GASKAP: The Galactic ASKAP Spectral Line Survey

Abstract

The Galactic Australian Square Kilometre Array Pathfinder (GASKAP) survey is a high spectral resolution study (0.2 km s^{-1}) of the λ21-cm H I line, the λ18-cm OH lines, and the comb of recombination lines around λ18-cm. The area covered by GASKAP includes all the Milky Way Galactic plane south of declination $+40°$ with $|b| < 10°$, selected areas at higher latitudes covering important interstellar clouds in the disk and halo, the Large and Small Magellanic Clouds, and the Magellanic Bridge and Stream. GASKAP is several surveys combined in one mighty project; it is the most ambitious cm-wave spectral line survey of the Galaxy ever done. Compared with existing data, GASKAP will achieve an order of magnitude or greater improvement in brightness sensitivity and resolution in various combinations of beam size and mapping speed matched to the astrophysical objectives.

GASKAP will detect and map OH masers from evolved stars and star formation regions, diffuse emission from molecular and atomic clouds, H I absorption toward background continuum sources and in front of the diffuse 21-cm line emission itself, and the structures in the gas that trace the effects of stellar winds and supernova explosions on the interstellar medium. The Magellanic Clouds will show all these processes as they appear in two other, very different environments. The GASKAP spectral line cubes of the Magellanic Stream will probe the gas properties in the outer halo of the Milky Way, and show how the halo regulates gas flow in and out of the disk. GASKAP will show quantitatively the relative importance of the astrophysics drivers that determine how galaxies evolve, including the formation of interstellar clouds and the exchange of matter between the disk and halo. It will also provide stunning images of the interstellar medium that will be indispensible for astronomers working at other wavelengths, and for popularizing the Square Kilometre Array project.

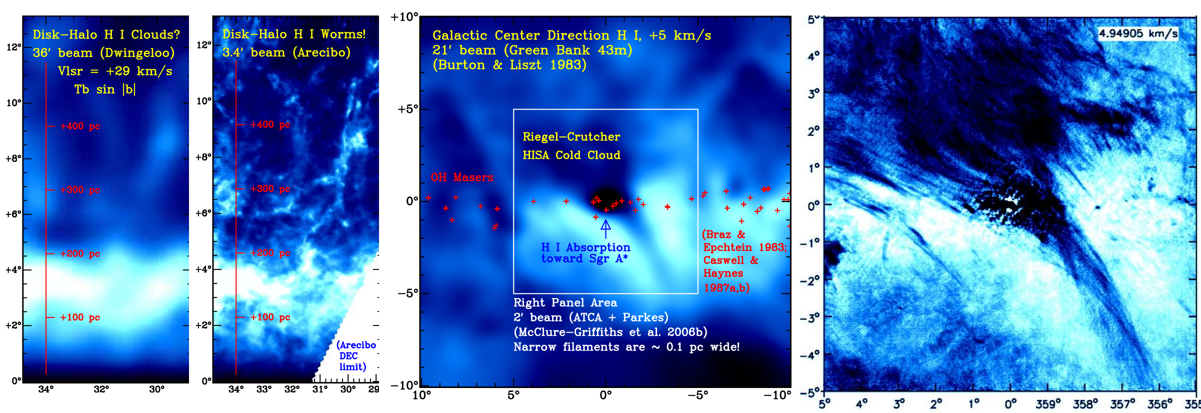

Figure 1: GASKAP will image spectral line emission in large areas of the Galactic disk and halo with unprecedented angular resolution, revealing key structures in extraplanar emission (left) and absorption in the plane (right). Shocks, interfaces, knots, and filaments abound in higher-resolution images, and more numerous and sharper absorption features can be measured with greater accuracy. The above examples illustrate the merits of a factor of 10 increase in resolution in H I imaging in and off the plane; GASKAP will provide *another factor of 10 improvement* in H I image detail. In addition, we expect to increase the number of detections of OH masers in star-forming regions (center panel) by at least an order of magnitude throughout our survey coverage areas (shown on the sky in Figures 3 and 4).

Changes between Expressions of Interest and Proposal

Because this proposal is a combination of ten different EoIs, we have a large team of 78 co-investigators at 42 institutions in 11 countries. The seven original EoI authors form a steering committee that has worked very closely together to prepare this proposal. The research potential of the survey data is so broad that it is not possible to include all the ideas that have been suggested by the team members. Several themes that motivate the project are outlined below in §1, with details on a few specific questions that the survey is designed to answer. We will involve a large group in the planning, operation, and analysis of the survey; these people and our students will become the Galactic Square Kilometre Array community of the future.

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1. Scientific Justification

Galaxy evolution begins at home. One of the great challenges of modern astrophysics is understanding how galaxies form and evolve. This is intimately connected with the outstanding problem of star formation: as star formation transforms the interstellar medium (ISM), adding heavy elements and kinetic energy, it determines the structure and evolution of galaxies. While modern cosmological theories can predict the distribution of dark matter in the Universe quite well, predicting the distribution of stars and gas in galaxies is still extremely difficult (Bryan 2007, Tasker et al. 2008, Putman et al. 2009). The reason is the complex and dynamic ISM: simulations reach a bottleneck on size-scales where detailed understanding of star formation, its feedback, and the interaction between galaxy disks and halos need to be included. To make advances in the area of galaxy formation and evolution, we must begin with our home neighborhood where the physics that drives this process can be exposed and studied in detail.

The GASKAP survey is a spectroscopic mapping project covering the Milky Way (MW) disk and lower halo and the Magellanic Clouds (MCs), Bridge (MB) and Stream (MS) using the 21-cm line of atomic hydrogen (H I), the 18-cm lines of OH (1612, 1665, and 1667 MHz), and the comb of recombination lines in between. The survey focuses on the generic physical processes that drive galaxy evolution by revealing their astrophysical basis here at $z = 0$. GASKAP will provide a new and vastly improved picture of the distribution and dynamics of gas throughout the disk and halo of both the MW and the MCs.

The GASKAP survey data will provide the image detail and broad range of scale sizes that are essential for a quantitative understanding of the physics of the gas in the MW and MCs, including the effects of radiation, shocks, magnetic fields, and the varying gravitational potentials of the disk and halo. Comparing the mixture of warm, cool and molecular ISM phases in the MW and the MCs shows the variation of the heating and cooling rates with metallicity, and how these processes affect the star formation rate. The MCs studied with GASKAP resolution will show two entire galactic systems in enough detail to trace the connection between star formation and gas infall and outflow. The specific scientific applications that set the GASKAP survey parameters are: the initial conditions for star formation and ISM phase transitions, the feedback processes in the ISM, and the exchange of matter between the disk and halo.

Studies of the MW and the MCs are essential for determining the physical processes responsible for converting atomic gas to molecular clouds, and ultimately to stars. What is the relationship between the atomic, molecular, and ionized phases of the ISM in different interstellar environments? GASKAP will trace these phases through H I emission, diffuse OH emission, and recombination line emission. Comparing these over a large area that contains many kinds of clouds, some forming stars and some not, will show how and where the gas makes the transition from one to another. How does the temperature of the gas vary, and how are the different thermal phases mixed in different interstellar environments? GASKAP will investigate this by comparing emission and absorption spectra and by measuring the excitation temperatures of the H I and OH lines. GASKAP data cubes will finally approach the angular resolution provided by the *Spitzer Space Telescope* and the *Herschel Space Observatory*, providing a comparison with ISM tracers at infrared, millimetre, and sub-mm wavelengths. With this survey it will finally be possible to obtain images of structures in the H I medium with the richness and detail routinely available in the infrared and optical for the dust and ionized gas.

Feedback processes are the wild cards in galaxy evolution. Galaxy evolution is largely driven by star formation and the subsequent enrichment of the interstellar gas with heavy elements through red-giant winds and supernova explosions. By undertaking a blind, flux-limited survey of OH masers in the MW and the MCs, GASKAP will image the gas at both ends of this cycle: the first stages of high-mass star formation and the last evolutionary phases of massive (8-25 $M_\odot$) supergiant progenitors of Type II supernovae and the more plentiful low- and intermediate-mass stars (oxygen-rich AGB to PNe).

