dark gas fraction* even in CO-bright sightlines from differences in the total column of molecular material traced by CO, OH and HI. So far, the total mass and distribution of DMG in the Milky Way as a whole have only (to our knowledge) been addressed observationally by two studies: the *Herschel* GOT-C+ survey using the 158μm CII line (Langer et al., 2014; Pineda et al., 2013), and recently by Busch et al. (2021) with the GBT in very weak OH emission in the Outer Galaxy. GASKAP-OH may provide the best measurements to-date of our Galaxy's dark molecular gas.

GASKAP-OH will also observe the high-latitude local molecular cloud complex, Chameleon I, which has been well-studied in a multitude of wavelengths, and for which detailed dust- and γ-ray based DMG maps already exist (Planck Collaboration et al., 2015). Sensitive HI and OH absorption measurements of this cloud will provide a vital window into the physics of the ISM in an archetypal local star forming cloud. Critically, they will also allow us to benchmark our OH measurements against IR and γ-ray estimates of the total proton column density (impossible in the Disk, due to line-of-sight confusion), firmly grounding the interpretation of the full survey.

Magnetic fields in Molecular Clouds: GASKAP-OH will directly probe the magnetic fields in molecular clouds via Zeeman splitting measurements of the strongest absorption lines. Magnetic fields are critical in star formation, but quantifying their importance requires measurements of the field strength, field structure, and comparisons of the magnetic force with gravity and turbulence. The only way to directly measure magnetic field *strengths* in molecular clouds is via the Zeeman effect, to which only a few molecular transitions are sensitive; in non-masing lines the effect has only been detected in 18-cm OH and in CN at 113 GHz (Crutcher, 2012; Crutcher & Kemball, 2019).

The Zeeman effect has been previously detected in OH absorption associated with HII regions (e.g., Crutcher et al., 1999; Bourke et al., 2001; Sarma et al., 2013), as well as in emission from dark clouds forming low-mass stars (e.g., Crutcher et al., 1993; Troland & Crutcher, 2008), but these observations are few and have been laboriously obtained, due to the general weakness of quasi-thermal OH lines. GASKAP-OH will strongly detect OH in absorption from many more molecular clouds than has been possible to date, only hinted at in THOR, (a) enabling a significant increase in the number of field strength measurements (in cases where a clear Stokes V signal is obtained), and (b) providing new targets for more sensitive follow-up Zeeman observations with both ASKAP and MeerKAT.

3.2 Star Formation

GASKAP-OH will address one of the most fundamental questions of modern astrophysics: How do high-mass stars form? High-mass stars power the evolution of galaxies: Their enormous energy output, their role in triggering or halting the formation of the next generation of stars, and the heavy elements they supply – all these factors must be understood in detail if we are to build a real physical model of how galaxies are born and die over cosmic time. GASKAP-OH will probe elusive regions of

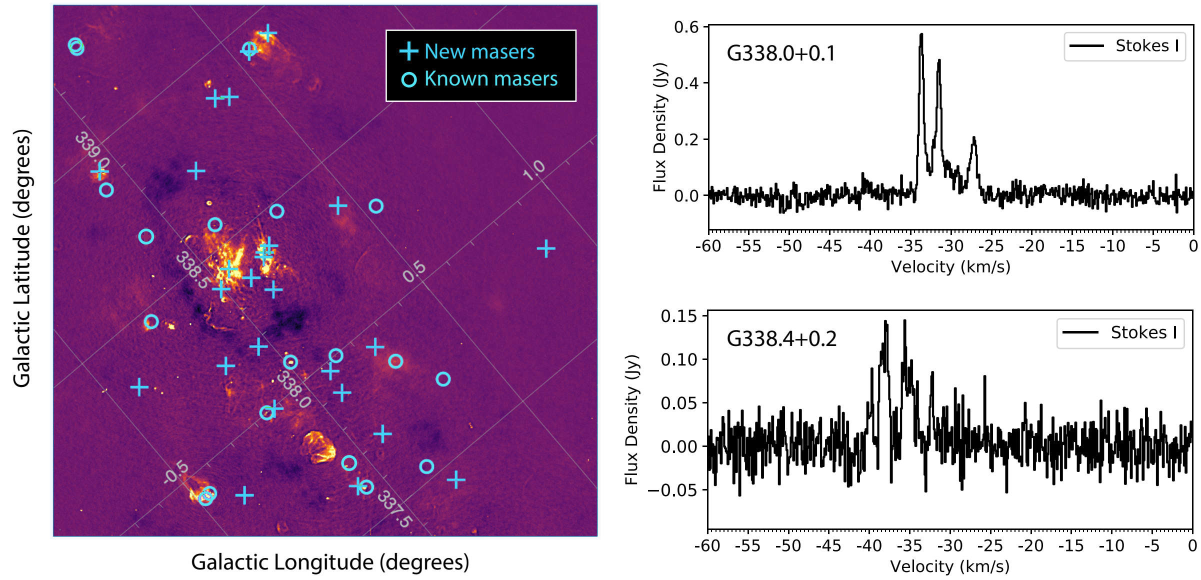

Figure 1: Newly-detected 1665 MHz masers in a portion of the G340 test field, overlaid on the 1665 MHz continuum image. Preliminary source-finding using SELAVY recovered all 19 previously published sources in this region and detecting 26 new ones, down to a detection limit of $\sim$ 100mJy.

high-mass star formation through the detection and analysis of OH maser emission. While a number of OH maser searches have been conducted in the Southern Hemisphere, they cover relatively small positions of the Plane, have inadequate sensitivities and/or cover only some of the 4 ground-state transitions (e.g. Caswell, 1998; Qiao et al., 2016; Ogbodo et al., 2020). The severe biasing of the known OH maser population is highlighted in Figure 1 – even in a small portion of the ASKAP footprint we have identified 19 previously published sources and 26 new discoveries. GASKAP-OH will be a definitive search, revealing the currently invisible population.

Masers are sensitive to the physical conditions in high-mass star formation regions; as the conditions change, so do the favoured maser transitions. In particular, main-line OH masers are widely regarded as a signature of the later stages of star formation (Forster & Caswell, 1989), and are the most commonly detected. However, all four ground-state OH maser transitions may be seen (see for example Qiao et al., 2018), with uncommon combinations indicating the presence of unusual physical conditions, either associated with a rare type of star formation region, or a short-lived evolutionary phase (e.g. 1667 MHz OH masers associated with a bipolor outflow Argon et al., 2003). Combined with maser pumping models, we may use the characteristics of the OH maser detections and their associated properties to significantly constrain the physical conditions in the star-forming gas.