The motion of the gas in the disk and halo traces both stochastic processes such as turbulence as well as discrete, evolving structures such as chimneys and shells. We will study this motion primarily in H I cubes that show the velocity structure of the diffuse medium, supplemented by more detailed maps of molecular clouds in diffuse OH emission and OH masers in regions of massive star formation. These are the sources of the feedback that stirs up the gas. GASKAP is designed to trace the effects of this feedback throughout the MW disk and lower halo.

How do galaxies get their gas? Cosmological simulations predict that gas accretion onto galaxies is ongoing at $z = 0$. The fresh gas is expected to provide fuel for star formation in galaxy disks (Maller & Bullock 2004). Some of the H I we see in the halo of the MW comes from satellite galaxies, some is former disk material that is raining back down as a galactic fountain, and some may be condensing from the hot halo gas (Putman et al. 2009). However, the detailed physics of gas loss due to stripping and galactic winds, and the fate of the gas that is lost, are still missing in the simulations.

How much gas flows in and out of the disk through the halo, how fast does it flow, and what forces act on it along the way? How do halo clouds survive their trip down to the disk? These questions can be studied both through H I structure in the MS, which shows the conditions in the outer halo, and, at low to intermediate latitudes, by the galactic fountain that constantly circulates H I between the disk and the lower halo as seen in chimneys and H I high velocity clouds. In low-mass galaxies, outflows are a determining factor in their gradual chemical enrichment. The 30 Doradus mini-starburst in the LMC may be responsible for part of the MS (Nidever et al. 2007), and the actively star-forming SMC has a porous ISM from which gas easily escapes. With GASKAP we can compare outflow and accretion rates in galaxies of different masses in the range where these rates are expected to change dramatically.

ASKAP's unique capabilities are applied to the fullest in GASKAP. The ability to survey H I emission and absorption as well as maser emission, diffuse thermal emission, and absorption in OH, all simultaneously with high spectral resolution, is one of the technical advances that ASKAP will bring to Galactic cm-wave spectroscopy. This project makes the most of this new capability to do several different surveys at once. ASKAP's broad range of *uv* spacings allows various combinations of brightness sensitivity and resolution that are optimised for different applications. These different data products are constructed from a single set of spectral cubes that are obtained from a single pass through the standard data reduction pipeline. GASKAP covers seven different survey areas with three standard observing speeds, differing by factors of two in sensitivity. These are detailed below in §§5 and 6. A low latitude survey of the entire Galactic disk ($|b| < 2.75°$ over the full $\sim 270°$ of longitude south of $\delta = +40°$, i.e. $l < 79°$ and $l > 167°$) with dwell time 50 hours provides brightness sensitivity (T_{rms} vs. beam width (FWHM) of: 1.5 K at $20''$, 0.81 K at $30''$, 0.28 K at $60''$, 0.19 K at $90''$, and 0.08 K at $180''$. At the other survey speeds these numbers are a factor of two larger (MS, MB) or smaller (MCs, Galactic Centre/Bulge). All these combinations of sensitivity and resolution constitute an order of magnitude improvement (in $\Omega_{\rm beam} \times T_{rms}$) over the best existing surveys of these regions at 21-cm, and two orders of magnitude improvement for the OH lines.

The rest of this section describes in more detail how the GASKAP data will be applied to answer some of the outstanding astrophysical problems in the MW disk and halo and the MCs and MS.

What will we learn with GASKAP ?

GASKAP will show disk-halo mass exchange and the energy flow in the ISM. For H I emission, the GASKAP survey will provide the biggest improvement over existing survey data in the range $20'' - 90''$ with a *tenfold* increase in resolution in most areas (Figure 1). The Galactic plane has been mostly covered at low latitudes ($|b| < 1°$ or greater in some regions) by the combination of the Canadian (Taylor et al. 2003), Southern (McClure-Griffiths et al. 2005), and VLA Galactic Plane Surveys (Stil et al. 2006), with resolution ranging from $1'$ to $2'$ and brightness sensitivity 1.5 to 3 K rms, and GALFA-HI at $3'$ resolution and sensitivity 0.1 to 1 K rms (Peek et al. 2007). From these surveys we get a hint of the glorious images that GASKAP will produce. These images will show the structure and motions of the ISM on scales of kiloparsecs, where we see how spiral arms influence gas streaming motions, shocks, and star formation (McClure-Griffiths et al. 2005, Strasser et al. 2007). Continuing to $10 - 100$ pc scales we see shells, bubbles, and chimneys that trace the collective effects of many supernova remnants and stellar winds (Normandeau et al. 1996, Stil et al. 2004, McClure-Griffiths et al. 2006a, Kang & Koo 2007, Cichowolski et al. 2008). Moving on down to scales of 1 parsec and smaller, GASKAP will reveal tiny drips and cloudlets in shell wall instabilities (McClure-Griffiths et al. 2003), colliding flows in the turbulent disk ISM (Vázquez-Semadeni et al. 2006, Hennebelle & Audit 2007), and ram-pressure interactions between high velocity clouds and the Galactic halo (Peek et al. 2007, Kerton et al. 2006). All these processes drive interstellar turbulence, seen in both the ionized and neutral ISM to have very similar spatial power spectra (Lazarian & Pogosyan 2000, 2006, Haverkorn et al. 2006). The GASKAP data will allow power spectra to be measured in more different environments, with greater precision, and over a broader range of scales than any survey of neutral gas has done before.

GASKAP will trace phase changes in the gas on its way to star formation. In H I absorption, GASKAP will be an even greater advance over existing surveys than it is in H I emission, with astrophysical results to match. We expect at least four extragalactic continuum sources per square degree with peak flux density of 50 mJy or greater. The rms noise is $\sigma_S \simeq$1 mJy for the main Galactic plane area, giving optical depth noise of $\sigma_\tau \leq$0.02 for such sources (Dickey et al. 2009). These will give absorption spectra of excellent quality. The more abundant, fainter continuum sources will give absorption spectra useful for statistical studies of the cool gas distribution. The big question here is how the thermal interstellar pressure, which changes by several orders of magnitude from midplane to the lower halo and from the inner Galaxy to the outer disk, determines the mixture of warm and cool H I (Wolfire et al. 1995).

The H I absorption spectra GASKAP produces will yield a rich set of gas temperature, column density, and velocity measurements over most of the Galaxy. Anchored to these will be complementary, contiguous maps of the cold H I structure and distribution from H I *self-absorption* (HISA) against Galactic H I background emission (Gibson et al. 2000, 2007). HISA arises from H_2 clouds as well as dense H I clouds actively forming H_2, so it directly probes molecular condensation prior to star formation (Kavars et al. 2005, Klaassen et al. 2005). In fact, a cloud's age can be measured by comparing its HISA and molecular content to appropriate models (Goldsmith & Li 2005, Goldsmith et al. 2007). GASKAP's low-latitude survey will easily map the HISA content of $10-20$ K clouds with $N_{HI} >$ a few $\times 10^{18}\,\mathrm{cm}^{-2}$. This sensitivity — enough to see the ∼1% trace H I in H_2 cores, plus warmer gas in H I envelopes — will be applied to most of the Galactic disk, enabling comprehensive population studies of H_2-forming clouds, including their proximity to spiral shocks (Minter et al. 2001, Gibson et al. 2005a). GASKAP HISA will offer a rich new database for rigorous tests of theoretical models of gas phase evolution in spiral arms (Dobbs & Bonnell 2007, Kim et al. 2008), including phase lags between spiral shocks and star formation (e.g., Tamburro et al. 2008). On much smaller scales, the turbulent froth of HISA filaments that appear to be pure cold H I will be revealed at threefold finer angular and velocity resolution in GASKAP than in prior synthesis surveys, with sufficiently improved sensitivity to follow their spatial power spectrum down to sub-parsec scales where considerable rich structure is already known in isolated cases (Figure 1). This investigation will extend to a wide variety of environments to relate clouds' turbulent support to their stage of molecular condensation. Both 21-cm continuum absorption and self-absorption toward Galactic objects are also helpful for distance determinations (Kolpak et al. 2004). The GASKAP survey is much more efficient in terms of telescope time for this than single pointed observations using the VLA or ATCA.

In addition to H I spectroscopy, GASKAP will further enhance the exploration of gas phase evolution with a new view of molecular clouds. The OH 18 cm lines have long been used as an alternative to the standard CO proxy for H_2, which is subject to the vagaries of UV shielding, interstellar chemistry, and sub-thermal excitation at densities below 10^3 cm^{-3} (Liszt & Lucas 1996, 1999, Grenier et al. 2005, Sheffer et al. 2008). However, diffuse OH emission is typically about 100 times fainter than the H I 21-cm line, and there have been no large-area OH surveys since Turner's (1979) heroic GB 43m work. ASKAP's new capabilities bring an unbiased and detailed view of the OH sky within reach at last. By simultaneously mapping cold H I absorption at $20'' - 60''$ and diffuse OH at $90'' - 180''$ to give the necessary brightness sensitivity, GASKAP will directly probe the H_2 formation process in cold H I clouds by providing a comprehensive H I + OH database of diffuse molecular clouds, against which both quiescent evolutionary models (e.g., Goldsmith et al. 2007, Liszt 2007) and converging-flow dynamical models (e.g., Bergin et al. 2004, Vázquez-Semadeni et al. 2007) can be thoroughly tested and compared to address a key question in the field: *How long do H_2 clouds take to form from the diffuse ISM, and how does this affect star formation?* These measures of cloud total column density, temperature, mass, and other properties will be needed to interpret mm-wave molecular line surveys, infrared dust emission surveys, etc. (§3). Of particular interest would be a broad-based analysis of cold H I, OH, CO, and dust in diffuse clouds throughout the Galaxy to establish a common evolutionary clock for clouds seen with multiple tracers. GASKAP's $3\,\sigma$ OH 1667 MHz sensitivity translates to a minimum detectable H_2 column of $\sim 1.0 \times 10^{21}\,\mathrm{cm}^{-2}$ for a 2 km s^{-1} FWHM line at 180″ resolution, which is sufficient to sample the molecular content of an $A_v \sim 0.6$ mag diffuse molecular cloud, or the early OH formation in a dense H_2 cloud. This sensitivity will exceed Turner's (1979) with better velocity sampling and angular resolution an order of magnitude sharper over a larger and unbiased area, including the hitherto unexplored fourth Galactic quadrant. At the same time, OH absorption toward continuum sources will be probed along with H I absorption to show the excitation temperatures of the 18-cm mainlines.

Recombination Lines from the ionized gas trace H II regions of all sizes, and thus give a longitude-velocity diagram of current star formation. This is particularly important for finding deeply embedded compact H II regions in massive star formation complexes, and for mapping the distribution of the emission measure on the l-v diagram without the effects of extinction. In the stronger regions, we can use the recombination lines to derive electron temperatures in the H II regions. In the brightest regions we can even determine the He abundance. We will observe the full comb of H$n\alpha$ recombination lines with $155 < n < 163$ in a second pass survey using multiple zoom bands for the region $|l| < 60^o$ at low latitudes. This will also cover the frequencies of several molecular lines, including 1720 Mhz OH, CH_3OCHO at 1611 MHz, HCOOH at 1639 MHz, and formamide (NH_2CHO at 1539 MHz), as described on Table 3 in §5.

OH masers allow us to study stellar birth and death, and give a complementary picture of Galactic structure and dynamics to that shown by the interstellar gas. The GASKAP survey for OH masers aims specifically to study the first stages of high-mass star formation and the last evolutionary phases of low- and intermediate-mass stars (AGB to PNe). With a sensitivity at least one order of magnitude higher than previous, spatially-limited surveys of OH masers (e.g., Sevenster et al. 2001, Caswell 1980), we expect to find several thousand new OH sources. Such a sensitive and unbiased survey will allow us to make statistical studies of the processes in these evolutionary phases as well as proper comparisons with the results of Galactic surveys at other wavelengths.

For the brightest (> 0.5 Jy) sources, we will be able to localize the maser emission at each velocity to angular scales ∼1″, ie. the beam width divided by the signal/noise ratio. This will allow us to trace structures such as disks or outflows in some objects (Sahai et al. 1999, Cohen et al. 2006). These will be excellent targets for follow-up VLBI observations. Spatial and kinematical information can give us insights on the formation mechanism of massive stars (Bally & Zinnecker 2005), the shaping of PNe (Zijlstra et al. 2001), and how these processes are affected by different physical and chemical environments (e.g., disk, bulge, and halo).

Using the systemic velocities of masers in OH/IR stars we will study galactic kinematics as traced by this stellar population with much more detail and spatial extent than previously (e.g., Baud et al. 1981, Sevenster et al. 1999). This will provide a picture of MW stellar dynamics that complements those from the gas and the other stellar populations to be sampled by GAIA at optical wavelengths.

With sufficient polarimetric capabilities, ASKAP will be able to estimate magnetic field strengths by measuring Zeeman splitting in thousands of OH maser sources accross the Galaxy. Correlating these measurements with source characteristics, we will study the role of magnetic fields in different evolutionary phases, and study to what degree the local Galactic field is conserved in the star formation process (Han & Zhang 2007).

In the Magellanic Clouds the GASKAP survey will show galactic metabolism in action. GASKAP will provide maps of both MCs with a 20″ beam, which is 3–5 times better than that of the seminal ATCA+Parkes H I maps of the LMC (Kim et al. 2003, 1′ beam) and SMC (Stanimirović et al. 1999, 98″ beam). The GASKAP maps will have better velocity resolution (0.2 km s^{-1} vs. 1.65 km s^{-1} for the earlier maps), and they will have tenfold better sensitivity — T_{rms} = 0.18 K when smoothed to 1.65

km s^{-1} and a 1′ beam, compared to $\sim$ 2 K for the existing data. The wide velocity range covered by the GASKAP maps will include all high-speed gas. Crucially, the GASKAP maps will match the resolution of the Spitzer SAGE survey maps at 70 μm (18″) and the Herschel HERITAGE maps at 160 μm (12″). At the MC distance, resolution of $\sim$20″ gives linear size $\sim$5 pc, typical of supernova remnants and IR Dark Clouds. The improved resolution allows direct links to be established between the sources of stellar feedback and the ISM's response, as well as to locate cold atomic clouds in absorption or self-absorption that are lost in the bright extended emission in lower resolution data.

Two fundamental questions that GASKAP can answer about the gas in the MCs are how effectively star formation can drive gas out of dwarf irregular galaxies, and how differently star formation progresses in a low-metallicity environment (Nidever et al 2007, Krumholz et al. 2009). These are both critical issues for understanding the epoch of galaxy formation. Specific issues related to these questions include how much gas is driven out of the MCs into the Bridge and Stream that will ultimately fall back to the MCs, how much will fall to the MW disk, how much will blend into the hot halo, and how much will be lost from the system altogether. GASKAP will provide hundreds of H I absorption spectra through the MCs, these will measure the mixture of warm and cool atomic gas and their respective spatial distributions. The lower metallicity of the ISM in the MCs will inhibit cooling in the medium. This effect has already been seen in absorption surveys that have been done with a few background sources (Dickey et al. 1994, Marx et al. 1997), but GASKAP will give a quantitative foundation for future studies.

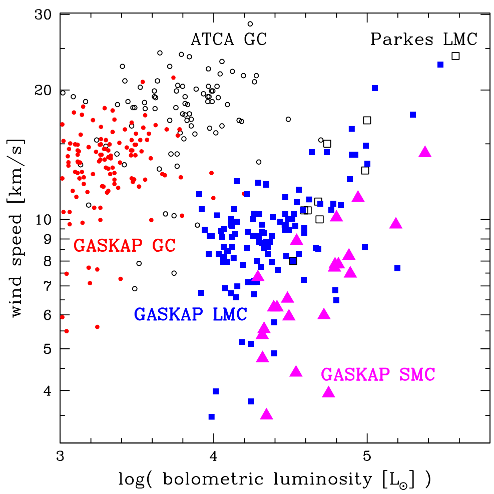

Figure 2. Predictions for the numbers of circumstellar OH masers that will be detected in three fields with existing survey data (black dots, Wood et al. 1998, Marshall et al. 2004). Expanding this model to the total MW survey area predicts that we will detect $\sim$15,000 masers.