Understanding how masers can be used to measure evolutionary changes in high-mass star formation regions (e.g. Breen et al., 2010), requires sensitive, high-spatial resolution complete surveys in a variety of maser transitions in order to minimise selection biases and overcome confusion in the crowded environment of high-mass star formation. We will capitalise on the wealth of Southern Hemisphere surveys (some of which are highlighted in Section 2) conducted in the past decade, each adding small details to the star formation puzzle, combined with GASKAP-OH data to piece together a cohesive picture. One of our key science investigations will be determining where OH masers fit in the maser evolutionary timeline, both in phase and duration. We will do this by combining our detected maser with surveys of other strong and common maser lines, (class II methanol, water, and OH from the StarFISH, MMB, HOPS and SPLASH; Green et al., 2009; Walsh et al., 2014; Dawson et al., 2014), together with a host of multiwavelength data, analysing the correlations and anti-correlations of both presence and absence and other key properties. This novel probe of the evolutionary stage of high-mass stars provides a crucial measure of age, critical to refining theoretical models of high-mass star formation and interpreting observations.

Masers also have the ability to reveal information about the in-situ magnetic fields (e.g. Green et al., 2014; Ogbodo et al., 2020). The Zeeman splitting effect (figure 5 of Green et al. 2014), particularly prominent in OH masers due to the large splitting factor, can reveal not only the strength of the field, but also the direction - at the very least the line-of-sight orientation.Understanding the role magnetic fields have in star formation is a key component in developing an understanding of the processes involved. Either through GASKAP itself, or targeted followup of GASKAP detections, and use of ancillary data such as the magnetic fields implied by the higher frequency excited-state OH transitions from the MMB survey (Avison et al., 2016), new insights will be garnered.

For star formation studies the coverage of the Galactic Plane is key – we know from previous surveys that the detectability of masers can be affected by the environment in which the star formation is occurring (e.g. Carina and the LMC; Contreras et al., 2019; Green et al., 2008). The GASKAP-OH survey strategy has been carefully constructed to incorporate a large number of different environments (Galactic Centre, molecular clouds) to constrain the conditions in which OH masers occur (and hence how the star formation is differing).

3.3 Evolved Stars

Evolved stars, especially in the AGB and post-AGB phase, play a major role in returning metal-rich stellar mass to the ISM, but the total rate of mass return is poorly constrained. An accurate assessment of this rate requires knowledge of the luminosity function of stars exhibiting present-day mass loss, as well as the mass loss rates of the individual classes of stellar luminosities. Another outstanding question is the precise relationship between the mass-loss rate and luminosity: the underlying driving mechanism is poorly understood, and depends sensitively on the dust fraction in the outflow. OH masers (primarily at 1612 MHz) associated with circumstellar envelopes (CSEs) provide an excellent tool for addressing these questions, allowing us to derive the luminosity function of CSE OH maser sources, and directly measure the CSE wind speed – the key to understanding wind driving, to determining the dust-to-gas ratio (Marshall et al., 2004; Goldman et al., 2017), and to determining the mass-loss rates of individual stars. This analysis is especially powerful in the LMC, where the luminosities (distances) can be determined accurately and thus the dust fraction can be derived, telling us how the dust condensation efficiency changes as the star evolves.

Evolved Stars in the Milky Way: Previous surveys have investigated the luminosity function and wind speeds of circumstellar OH masers in individual sub-regions of the Milky Way, including the Galactic Centre (GC), ($<18'$ from Sgr A*, Sjouwerman et al. 1998), Galactic Bulge ($|b| < 3°$, $|l| < 10°$, Sevenster et al. 1997a), and the Disk ($|b| < 3°$, $315° < \ell < 350°$, Sevenster et al. 1997b). Together these have revealed statistical properties of ~650 OH masers. However, surveys of circumstellar SiO masers (around half of which should also host OH masers; Imai et al., 2002), have yielded thousands of SiO masers over very similar regions, suggesting a missing population of OH sources. Since (while several species produce CSE masers) only OH masers can provide reliable physical measurements of the luminosity and wind speed, detecting these is critically important. GASKAP-OH will address this by providing the deepest ever unbiased sky survey of CSE OH masers, crucial to understanding the statistical properties of the whole population of OH masers and the final stages of stellar evolution.

GASKAP-OH will observe the Galactic Plane, the Galactic Centre and the Galactic Bulge for CSE OH masers, allowing us to probe their properties in very different environments. The cluster of CSE OH masers in the GC (Sjouwerman et al., 1998) is particularly interesting; their mean expansion velocity is higher than in the rest of the Milky Way, indicating a high-mass population and recent starburst activity (Sjouwerman et al., 2000), and their distance is very well determined (~8 kpc). GASKAP-OH will also observe an off-Plane, Galactic Halo field that includes globular cluster NGC 6171. This will allow us to probe the history of stellar stream and cluster formation via the age estimates of the OH maser sources. Halo field observations also enable us to better understand the differences in OH maser properties in the Milky Way and the Magellanic System.

CSE OH maser sources probe the spatio-kinematics of stellar mass loss, signposting the transition from the AGB to post-AGB phase. Because of the short period of this transition (10^2–10^5 yr), large surveys are needed to turn up sub-stages within it. Via multi-epoch observations of the same fields, GASKAP-OH will provide time-domain data on CSE maser emission, at a cadence of (a) months (over the course of the survey) and (b) decades (via re-observations of previously surveyed fields). This provides an unparalleled opportunity to estimate the true duration of OH maser excitation in individual stars. GASKAP-OH also has great potential to increase the population of sources in very short-lived sub-phases. Chief among these is planetary nebulae (PNe) harbouring OH masers, which seem to be among the youngest objects in this evolutionary phase. Identifying and characterizing new members (only 6 OH-emitting PNe have been confirmed so far) is crucial to understanding the final stages of stellar evolution.

Evolved Stars in the LMC: Much of what we know about mass loss from cool evolved stars has been derived from OH maser surveys in the LMC (Wood et al., 1992; Marshall et al., 2004; Goldman et al., 2017), because the distance is well known and thus accurate luminosities can be determined to which to compare the wind speed measured from the OH maser emission profile. The proposed LMC deep field will take another leap towards reliable wind speed measurements for an enlarged sample of evolved stars better covering the luminosity and mass-loss rate (dust fraction) range as it surveys a large area in an unbiased way rather than targeting candidate sources.

Circumstellar OH masers have been previously detected in the LMC, enabling reasonably accurate predictions for what to expect with deeper ASKAP observations. (The tally in the SMC stands at zero Goldman et al. 2017 despite equally deep ATCA observations.) Better knowledge of the maser behaviour in the LMC (e.g., OH/IR luminosity ratio, OH emission profile asymmetry as function of luminosity and mass-loss rate) will help us understand this conundrum – and wind driving at low metallicity (1/5 solar). The proposed LMC field centres on the star forming regions, maximising coverage of the high-mass red supergiant and intermediate-mass AGB populations – indeed, it includes all known OH masers (improving their measurements too).

3.4 Supernova Remnants

SNe explosions mark the death of stars and produce massive energy output and chemical enrichment to the ISM. Over time this becomes a supernova remnant (SNR) typically interacting with the molecular cloud of its massive star progenitor. Studies of SNRs and their contribution to Galaxy kinematics, chemical evolution of the ISM and their role in future star formation all depend on knowing where the SNRs are located and their evolutionary stage. This is a challenge since the vast majority of SNRs are identified from radio continuum surveys of their synchrotron emission which provides no distance information.

A powerful tool for directly measuring the distance and physical parameters of SNRs comes when we search for the 1720 MHz OH satellite transition, typically detected without the other 18cm lines. This transition is collisionally excited under specific physical conditions – cool temperatures (25–150 K), dense gas (about 10^5 cm^{-3}) and following a non-dissociative C-shock. Furthermore, the maser lines are produced tangentially to the expanding shock wave so they are a direct measure of the systemic velocity of the SNR, and can be used to estimate the location using Galactic rotation models (Elitzur, 1992; Lockett et al., 1999). These masers are well correlated with Gamma-ray detections from SNR – molecular cloud interactions, indicating sites of possible CR acceleration (Hewitt et al., 2009). If the Stokes V-profile from Zeeman splitting of the OH line is obtained, a direct measure of the magnetic field strength is possible. (Crutcher, 2012).

To date only about 10% of SNRs have had 1720 MHz maser detections, largely because surveys have been limited and time-consuming. The GASKAP-OH survey of the richest quadrant of the Galactic Plane (Q4) covers several spiral arm tangent directions and many new detections are expected. Current SNR numbers (Green, 2019) are still curiously smaller than numbers predicted from observations of SNe in external spiral galaxies. This survey could help resolve this anomaly.

3.5 Galactic Structure

What does the Milky Way look like? This question remains a long-standing problem in astronomy. GASKAP-OH will help to address this by providing the first complete census of OH maser targets for VLBI astrometry in the Southern sky. Trigonometric parallax is the 'gold standard' for distance measurement in astronomy, and parallax measurements of star-formation masers are *the only* way to obtain distances to distant spiral arms (where optical tracers are extincted). But while maser parallax (of 6.7 GHz methanol and 22 GHz water masers) has now produced unprecedented models

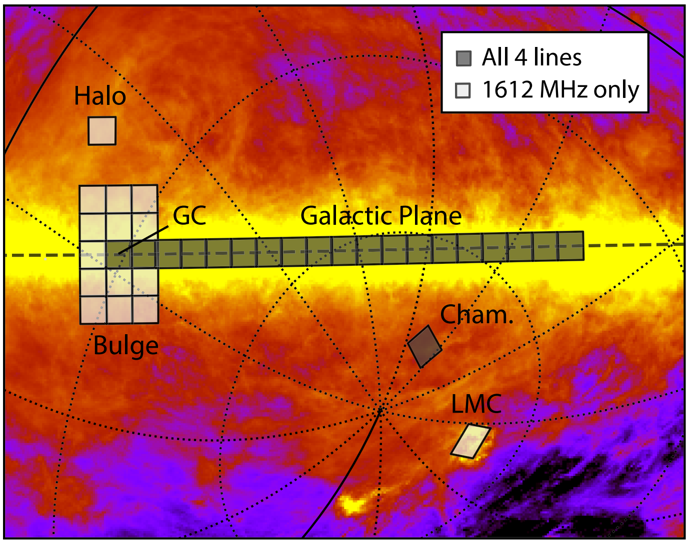

Figure 2: GASKAP-OH survey fields shown in equatorial coordinates overlaid on an integrated column density map of the HI emission from the HI4PI survey. See table 1 for integration times. Note that observing all four lines requires that a field be observed only three times, since the 1665 and 1667 lines can be observed simultaneously.

of spiral structure in the Northern sky (Reid & Honma, 2014), no such map exists for the South.

OH masers may provide the best means of mapping the Southern spiral arms, particularly in the Outer Galaxy, where few methanol masers exist (likely due to metalicity effects, Green et al., 2017). Until recently accurate astrometry at 1.6 GHz had not proved feasible with the heterogeneous VLBI arrays of the Southern hemisphere, but members of the GASKAP-OH team have recently developed a new astrometric technique which has achieved astrometric accuracy of 10 μas at 6.7 GHz with an array of four Australia/New Zealand antennas (Hyland, 2021). This is a critical advance that will allow us to obtain accurate trigonometric parallax measurements to 1.6 GHz OH masers for the first time. These maser-based Galactic structure investigations complement the astrometry being undertaken with Gaia, as the spiral arms are by definition regions of high optical obscuration.

4 Observational strategy and updated time request

4.1 Coverage and Integration Time Request

To accomplish our science goals GASKAP-OH must observe several different areas with different integration times, some in all four OH lines, and some in the 1612-MHz line only. The six sub-surveys are summarised in the table below, and shown in Figure 2. We have listed these sub-surveys in order of priority, based on the projected science return and legacy value of the datasets.