Simultaneously with the H I survey, we will cover the MCs for the first time with a blind, flux-limited survey in the OH lines. Previous OH observations were targeted and had worse sensitivity than GASKAP, and they have found only the very brightest sources; the GASKAP OH survey of the MCs will detect many more OH maser sources in star-forming regions. Previous OH maser detections of evolved stars in the MCs had rms sensitivities in excess of $\sim$10 mJy per 0.2 km s^{-1} channel. GASKAP achieves a ten times better sensitivity, yielding an expected two orders of magnitude more OH sources in the LMC (c.f. Fig. 12 in Marshall et al. 2004) and the first such samples in the metal-poor SMC. Large samples of masers in such low metallicity populations of cool giant and supergiant stars will test theories of the driving mechanism of the winds through measurement of their speeds from the double-peaked OH 1612 MHz maser profile (Marshall et al. 2004, van Loon 2006). The proper motion of the masers can be measured with follow-up VLBI to improve our knowledge of the space motion of the MCs. This is a hot topic, since the recent revision of the orbits of the MCs based on HST measurements (Kallivayalil et al. 2006) requires dramatic modifications to our model of the SMC–LMC–MW interaction history (Besla et al. 2007).

The Magellanic Stream is a template for galaxy fueling processes. GASKAP will survey about 5000 square degrees of the MS, the MB, and the Leading Arm (LA, Putman 2003). After smoothing the data cubes to 3′, we will achieve a 3-σ sensitivity limit of N(H) = 3.6×10^{18} cm^{-2} per 20 km s^{-1} channel. GASKAP's combination of angular resolution, sensitivity and spatial coverage is superior to all previous surveys of the Magellanic System (e.g., Putman et al. 2003, Brüns et al. 2005, McClure-Griffiths et al. 2009).

Moving along the Stream from the MCs toward the Northern tip (near $\delta \sim +40°$), the H I shows a wealth of small-scale structure down to the resolution limit of the existing surveys (3′ with the Arecibo radio telescope, Stanimirović et al. 2008). It is not clear what drives the onset of this turbulent structure in the MS, or accreting flows in general. Various dynamical instabilities are expected to disrupt the MS (Bland-Hawthorn et al. 2007, Heitsch & Putman 2009). Each has a distinct signature in the density and velocity fields, so that the GASKAP data will measure their relative importance. Strong dynamical instabilities will lead to gas streamers and coherent structures, while thermal instabilities are expected to lead to fragmentation down to parsec and sub-parsec scales (Palotti et al. 2008, Heitsch et al. 2008, Burkart & Lin 2000). H I clouds re-forming in the MW halo will have compact morphology and small velocity gradients, contrary to the freshly-stripped MS material that is expected to have a head-tail morphology. These morphological and kinematic signatures are powerful diagnostics of the eroding agents essential for feeding the accreting material into the galaxies. Such studies require high spatial and velocity resolution; they are not possible with existing survey data.

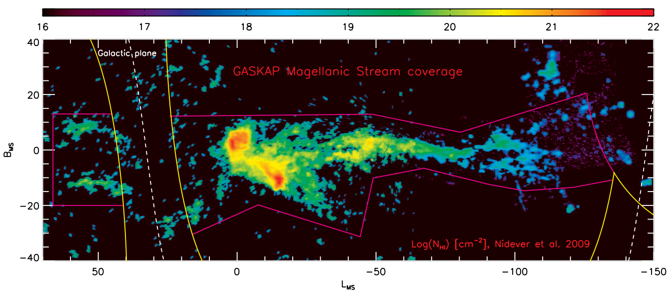

Figure 3. The Magellanic Stream in Magellanic coordinates (Nidever et al. in prep.), with the GASKAP survey areas shown (see Figure 4 in §5).

Recent studies (Westmeier & Koribalski 2008, Stanimirović et al. 2008, Nidever et al. in prep.) suggest that the MS is ∼40% longer than previously thought, and it contains several long filaments. This extended filamentary structure is directly related to the history and evolution of the MS. Numerical simulations that consider only gravitational interactions between the MCs and the MW (e.g., Connors et al. 2006) can reproduce such multiple filaments. However, these simulations require separate encounters between the SMC, the LMC, and the MW that are inconsistent with recent proper motion measurements of the MCs (Piatek et al. 2008) and complementary orbit calculations (Besla et al. 2007, Shattow & Loeb 2009). Using the combination of spatial coverage and angular resolution provided by GASKAP, we will model the evolution of individual MS filaments along the MS and provide key steps toward realistic models for the orbital history of the MCs, and the role of both the luminous and dark-matter components of the MW halo.

The Magellanic Stream and Bridge are templates for the cool neutral medium (CNM) and star formation in low density environments. The MB presents a sliding scale of column density decreasing as one moves from the SMC toward the LMC. Star formation is observed to happen at the SMC end but not near the LMC (Gordon et al. 2009, Harris 2007). Recent Arecibo and ATCA observations show the existence of a multi-phase medium in the MS (Stanimirović et al. 2008, Westmeier et al. in prep). H I emission profiles show clear evidence for a warm and a cold component, at a distance of 60 kpc above the MW disk. Matthews et al. (2009) detect an H I absorption line in the MS, revealing a CNM core with a temperature of 70 K and H I column density of 2×10^{20} cm^{-2}. Such a multi-phase medium with cold cores is totally unexpected in an environment such as the MS, based on the theoretical constraints on cooling/heating processes in the MW halo (Wolfire et al. 1995). GASKAP will reveal and resolve many more cold cores in both the MS and the MB, allowing us to investigate the nature of the CNM in tidal tails, and thus the possible conditions for the formation of molecules, and ultimately stars, in low-density environments (Heitsch et al. 2008, Bournaud et al. 2004, Schaye 2004).

The GASKAP survey will be the most powerful scientific advertisement for the Square Kilometre Array. The results of previous Galactic surveys demonstrate that GASKAP will produce images of structures in the ISM with stunning detail and compelling aesthetic quality. For the general public these may be the most meaningful and interesting results to come from the entire ASKAP project. The GASKAP survey is designed to have the maximum possible impact to further the Square Kilometre Array project. The results will appeal to astronomers and non-astronomers and contribute to fields of study in a broad base of theoretical and observational research well beyond the traditional radio astronomy community.

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2. Design Study Implementation Plan

The GASKAP science team is committed to the technical development of the ASKAP telescope, the successful reduction and interpretation of the survey data, and its dissemination to the wider community of astronomers. This will be the best way to advance the SKA project, both in terms of community engagement and in developing and demonstrating the hardware and software technology that will be used in the SKA. We intend to contribute to the enhancement of the spectroscopic capabilities of ASKAP, thus making it an even more powerful and versatile instrument.

Deliverables

Our contributions to the ASKAP programme include an optimised observing strategy, software instruments, simulations of ASKAP data, data analysis and visualisation tools, and the maintenance of public archives of advanced data products.

Software instrument design

As our single-most important contribution of to ASKAP design implementation, the GASKAP team will work with the ATNF to develop an advanced and versatile spectral-line software instrument. This is one of three basic software instruments necessary for ASKAP science operations. The standard spectral line mode as described in the documentation will be sufficient to achieve many of our science goals, but to get the most out of the data we will try to do more. We want to image complex spatial and kinematic structures, from several degrees down to 20", in emission in the H I and OH lines. For strong OH masers and for H I absorption toward bright, extended sources we hope to get "postage stamp" cubes with even finer resolution. This high sensitivity to a broad range of angular scales is what will produce the most striking images. It is also needed as input to statistical measures like the structure function of the gas, or two/three-point correlation functions.