1. **The Galactic Plane**: This sub-survey provides the foundation for GASKAP-OH, touching on all science goals to varying degrees. The area $270° < \ell < 2.5°$, $2.5° < b < 2.5°$ will be observed in all four OH lines, at 12 hours per transition per field. Science goals: Star formation, evolved stars, molecular cloud evolution, SNRs, Galactic structure.
2. **The Galactic Centre:** The area $|b| < 2.5°$, $|\ell| < 2.5°$ will be observed in all four OH lines, for an additional 36 hours per transition on top of the Galactic Plane observations. The GC is a special environment and a deep integration of this field will complement our other sub-surveys, increasing the return of all. In order to return the greatest benefit to the maser observations, especially associated with evolved stars, the additional integration time should be observed in a series of nine 4-hour epochs separated by a couple of months. This will allow us to both detect variable sources leading to a more complete population but also possibly identify periodic variations. Science goals: star formation, evolved stars (including diagnostics of starburst activity), molecular cloud evolution, SNRs.
3. **Large Magellanic Cloud:** A single footprint centred on the star formation, high-mass red supergiant and intermediate-mass AGB populations in the LMC in the 1612 MHz transition of OH. This field contains all currently known OH masers within the LMC and gives us the best possible chance of further OH detections. The target sensitivity equals the very deepest existing observation but crucially achieves this uniformly across much of the relevant part of the LMC. Science goals: Evolved stars at low metallicity.

Sub-survey	Number of Fields	Time per Field (h)	No. of OH lines	Total Time (h)	Cumulative Time (h)	Target rms (mJy/beam)	Vel chan (km s^{-1})
1. Galactic Plane	19	12	4	684	684	26, 10	0.1, 0.7
2. Galactic Centre	1[a]	36	4	108	792	13, 5	0.1, 0.7
3. LMC	1	200	1	200	992	4	0.2
4. Galactic Bulge	13	12	1	156	1148	26, 10	0.1, 0.7
5. Chameleon MC	1	24	4	72	1220	18	0.1
6. Galactic Halo	1	12	1	12	1232	26, 10	0.1, 0.7

Table 1: Summary of sub-surveys and their observational parameters. The Target rms is quoted for the velocity channel width listed in the final column. Note the 1665 and 1667 MHz lines can be covered in a single 9 MHz band.

[a]This tile is duplicated in the Galactic Plane region, but observed for additional time here. Noise is combined time.

4. **Galactic Bulge:** The area $|b| < 12.5°$, $|\ell| < 7.5°$ (excluding the two footprints already included in the Galactic Plane observations) will be observed in 1612 MHz line, at 12 hours per field. For the greatest science impact, the integration time should be split into three 4-hour epochs, each epoch separated by around 6 months, per field to quantify maser variability (sometimes periodic) and derive a more complete population of sources. Science goals: Evolved stars.
5. **Chameleon I Molecular Cloud:** A single footprint observed in all four lines at 24 hours per transition per field. The longer integration time is needed to reach our target optical depth sensitivities in this off-Plane field (where we cannot rely on HII regions for bright continuum background emission). Science goals: molecular cloud evolution.
6. **Galactic Halo field:** A single field in the Halo including the globular cluster NGC 6171 (in which SiO masers were detected by Matsunaga et al., 2005), will be observed in the 1612 MHz line for 12 hours. Similarly to the Galactic Bulge, the integration time should be split into three 4-hour epochs, separated by around 6 months. Science goals: evolved stars.

4.2 Data Requirements

Spectral Resolution: High spectral resolution is critical to GASKAP-OH. The individual emission components of star-formation masers are as narrow as 0.2 km s^{-1}, and the ability to identify Zeeman splitting hinges critically on how well we can resolve this velocity structure. Similarly, OH absorption may include very narrow components ($<$ 0.3 km s^{-1}, Thompson et al. 2019), and a failure to resolve these would compromise optical depth measurements of the absorbing gas. GASKAP-OH will therefore use the $\times$32 zoom correlator mode which gives 15,552 fine spectral channels of width $\Delta\nu \approx 0.579$ kHz or $\Delta v \approx 0.1$ km s^{-1} over a total bandwidth of 9 MHz. At its widest, the OH signal will be present over $\sim$ 600 km s^{-1} (in and around the GC), and in most fields will be contained within a significantly narrower velocity range ($\sim$ 200 km s^{-1} is typical over much of the Fourth Quadrant), meaning that the full 15,552 channels will generally not be needed.

Sensitivity: Recent complete OH maser surveys have searched smaller sections of the Galactic plane and reached sensitivities of 10 mJy/beam in $\sim$1.5 km s^{-1} (THOR; Beuther et al., 2016) and 65 mJy/beam in a 0.2 km s^{-1} (SPLASH; Dawson et al., 2014). In the GC, small-area observations have reached 7 mJy/beam in $\sim$1.1 km s^{-1} channels in the 1612 MHz line only (Sjouwerman et al., 1998). In GASKAP-OH, with our much broader Galactic Longitude and Latitude coverage, we aim to do significantly better, allowing us to conduct the definitive study of star formation, evolved star and SNR OH masers, surpassing all previous works. To achieve this we propose to reach a sensitivity of at least 26 mJy in a 0.1 km s^{-1} channel (see Table 1 for details of individual regions). Note that this is superior to (THOR; Beuther et al., 2016), whose ability to detect maser emission is compromised due to coarse velocity resolution.

High-mass star formation masers span a very wide range of intensities (e.g. Caswell & Haynes, 1987; Qiao et al., 2016), and the best available determination of the luminosity function suggests it is still increasing at 100 Jy kpc^2 (Caswell & Haynes, 1987), supported by the huge numbers of masers we have discovered in the G340 test field (see Fig. 1). In particular, the low-luminosity population of star forming OH masers is poorly understood. With an RMS of 26 mJy at 0.1 km s^{-1} resolution we will detect all OH masers in the Milky Way with a luminosity of 50 Jy kpc^2 or greater, and probe even lower luminosity sources in the deeper integration fields, especially towards the GC.

Velocity resolution is less critical in CSE masers, and moderate velocity binning yields a rms of $\sim$10 mJy (for $\Delta v \sim 0.7$ km s^{-1}), leading to an unbiased census of CSE masers stars down to 3×10^{14} watt Hz^{-1} in the Galactic Plane. This includes in particular the 'low luminosity sub-group', which probes the early and late OH emissivity-stages, including eruptive events to a distance of $\sim$2 kpc, at a 5-σ level (see Etoka et al. 2015). In the Galactic Centre, the OH luminosity function is predicted to peak at Log($L_{\rm OH}$[photon/s])$\sim$43.3 (Sjouwerman et al., 1998), corresponding to a flux density of $\sim$20 mJy (at $\sim$8 kpc). Our longer integration time on the GC field (48 hours) yields a sensitivity of $\sim$ 5 mJy/beam (for $\Delta v \sim 0.7$ km s^{-1}), sufficient to constrain this peak. Our deepest field, the LMC, reaches a sensitivity of $\sim$ 4 mJy/beam at $\Delta v \sim 0.2$ km s^{-1} in 200 hr total integration, optimising peak detection at the same level of the deepest Parkes+ATCA targeted observations of the LMC.

The sensitivity of OH absorption measurements is driven by the flux density distribution of the continuum source population, which for resolved Galactic Plane sources is strongly affected by *uv* coverage and imaging parameters. The expected optical depth distribution of OH in the Galactic Plane is not well constrained, but likely ranges from $\sim$ 0.01–0.05 (as seen in very diffuse, off-Plane sightlines; Li et al., 2018) to $\tau \sim 0.5$ (as seen in the Galactic Plane in THOR; Rugel et al., 2018). Figure 3 shows preliminary detection statistics for the G340 test field, demonstrating that we can probe the full range of expected optical depths. (Note that we have smoothed to $\sim$1km s^{-1} in this example, which is sufficient to fully sample the absorption along many sightlines, but will retain full velocity resolution data for very narrow lines.) Extrapolating these detection statistics to a 12h integration increases the number of detections by a factor of $\sim$ 1.3, and (crucially) enhances our ability to probe the low-optical depth end of the distribution. The expected detection rate is $\sim$ 4 sources/deg^2 within $|b| < 2°$, a four-fold improvement over the only other comparable survey, THOR.

Spatial resolution, weighting & baseline distribution: The surface brightness of quasi-thermal OH in emission is exceptionally low. Even the brightest lines are typically no more than a few 100 mK, and may be an order of magnitude fainter in the CO-dark regime (Allen et al., 2015; Busch et al., 2021). Even at the best surface brightness sensitivities achievable by ASKAP, we do not expect to detect significant extended OH in emission (GASKAP-HI achieves an rms of $\sim$1K with a $\sim$30$''$ beam, longer integration times, and significant spectral smoothing). Our ability to detect OH comes primarily from absorption against bright continuum sources, which in the Plane are complex and highly structured. The ideal array configuration (and weighting scheme) balances the recovery of continuum flux, while resolving the brightest knots of structure against which absorption can most

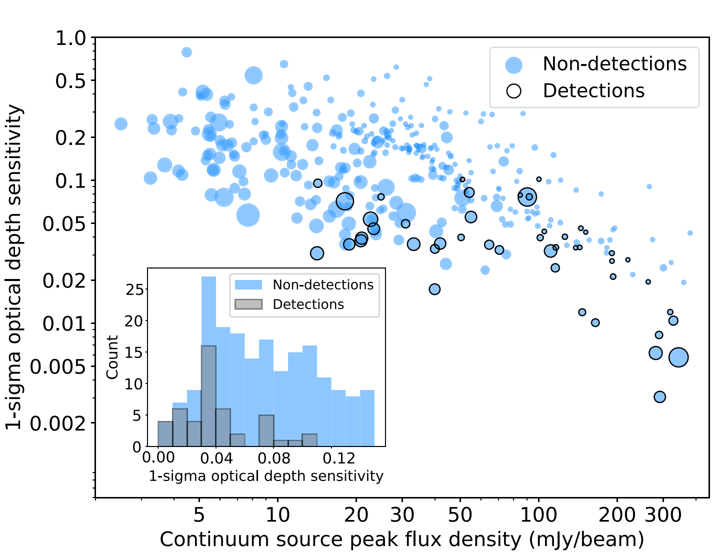

Figure 3: OH absorption detection statistics for the G340 test field (8h integration, smoothed here to $\Delta v \sim 1$km s^{-1}). The scatter plot shows the 1σ optical depth sensitivity as a function of continuum source peak brightness for SELAVY source "islands" output as part of the standard ASKAPSOFT processing workflow. The symbol size is proportional to the island major axis. The inset panel shows optical depth sensitivity histograms for detected and non-detected continuum sightlines. 70 distinct velocity components are detected towards 47 continuum islands.

readily be detected. Masers (as point sources) do not strongly drive the image weighting requirements for GASKAP-OH, but do benefit somewhat from the highest available spatial resolution to minimise uncertainties in the derived positions.

These requirements mean that both short and long baselines are essential. Good coverage across the full baseline range, and imaging with a robust weighting of 0.5, have produced adequate images for the G340 test field, with a synthesised beam size of $\sim 7''$ and good sensitivity to both masers and absorption. The positions of the known OH masers in the field agree with previously derived values to within ∼0.5 arcsec (which is comparable to the limitation of the ATCA), demonstrating that we can achieve the positional accuracy required for comparisons of maser populations with multiwavelegth data. While the data in-hand is promising, we note that we have not yet been able to fully explore the optimum parameters for OH imaging.

Calibration: Given the complex structure of the Galactic Plane, we have found (based on the G340 test data) that excluding the short baselines provides the best self calibration solutions. For bandpass calibration, we have found the currently-implemented GASKAP-OH workflow to be adequate. These data use a single BP calibration observation of PKS B1934-638 for an 8 hour observation, but we note that longer observations may need multiple BP scans.

Continuum Subtraction: Both continuum-subtracted and non-continuum subtracted cubes are required for GASKAP-OH. Continuum subtraction is required for maser cubes, since maser source finding cannot effectively proceed with continuum present. While continuum subtraction in the Galacic plane was initially challenging, we have worked collaboratively with ASKAP staff to overcome this, ensuring that the continuum data used by ASKAPsoft "CleanModel" includes all baselines (not just the ones used for selfcal) which are needed to effectively remove the extended continuum emission present in the Galactic Plane. For OH absorption cubes it is essential that no continuum subtraction is performed, to allow reliable calibration of optical depth spectra.

Polarisation Products: Fully exploiting the scientific potential of our observations requires both Stokes I and Stokes V. Detailed holography is needed for accurate off-axis calibration of the Stokes V data which is needed for Zeeman splitting measurements. An example on-axis source is shown in Figure 4. ASKAP Operations are in the initial stages of interpolating the on-axis leakage correction table below the 1MHz beamforming frequency for spectral line use, but the preliminary spectrum indicates no issues with this process.