Technical challenges for GASKAP:

- **Zoom mode for spectral line.** Our optimal configuration requires splitting the available channels among two or more separate windows across the 300 MHz band. The implementation of this zoom mode will allow parallel observation of the H I and OH lines at high spectral resolution, which more than doubles the value of the telescope time given to Galactic line surveys.
- **Calibration.** Because of the narrow total bandwidth in zoom mode, GASKAP may force us to experiment with calibration techniques, perhaps including occasional point source observations to fix the focal plane array gains, or calculating gains in channels with strong OH maser emission.
- **Deconvolution.** Present ASKAP specifications may not allow full deconvolution of whole data cubes in the *uv*-plane. However, image-plane deconvolution could be necessary for some science applications.
- **Field construction and mosaicking**. Obtaining good flatness of the field of view (of special concern at the highest frequencies) and properly stitching adjacent fields is important to map extended emission.
- **Continuum subtraction and bandpass calibration.** We will investigate whether strategies for these spectral corrections, as planned for the standard pipeline, are adequate for our requirements, and how to improve them if necessary.
- **Extended emission.** The largest scales of H I emission will not be properly sampled by ASKAP. Combination with existing single-dish maps will be necessary.

We intend to work together with ATNF staff to tackle these issues. The GASKAP team will contribute data simulations, improvements to the data pipelines, and tests with the first six ASKAP dishes (BETA).

Simulations

GASKAP comprises a range of different spectral line studies, as part of the over-arching Galactic science theme. For each survey component, detailed calculations and simulations will be developed during the design phase, based on what is already known (with some extrapolations) to show what we expect to see with ASKAP, the requirements imposed on the data reduction pipeline, and what science we can get out of the ASKAP data. In the final phase, this will involve checks of the data pipeline, to justify that we really can achieve what we aim to do.

Examples of planned simulations and ancillary test observations (in approximate chronological order) include:

- Simulations of H I emission, including estimates of missing flux for emission at large scales. We will investigate how best to combine ASKAP data with single-dish surveys like GASS and GALFA. This could be done in the map plane.
- Simulations of H I absorption against bright, compact continuum sources behind the Milky Way Disk and Magellanic Clouds.
- Simulated sky of OH maser sources in the Galaxy and Magellanic Clouds, based on already detected sources, estimates of completeness, and scaling for metallicity. Different types of sources will be considered (e.g., evolved stars and star-formation regions).
- Simulations of radio recombination line emission in the inner Galaxy.
- Possible observations of different fields, close to the sensitivity goal of ASKAP, to improve and test simulations. Sample observations may be done using the EVLA or ATCA.
- Simulate how maps will look with ASKAP *uv*-sampling, and how best to flatten the fields of adjacent beams.
- Visualisation tools for exploring the (x, y, v) cubes (*e.g.*, moment maps, as well as basic image statistics). We can start their development once we get realistic simulations.

Pertinent results emanating from these simulations will be published as part of the GASKAP Science Survey overview paper, and form the basis for the design of optimised observing and data processing strategies, to be tested with the BETA array and implemented for execution with the ASKAP.

Tests with BETA

The first six ASKAP dishes (BETA) will be used to test the hardware, data pipeline, and data quality control. We will develop and test observing strategies on the following points:

- Observing scripts. Codes will be written that generate observing scripts with specific pointings.
- Data quality control. Codes will be written that automatically monitor data quality on a daily basis by doing tests of dynamic range, bandpass stability, and continuum subtraction. Additional codes will select and stitch together observed fields to conveniently monitor survey progress.
- Field construction. Interlacing (dithering) algorithms will be developed and tested.
- Mosaicking. Patterns of stitching together adjacent fields will be investigated.
- Data reduction pipeline. We will work with ATNF staff to help test and improve the basic pipeline, which we understand will include calibration, continuum subtraction, RFI excision, and imaging.
- Deconvolution. For H I spectral line data cubes or channels with strong OH maser emission, deconvolution may be necessary. We will work with the ATNF to explore and design the best possible scheme for deconvolution. We will test whether it is practical to perform deconvolution in the image domain, for instance based on maximum entropy algorithms, given the limitations on computing power.

- Postage stamps. We will help testing ASKAP capabilities for postage-stamp data processing and storage with high angular resolution ($\sim 8''$). This will be of interest for H I absorption and strong OH masers.

- Synoptic capabilities. Tools will be developed for the automatic detection of OH maser sources, involving separating OH maser from thermal OH emission or from possible artificial interference signals, and detecting variable OH masers.

In the post-commissioning phase of ASKAP, we will concentrate on working with the ATNF to implement zoom modes, combining different sub-bands at high spectral resolution. This will enable the simultaneous execution of the H I, OH and other molecular/recombination line surveys.

Advanced products

The extraction of science products requires significant post-processing of the (x, y, v) cubes provided by the pipeline. The expected spectral cubes data rate is 2.2 PB per year. Hence we endeavour to establish data archives hosted at a minimum of three locations. These can be searched, examined, and data subsets can be extracted via virtual observatory (VO) tools, some of which we may have to develop ourselves. To do this translates into significant hardware requirements (parallel processing and rapid random access to TB archives).

Software tools will be developed to explore the data and obtain scientific results. Examples include:

- As final data products will be deconvolved H I cubes of particular (fixed) size, we will develop a tool to mosaic/bin/smooth data cubes into larger entities required for science applications.

- Correlation of H I maps and OH maser catalogues with other survey data, e.g., radio continuum (including other ASKAP survey data), Spitzer, Herschel, AKARI, 2MASS, and H_2O, SiO and methanol maser catalogues. This could be done with existing VO tools, and additional tools will be developed as needed.

- Software to automatically determine position-velocity distributions and Zeeman splitting for each OH maser source source, and to identify the nature of these sources based on spectral characteristics and correlation with other surveys.

- Software for constructing the Galactic kinematical/number density models from the OH maser database.

- We will test and adapt codes for cloud extraction, such as Clumpfind (Williams et al. 1994) and Duchamp (Whiting 2008), to identify discrete clouds from H I, OH and RRL emission, as well as from H I self-absorption (Gibson et al. 2005b).

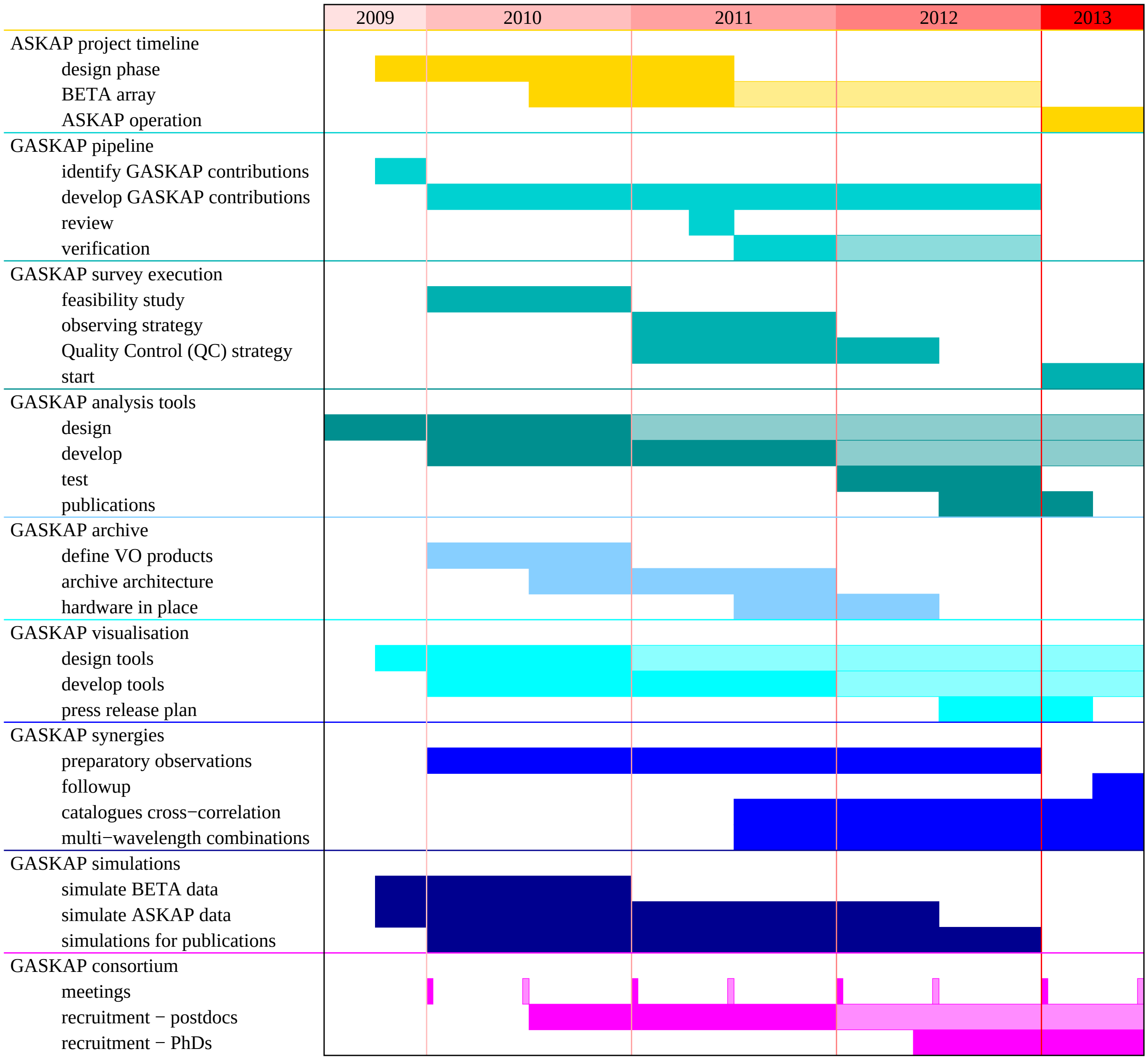
We will deliver advanced data products, comprising H I kinematic maps and cubes, H I and OH absorption-line maps, and a VO-compliant database of OH masers.

Early Science

When the products of our design study are completed, and ASKAP is commissioned, we plan to start our survey with particular regions of interest. In principle, our first choice would be the SMC, which fits into a single ASKAP pointing. Observations in this region would be an important test bench, before we undertake the main MW survey, and would form the basis of an early, self-consistent publication with ASKAP data, yielding high-impact science results.

Timeline

The GASKAP Design Study phase and subsequent implementation in the execution and exploitation of the Science Survey with ASKAP adheres to the following timeline:



3. Benefit to Community

GASKAP will have great synergies with other surveys. Multi-wavelength studies of the interstellar and intergalactic media are essential for understanding the interchange of gas among different phases. In the recent past, surveys at infrared and sub-millimetre wavelengths have achieved large spatial coverage with angular resolutions measured in arcmin or arcsec, while at 21-cm only selected regions of the Galactic plane and the MCs have reached a high angular resolution of $1'$. For example, the *Spitzer* GLIMPSE and MIPSGAL, *Herschel* Hi-Gal, and APEX ATLASGAL Galactic plane surveys all have resolutions of $2'' - 30''$ at wavelengths of $3\,\mu$m $- 1$ mm. In addition, the *Spitzer* (SAGE) and AKARI surveys of the MCs and the MB have provided exquisite images at arcsec resolution, while the approved *Herschel* HERITAGE project will use several hundreds of hours to map cold dust and embedded star formation in the MCs.

GASKAP data cubes will match the angular resolution provided by *Spitzer*, *AKARI*, *Herschel,* and APEX, enabling a direct comparison with other important ISM tracers (dust, molecular lines, shocked ionized gas). This will provide a complete picture of Galactic morphology and kinematics for different ISM phases down to small ($< 1'$) scales. GASKAP's H I and OH images will be the crucial complement to dust and CO (from NANTEN and ALMA) images for estimating the dust-to-gas ratios for individual atomic and molecular clouds. This will enable an independent check on the "constant" conversion factor between CO flux and H_2 column density. In addition, while GASKAP will have a lower resolution than ALMA, H I and OH will be essential for mapping the large-scale kinematics of molecular clouds targeted by ALMA, and the CO-dark cloud envelopes postulated to represent the missing link between low and high-density gas.

GASKAP will provide several tiers of data products:

(i) As ASKAP data have no proprietary period, we will release data cubes as soon as calibration is finished and essential data quality checks are completed. We will work with ATNF scientists to store these data cubes in the central (ASKAP) science archive with appropriate organization and documentation. We envision that H I and OH postage stamps will be provided in the same fashion. This on-going transfer of science data to the archive will happen periodically. We expect that within the first 1–2 months of GASKAP observations a steady stream of science data products will start running into the central science archive. We will have a dedicated team member in charge of data archiving and distribution, doing survey book-keeping, and alerting the team of problems arising.

(ii) We expect that some additional operations and improvements will take place after observations and initial data reduction/release. For example, cubes of individual pointings will be combined into larger fields. During the design study phase, we will investigate the most economical ways of storing and manipulating the larger data cubes. These larger cubes, organized by scientific region (e.g., the SMC, the Galactic bulge, etc.) will constitute the second tier data product for public distribution. This tier of data products will be hosted at three of our PI institutions, and all necessary infrastructure for this will be provided by external funding (by individual PIs) during the Design Phase.

(iii) We will provide catalogs of H I absorption profiles and OH masers in a timely fashion through our regional data release centers, compatible with the Virtual Observatory (VO) requirements. These data products will be also published in major scientific journals.

We would like to stress that our team has substantial experience in conducting large radio spectral-line surveys with the ATCA, VLA, DRAO-ST, Parkes, and Arecibo. For example, the core members of the GALFA-H I survey are on our team. GALFA-H I has been surveying $\sim 12,000$ square degrees with the Arecibo radio telescope with a streamlined observing, reduction, and data archiving scheme. This survey is in the process of producing legacy-style data products (data cubes) available for the astronomy community at large. We will draw on our experience and lessons learned from GALFA-H I, the SGPS, VGPS, and CGPS and apply these to GASKAP.

Software tools: As outlined in §2, we plan to develop tools for manipulating large data cubes (e.g., making arbitrary subsets and slices, or merging smaller cubes). We will also investigate the existing capabilities and requirements for the VO to make sure our 2nd- and 3rd-tier data products are compliant with the VO formats and requirements. This will result in easy cross-correlations of GASKAP H I images and catalogs with other survey data. The software tools will be released to the community through our survey web page and/or any script repositories established by the ANTF.

Education: GASKAP will provide numerous educational opportunities for undergraduate and graduate students. An important characteristic of the GASKAP team is its wide international nature. The PIs of the EoIs merging into GASKAP are spread across four continents, and the team now comprises scientists from 11 different countries. GASKAP will be an exceptional vehicle for training of the next generation of radio astronomers throughout the world. We envision that GASKAP will provide core topics for many PhD, masters and senior thesis projects, fostering the confluence of research and education. We already have at least 4 PhD students involved with this proposal and working (or just about to start) on topics directly related to GASKAP development. In addition, as shown by the on-going Arecibo surveys, H I images and data cubes are ideal data sets for providing research experience to high-school and undergraduate students. Lastly, being a key step towards the SKA, GASKAP will play an important role in preparing and training the whole scientific community for the future use of the SKA.

Public Outreach: GASKAP will produce public images with stunning detail and aesthetic quality. This will be of great interest to the general public, and a very effective way to enhance the interest of young people for astronomy. We plan to take full advantage of this opportunity! As our team has a strong multinational representation, we will easily reach a world-wide audience, fostering public awareness of ASKAP/SKA projects and the scientific importance of radio astronomy in general.

Firstly, we plan scientific exhibits in many institutions. Large GASKAP images, as well as movies stepping through different velocity channels, are easily affordable. We will make large posters and displays, especially emphasizing the multi-wavelength aspect of our living Galaxy. For example, University of Wisconsin has an outreach center, "Space Place", where an exhibit about the GLIMPSE Galactic observations already occupies a prominent space. GASKAP H I images will be a wonderful complement to this display. Similarly, Instituto de Astrofísica de Andalucía has a strong collaboration with "Parque de las Ciencias" in Granada, one of the leading science museums in Spain, which is also one of the top tourist attractions in Granada. The National Astronomical Observatory of Japan has established the "Three-Dimensional Theater", where H I images of the Milky Way are presented. GASKAP images, together with numerical simulations of the Milky Way dynamics, will add a new dimension to this exhibit. And Keele Observatory, frequently visited by local schools, is being refurbished to host a Science Visitor Centre; GASKAP imagery and movies would feature prominently.