Observing strategy in the absence of split-bands: In the Galactic Plane, Galactic Centre and Chameleon MC we require all four ground-state OH lines to be observed in a series of three observations. Given the expected variability of maser sources, each transition should be observed on consecutive days if ASKAP Operations allow.

4.3 Processing, Storage & Resource Requirements:

We wish to implement maser source-finding within the ASKAPsoft pipeline, and are currently engaged in tests with ASKAP staff to determine the optimum strategy for acheiving this. The provisional workflow used on the G340 test field uses the native Selavy source finder to extract the continuum sources needed for our OH absorption pipeline. Spectral line source finding on our $\sim$ 4TB data cubes is more challenging, and must make full use of Selavy's ability to intelligently divide processing tasks amongst different nodes. Incorporating source finding into the workflow would allow Stokes V cubelets to be generated only at the location of the detected masers rather than requiring a full field cube. It is not yet clear which option will minimise the processing burden, but we will work with ASKAP staff determine the most efficient process.

4.4 Commensal Observing

GASKAP-HI: If split-band mode is implemented, a return to commensal observing with GASKAP-HI is strongly preferred. The coverage of the HI and OH surveys are compatible (GASKAP-HI covers the entire GASKAP-OH survey field and more), and the boost in coverage and integration time would enhance our outcomes across the full suite of science goals. GASKAP-OH will already be the best survey of its kind; with commensality it will truly be a step-change.

Specifically, under the assumption that all four OH lines could be observed simultaneously with HI: Our sensitivity in the Galactic Plane would double, pushing the point-source sensitivity down to $\sim$13 mJy (in a 0.1 km s^{-1} channel), enhancing our ability to probe the poorly-characterised low-luminosity end of the maser distribution, and approximately doubling the number of OH absorption detections (based on an extrapolation of the G340 test field detection statistics). Observing all four maser transitions simultaneously is also advantageous, since it removes any impact of short-term variability. In a commensal survey following the HI observing plan, our coverage would expand to encompass large swaths of the Galactic Halo, intermediate latitude fields, and the entire Magellanic System – the LMC, SMC, the Bridge and the Leading Arm. Expanding our coverage of OH absorption to off-Plane fields would allow us to characterise star formation and molecular gas physics at the Disk-Halo interface, greatly enhance our ability to probe the low metallicity environment of the Halo, and also open up the tantalising possibility of the first circumstellar maser detection in the SMC.

VAST: We will work cooperatively with VAST to ensure that the data taken for GASKAP-OH is exploited fully. We note that our multi-epoch observations are an advantage for VAST.

5 Detailed requirements

Quality of Observations: It is crucial that our data has full and consistent coverage of the target OH transitions. This means that data with spectral 'drop-outs' that fall within $\pm$400 km s^{-1} from the central Galactic rotational velocity will require reobservation. Drop-outs beyond this range are tolerable but clearly not preferred. Likewise, observations with bad or missing beams should be reobserved as this would critically impact the uniformity of our coverage.

A further consideration for data rejection is the number of antennas. Flagged or missing antennas not only reduces our sensitivity (and therefore the consistency and potential legacy value of the dataset), but can directly impact the survey science goals. In order to both localise the detected maser emission and detect extended diffuse structure, we require the majority of the core and extended baselines to be available. We currently anticipate, based on the more extensive GASKAP-HI pilot data, in conjunction with the small amount of GASKAP-OH data, that 32 antennas are required including 5 of the 6 inner and 7 of the outer 10 antennas in order to meet our science requirements.

Spectral processing: The velocity coverage provided by a 9 MHz band is beyond that required for our science goals (see Section 4.2). We will specify that expected line-free channels for each field in advance; on average we will need to retain around $\sim$5000 channels for each line.

Beam arrangement and pitch: Our G340 test field was taken in closepack-36 with three interleaves, and a pitch angle of 0.9. In an attempt to reduce the processing load on the observatory, we requested additional test data in the square 6$\times$6 beam configuration with two interleaves. Acknowledging that this arrangement would result in a variable rms (or a sensitivity ripple as it is presented in the ASKAP observation guide) across the footprint, we were willing to make reasonable concessions in order to fit within the resource capacity available. A partial cube (6 beams in a 2$\times$3 configuration) was delivered to the team late October 2021. Unfortunately, we have identified clear issues with those data, including calibration differences whose stability across the larger field (and between beams) cannot be fully assessed with the subcube alone. We therefore cannot confidently determine at this stage whether the square 6$\times$6 arrangement will be adequate for our science and so have not deviated from our initial plan to use closepack-36 at this time.

6 Organisation and management structure

Membership: Although GASKAP-OH is new as a standalone survey, we are already supported by more than 30 active members[3]. from 9 different countries: Australia, the UK, the US, Canada,

[3] A full list of GASKAP-OH members can be found at https://gaskap.anu.edu.au/

France, Spain, Germany, the Netherlands, China, Japan, and Mexico. The team includes many members of the original GASKAP SSP, as well as several new additions, either through their own interest or recruited specifically to cover known science gaps or provide expert technical knowledge. Combined, these members have the skills and expertise to achieve the full range of science goals.

While we have been attracting a number of early career researchers (including science team leads H. Denes and S. Goldman), we have been reluctant to offer student projects while the delivery of science-quality data has been unpredictable. As Phase II pilot observations begin, we anticipate that membership will broaden to include a higher number of more junior astronomers. We also plan to mentor more junior members into the survey team lead positions as the survey progresses. GASKAP-OH will remain a friendly, collaborative and diversity-conscious survey team, open to new membership and ideas throughout its lifetime.

Management: The survey PIs, S. Breen & J. Dawson, broadly represent the maser and non-maser portions of GASKAP-OH, but work closely in managing all aspects of the survey, supported by Project Scientist C. Tremblay. Data validation has been managed by C. Tremblay and S. Breen, but we note that these positions have evolved slightly to include J. Dawson as a PI, and that these are the three GASKAP-OH team members that are the points of contact for ASKAP Operations. Other members of the team, such as M. Voronkov and C. Phillips (both CSIRO staff with active involvement in ASKAP) will provide expert technical support to the PIs and Project Scientist as required.