Secondly, we plan to develop public presentations about GASKAP and its scientific output. These will be presented in various public lectures, and also local schools and community colleges. For example, Yale University operates the Leitner Family Observatory and Planetarium in New Haven, Connecticut. We will use the Observatory's public nights, planetarium shows and display area to describe GASKAP project to the public and the importance of radio astronomy. Talks and displays will be in English and Spanish (in order to target the large Spanish-speaking community in the area).

Other benefits to the scientific community: disseminating data products and knowledge to the astronomy community at large, we will organize several workshops in Australia, US, Japan and Europe to introduce the scientific community to GASKAP and and train it to use GASKAP data products. As ASKAP is truly revolutionizing radio astronomy, many aspects about handling data sets will be totally new to even traditional radio astronomers. We envision hands-on demonstrations of basic tools to display and analyze GASKAP data products.

During the design phase and especially once the survey starts, we plan to have at least one scientific conference every year, or a session within a larger meeting (e.g., AAS, IAU assembly etc.). These meetings will focus on science topics addressed by GASKAP, and will be open to the astronomical community at large. We are especially interested in stimulating meetings that will bring theorists and observers together in order to push limits on the traditional ways of analyzing and interpreting H I and OH observations.

4. Team Organisation

The seven PIs of the original EoIs have formed a steering committee (SC). The SC coordinates GASKAP involvement in the design phase, and takes end-responsibility for survey design, data quality, software development, and archiving. SC and other GASKAP members have taken leading roles in major radio surveys in the past (e.g., VGPS, CGPS) and present (e.g., GALFA). A summary of key tasks, teams and responsibilities:

SC member	survey component	FTE	technical commitment
Dickey	Galactic Plane	0.3	overall coordination; absorption maps, continuum sources
Gibson	Galactic H I	0.3	simulations, deconvolution, visualisation, analysis, VO
Gómez	OH	0.5	simulations, preparatory OH observations
Imai	OH	0.3	simulations, OH/H_2O/SiO correlation, pipeline testing
Jones	RRLs, other lines	0.2	simulations of RRLs, testing
Stanimirović	Magellanic Stream	0.3	imaging, deconvolution, pipeline testing
van Loon	Magellanic Clouds	0.4	advanced analysis software and data products

work package	coordinator	key team members besides SC (PhD students in bold)
survey execution & QC	Dickey	McClure-Griffiths, Peek, Putman
pipeline and tests	Peek	Douglas, Ford, Kang, **Nigra**, **Saul**, Tafoya, Westmeier
data products I & II	Stanimirović	Douglas, Nidever, Girart
data products III	Imai	Green, Izumiura, McClure-Griffiths, Nakashima
data visualisation tools	Gibson	Arce, **Bailey**, English, Ford, Kang, **Nigra**, Westmeier
analysis tools & products	van Loon	**Bailey**, Begum, Ford, Kang, **Nigra**, Tiang

The Australian partners of the GASKAP consortium, the Universities of Tasmania (UTas) and New South Wales, together with the ATNF (McClure-Griffiths, 0.3 FTE; Green, 0.5 FTE), will play a leading role in the design phase. This will benefit from in-kind hardware and computing support from UTas and TPAC (Tasmanian Partnership for Advanced Computing). Western Kentucky and Keele have access to their faculty's Beowulf-style high-performance computer centres employing many parallel processors. Likewise, Wisconsin has "Condor", a computing centre based on large collections of distributed computing resources. IAA (Granada) owns a GRID node for distributed computing, and also has funds for a 1-year postdoctoral position (at least 50% dedicated to GASKAP) starting in Sept. 2009. Stanimirović has committed up to US$30,000 towards a joint GASKAP postdoc, travel or data storage; van Loon has committed US$5000.

We will use the design phase period to accrue and generate more technical and scientific expertise. To this aim we will advertise GASKAP and apply for funding of postdocs and MsC and PhD students.

Dickey will submit a 3-year Australian Research Council grant proposal for a postdoc to work full time on development of data analysis and storage, primarily in support of the continuum absorption (H I and OH) part of the project. Van Loon is discussing with the UK Science and Technology Research Council a Project Research and Development proposal for hardware and a postdoc. Gómez and van Loon are coordinating European funding applications (viz., FP7 Marie Curie actions). The Spanish group have requested research funds from the regional government of Catalonia, and will apply to the Spanish and regional Andalusian governments. Gomez plans a 1-year sabbatical leave at ATNF in 2010–2011. Stanimirović & Heitsch, and Gibson & Arce, will apply for NSF funding in 2009 for postdocs. Imai will apply to the Sumitomo and Yamada Foundations, each US$20,000 for travel and computing expenses. Imai is also coordinating postdoc applications to the JSPS foreign researcher program; he will apply to the grant-in-aid scheme of JSPS (US$200,000) in the next year for a postdoc and computing in 2011–2015.

Although there is no proprietary period, the SC guarantees that scientific results are published timely by way of a publication policy and plan. An overview paper will be published at the start of the survey, and early science papers are planned for the individual survey components — we anticipate that these will generate press releases and that we will publicise these also in our local communities. The SC will advise on science exploitation, to avoid conflicts and duplication and in particular to protect PhD projects.

The GASKAP consortium communicates through regular telecons, a website, and tailored e-mailing lists. The GASKAP consortium commits itself to annual meetings, the first in Hobart, Tasmania, in Jan. 2010.

5. Technical Requirements

- **Observing time, sky coverage, survey speed, and sensitivity:** The GASKAP spectral line survey is divided into 7 components with different areas on the sky. These fall into 4 different speed and sensitivity groups. We will use a variety of angular and spectral resolutions to map bright detailed structure while also detecting faint features. Thus, strong H I absorption or OH maser emission might use a $20''$ or $30''$ beam, while faint diffuse OH emission may require $90''$ or $180''$.