GASKAP-OH and GASKAP-HI have a long-standing combined Steering Committee that oversees the strategic, membership and policy aspects of the surveys, and a Management Committee to oversee their day to day running. The former is populated by the respective PIs and a number of the leads of the various original Expressions of Interest, while the latter comprises the five PIs and the GASKAP-OH Project Scientist. GASKAP-OH has broad science goals and a large team. Each science area therefore has its own working group, with leaders appointed to manage the overall activities: <u>star formation:</u> S. Breen, J. Green; <u>molecular cloud evolution:</u> H. Denes, J. Dawson; <u>evolved stars (Milky Way):</u> H. Imai, S. Etoka; <u>evolved stars (LMC):</u> S. Goldman, J. van Loon; <u>SNRs</u>: A. Green, D. Leahy; <u>galactic structure:</u> S. Ellingsen.

Funding and Resources: The international distribution of GASKAP-OH members places us in a strong position to access a myriad of funding and resource opportunities. The recent delivery of the first GASKAP-OH data greatly enhances our ability to leverage these resources, and to recruit university-supported PhD students into the team. Current funding sources (both secured and pending) include CSIRO Research Plus postdoctoral funding (planned, J. Green & J. Dawson), Australian Research Council Discovery Project (ARC DP) with a focus on OH absorption (pending, J. Dawson, M. Wardle), ARC DP with a focus on data visualisation, source finding, and astrochemistry with SKA Pathfinders (pending, M. Cunningham, C. Tremblay), collaboration and data processing support from the Amanogawa Galaxy Astronomy Research Center at Kagoshima University (secured, H. Imai), several funding allocations from Spanish agencies that can be accessed for hiring on GASKAP-related science (secured, J. Gomez).

Much like the plan for the SRC Network, GASKAP-OH has a distributed Network of computing resources, which, combined, will serve the needs of the survey – primarily visualisation and post-processing of ASKAPsoft data products. This currently includes high- and mid-performance computing resources at the SKAO, Macquarie University AAO-Data Central, the prototype SRC in Granada (Spain), and additional resources allocated through competitive time allocation at Pawsey for ASKAP spectral line processing. This model has the advantage that the compute is co-located with the researchers, meaning that the support is also much more readily accessible.

7 Plan for Creating and Distributing High-Value Data Products

GASKAP-OH will distribute a suite of high-value data products. As we are still working with the ASKAP Operations team to determine the exact line between 'standard' and 'advanced' data products, we present the full suite of outputs below. All products will be uploaded to CASDA, supplemented by publications where appropriate.

- Stokes I cubes: Provided by ASKAP Operations. Large-area datacubes from which users can extract cubelets or spectra, guided by our extensive catalogues. Postage stamp images are an unnecessary archiving load since CASDA is capable of creating cutouts.
- Stokes V cubes/cubelets: Expected to be provided by ASKAP Operations, either as full maps or postage stamps of detected sources. (This decision will be based on relative resource requirements.)
- Maser source catalogues: based on initial source finding run as part of the ASKAP Operations workflow using SELAVY, supplemented with auxiliary searches with varying parameters (to ensure no sources are missed). Catalogues will include Zeeman pairs, details of associated exciting sources expansion velocities, and associations with other maser species.
- Stokes I, RHCP and LHCP spectra (images and plain text) of all of detected maser sources.
- OH absorption spectra (images and plain text) together with metadata needed to interpret them.
- Catalogues of OH absorption derived properties, including optical depth spectral fit components.
- Full-field continuum images at each line frequency, needed to guide absorption analysis.
- Peak, maximum and minimum moment maps for a convenient 'quick look' guide of the full dataset.
- RMS maps to provide a realistic view of the data quality and source detectability.
- For fields observed on multiple epochs, all mentioned products will be provided for both the total integration and each epoch individually. This will allow the assessment of source variability.

8 Long Term Benefits

Legacy value: GASKAP-OH will provide legacy data products that will continue to be cutting edge well into the SKA era. The recently released US-decadal plan for astronomy 'Pathways to Discovery in Astronomy and Astrophysics for the 2020s' defines three priority areas, including *Unveiling the Drivers of Galaxy Growth*, which identifies the need to understand the lifecycle of interstellar gas on all scales. GASKAP-OH addresses exactly this, via tracking the transition of the ISM from diffuse molecular gas through to active star formation, at a sensitivity and resolution that can only be achieved in our Milky Way, It will thus play a major role in providing the astrophysical template needed to interpret future surveys of external galaxies with next generation globe-spanning telescopes such as the SKA. The SKA (with its many competing priorities) is unlikely to complete a similar wide-coverage OH survey in the immediate term, meaning that GASKAP-OH will remain the best interferometric OH survey available for many years to come.

Building science and techniques for the SKA: GASKAP-OH science goals either directly address or overlap with multiple topics identified in the 2015 'Advancing Astrophysics with the Square Kilometre Array' science planning, including Galactic and extragalactic OH maser science (Etoka et al., 2015), VLBI astrometry (Green et al., 2015) and Zeeman Splitting (Robishaw et al., 2015), and in the SKA1 high frequency science case (van Loon, 2020). While SKA key science projects are yet to be fully defined, GASKAP-OH will continue to interface with the science planning process through the established SKA Science Working Groups (particularly the 'Our Galaxy' and 'Extragalactic Spectral Line' Working Groups), in which we have active representation.

The expectation is that the SKA will eventually carry out deep 18-cm surveys, detecting as many as 20,000 OH masers from both stellar and interstellar sources (Etoka et al., 2015). GASKAP-OH will be a pathfinder in both the technical and scientific sense, by providing better constraints on the luminosity function of Galactic OH masers, and via the development and testing of sourcing-finding routines for huge cubes containing a high density of narrow-line, compact sources. It will also vastly increase the density of OH absorption detections both within and outside the Plane, against complex Galactic Plane continuum sources, providing a technical test case and blueprint that may inform the imaging parameters and sensitivies of future SKA surveys.

Given the close connection between many members of the GASKAP-OH survey team and a number of the proto-SRC facilities, and in particular the distribution of the PIs between the UK and Australia, GASKAP-OH will provide a powerful test case for the AusSRC and the broader SRC Network, particularly in connecting the Australian, Spanish and UK SRC facilities. This has already been recognised by AusSRC, putting us in a strong position to secure necessary resources in the 2022 call.

Synergies with other surveys: As a survey of the Milky Way and LMC, GASKAP-OH naturally has syngergies with a host of multi-wavelength surveys, the combination of which will bring long-term benefits to the astronomical community. The following are a few representative examples:

- **Local Volume Mapper:** The SDSS-V LVM will collect IFU spectra from HII regions over the entirety of GASKAP-OH's Galactic Plane coverage, at comparable spatial resolution. Combining LVM optical spectroscopy of local (low-extinction) HII regions with GASKAP-OH diagnostics of both the active star formation and molecular gas physics, will connect molecular and ionised gas properties, metallicity, star formation activity and its associated patterns of maser excitation.
- **StarFISH:** StarFISH provides information on dense molecular gas (as traced by CS), and low- and high-velocity interstellar shocks (class I methanol and SiO masers, commonly in star-formation and evolved stellar sources, respectively). These data will enhance the full suite of GASKAP-OH science goals.
- **Gaia:** The upcoming Data Release 3 (DR3) will precisely map the stellar and dust components of the Galactic disk out to 5 to 7 kpc from the Sun, providing 3D loci of the spiral arms. GASKAP-OH will provide the velocities of molecular gas and star-formation tracers needed to anchor these 3D maps to the Galactic velocity field, as well as identifying targets for VLBI astrometry, to allow accurate arm models to be extended deep into the extincted Disk where Gaia cannot probe.
- **BAaDE:** The definitive survey for SiO circumstellar masers in the Bulge, BAaDE will complete observations 6000 IR-selected red giant targets. Comparing common and distinct detections of SiO and OH masers will be invaluable in deriving detailed (circum)stellar physical parameters, and probing the structure, dynamics and evolution of the Bulge and Milky Way Galaxy.

9 Plans for STEM Promotion

Many GASKAP-OH members are skilled science communicators, and the team maintains an environment where Early Career Researchers and students are encouraged to develop their public engagement skills. We have written articles for the UK Magazine *All about Space*, *The Conversation* (including *Curious Kids*), collaborated on articles in Australian Journal *Cosmic Magazine*, and written for the online forum *SpaceAustralia*, reaching millions of people. Through the Australian *STEM Professionals in Schools* program, work experience programmes, and the Women in Technology WA "Techtrails" events, we have used pre-science quality GASKAP-OH test data to engage school students both in Australia and internationally, working with them to interact with the data using webtools and python. We have also engaged with communities local to the MRO by speaking on *ABC Wheatbelt* radio, and with children at several remote WA schools, including the Pia Wadjarri Remote Community School, and with aboriginal students in the 'Follow the Dream' program.

As results from GASKAP-OH begin to flow, we will seamlessly incorporate the images, cubes and discoveries into our social media, outreach, and education activities. Some specific plans include:

- Integrate GASKAP-OH results into our ongoing partnerships and programs such as 'Astrofest' in Western Australia and 'Astronomy on Tap'.
- Adapt Art-Science projects funded by the Royal Astronomical Society in India and South Africa for GASKAP-OH, giving underprivileged children a chance to connect with science.
- Use GASKAP-OH and personal social media accounts to promote the survey to the wider public and disseminate results.
- Leverage GASKAP-OH data in the Graduate Overseas Extension Studies (GOES) programme at Kagoshima University, training young researchers in English communication and research skills.
- Continue to develop our work with the *STEM Professionals in Schools* programme.
- Work with CSIRO's and SKA's communication and media teams to ensure coordinated and widespread coverage of newsworthy outcomes.
- Continue our long track record as mentors and ambassadors for careers in STEM and as advocates for equity and inclusion.

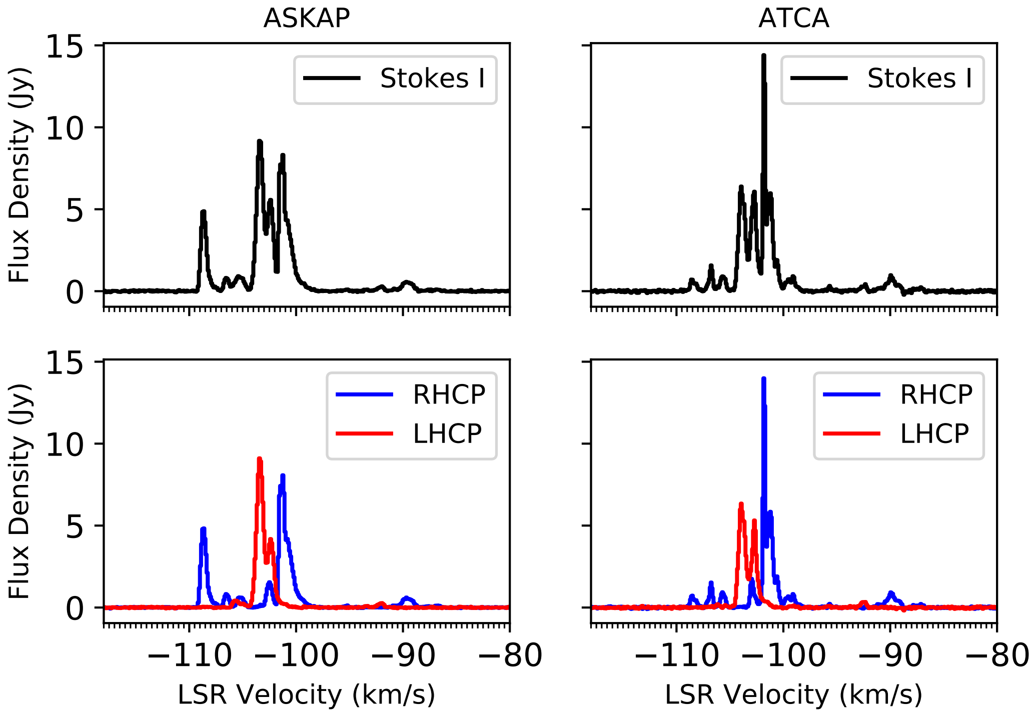

Figure 4: Comparison of ASKAP and ATCA observations of Stokes I and right-hand and left-hand circularly polarised emission spectra for the maser source G340.785−0.096. This source is on-axis in one of the ASKAP beams in the G340 test field. Note that differences in the flux densities of the emission components are due to variability over the intervening decade, but, importantly, the RHCP and LHCP components look correct.

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