Figure 4: Survey Sky Coverage

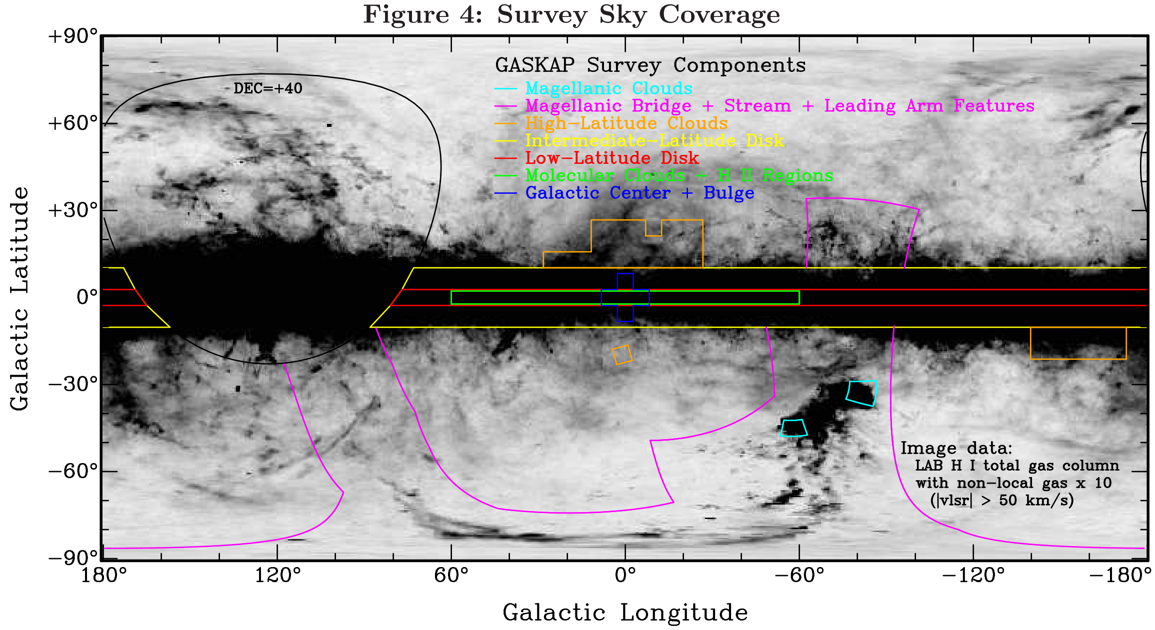


Table 1: GASKAP Survey Components

Component Name	Location on Sky (see Figure)	Area deg^2	Time hr	Speed deg^2/hr
Low Latitude	$\|b\| < 2.75°$, all ℓ for $\delta < +40°$	1,496	2,493	0.60
Intermediate Latitude	$2.75° < \|b\| < 10.25°$, all ℓ for $\delta < +40°$	4,080	1,700	2.40
Magellanic Clouds	LMC + SMC deep integration fields	94	627	0.15
Magellanic Bridge + Stream	$-135° < \ell_{ms}{}^a < +66°$, varying $b_{ms}{}^a$	5,219	2,175	2.40
High-latitude Fields	Mon + Ori + Aql + Oph + Lup + CrA	1,080	450	2.40
Galactic Center + Bulge	5 fields centered about $\ell = 0°, b = 0°$	150	1,000	0.15
Mol. Clouds + H II Regions	$\|b\| < 2.25°$, $\|\ell\| < 60°$	660	500	1.32
Total		12,779	8,945	

[a] Magellanic Stream coordinates (Nidever et al. 2008); see also Figure 3 in §1

Table 2: Benchmark Speeds vs. Sensitivity

Survey Component	Map Speed deg^2/hr	Dwell Time [hr]	T_{rms} [K], $\Delta\nu = 5$ kHz for $\theta_{FWHM} =$ $20''$	$30''$	$60''$	$90''$	$180''$	S_{rms} [mJy], $\Delta\nu = 5$ kHz for $\theta_{FWHM} =$ $20''$	$30''$	$60''$	$90''$	$180''$
Gal. Cent. + Mag. Clouds	0.15	200	0.76	0.40	0.14	0.09	0.04	0.5	0.6	1.0	1.3	2.3
Low Latitude	0.60	50.0	1.51	0.81	0.28	0.19	0.08	1.0	1.2	2.0	2.6	4.6
Molecular Clouds + H II	1.32	22.7	2.24	1.20	0.42	0.28	0.12	1.5	1.8	3.0	3.9	6.8
Int.+High Lat. + Mag.St.	2.40	12.5	3.02	1.62	0.56	0.37	0.15	2.0	2.4	4.0	5.2	9.2

- **Observing frequency, bandwidth, and spectral resolution / number of frequency channels:** GASKAP will use two spectral configurations. Both configurations divide 16,384 channels among a set of sub-bands within a 300 MHz range. The mode used by most survey components targets H I and OH in three sub-bands. The base channel widths in this mode are ~ 1 kHz to sample narrow absorption and maser lines and, if polarization is available, to measure Zeeman splitting of OH masers. An alternate mode supplements this view in the inner Galaxy with a variety of recombination lines and molecular lines in 16 sub-bands. Nine H $n\alpha$ lines are listed below ($n = 155 - 163$); corresponding He and C $n\alpha$ RRLs will be in the same bands for abundance work. The OH 1612, 1665, and 1667 MHz lines are re-observed in this mode to get additional sensitivity for diffuse OH and more visits for time-variable OH masers.

Table 3: GASKAP Spectral Parameters

Survey	Obs. Freq.	Spectral	Sub-Band	#	Chan. Width		Vel. Range
Comp.	**[MHz]**	**Lines**	**[MHz]**	**Chan.**	**[kHz]**	[km/s]	[km/s]
All Lat.		H I 21-cm	1420.4 ± 3.65	6384	1.144[a]	0.242	$\lvert v_{lsr} \rvert < 772$
Mag. Sys.	1543 ± 150	OH 1612	1612.2 ± 2.00	3500	1.144	0.213	$\lvert v_{lsr} \rvert < 372$
Gal. Cent.		OH 1665+7	1666.4 ± 3.15	5500	1.144	0.206	$\lvert v_{lsr} \rvert < 387$
		H163α RRL[b]	1504.6 ± 1.17	1024	2.289[a]	0.456	$\lvert v_{lsr} \rvert < 233$
		H162α RRL[b]	1532.6 ± 1.17	1024	2.289	0.448	$\lvert v_{lsr} \rvert < 229$
		NH_2CHO[c]	1539.6 ± 1.17	1024	2.289	0.446	$\lvert v_{lsr} \rvert < 228$
Molecular		H161α RRL[b]	1561.2 ± 1.17	1024	2.289	0.440	$\lvert v_{lsr} \rvert < 225$
		H160α RRL[b]	1590.6 ± 1.17	1024	2.289	0.431	$\lvert v_{lsr} \rvert < 221$
Clouds		CH_3OCHO[c]	1610.6 ± 1.17	1024	2.289	0.426	$\lvert v_{lsr} \rvert < 218$
		OH 1612	1612.2 ± 1.17	1024	2.289	0.426	$\lvert v_{lsr} \rvert < 218$
+	1630 ± 150	H159α RRL[b]	1620.7 ± 1.17	1024	2.289	0.423	$\lvert v_{lsr} \rvert < 217$
		HCOOH[c]	1638.8 ± 1.17	1024	2.289	0.419	$\lvert v_{lsr} \rvert < 214$
H II		H158α RRL[b]	1651.5 ± 1.17	1024	2.289	0.415	$\lvert v_{lsr} \rvert < 213$
		OH 1665	1665.4 ± 1.17	1024	2.289	0.412	$\lvert v_{lsr} \rvert < 211$
Regions		OH 1667	1667.4 ± 1.17	1024	2.289	0.412	$\lvert v_{lsr} \rvert < 211$
		H157α RRL[b]	1683.2 ± 1.17	1024	2.289	0.408	$\lvert v_{lsr} \rvert < 209$
		H156α RRL[b]	1715.7 ± 1.17	1024	2.289	0.400	$\lvert v_{lsr} \rvert < 205$
		OH 1720	1720.5 ± 1.17	1024	2.289	0.399	$\lvert v_{lsr} \rvert < 204$
		H155α RRL[b]	1749.0 ± 1.17	1024	2.289	0.392	$\lvert v_{lsr} \rvert < 201$

[a]Channel widths 1.144 kHz = 300 MHz / (16,384 × 16) and 2.289 kHz = 300 MHz / (16,384 × 8).

[b]Corresponding He and C $n\alpha$ recombination lines will be observable in these same bands.

[c]NH_2CHO = formamide (6 lines); CH_3OCHO = methyl formate (2); HCOOH = formic acid (1).

- **Field of View:** We can work with any shape and size FoV. Our main consideration is to keep the sensitivity function as flat as possible so as to provide nearly uniform sensitivity. The numbers in Table 1 are based on a square area of $(5.5°)^2$ at 1.4 GHz and $(4.5°)^2$ at 1.7 GHz.

- **Time resolution:** We have no requirements other than the need to have uniform sensitivity across the full field of view.

- **Polarization products:** Our primary science does not require polarimetry, but if it becomes available, it will greatly enhance our survey. Stokes V is expected to be a standard output of ASKAP, and it will allow us to study the Zeeman components of bright OH masers. We can use Stokes Q and U to study H I absorption of bright, linearly polarized continuum from SNRs (Kothes et al. 2004), and to estimate the orientation of magnetic fields with OH masers. Some of these products may only be needed in specialized postage-stamp image cubes around bright sources.

6. Detailed Functional Requirements

- **Survey strategy:**

  - **Overlapping field observations**, offset by fractions of a primary beam, are desired to ensure **(1)** continuous sky coverage for different fields of view at 1.4 vs. 1.7 GHz, **(2)** a relatively uniform sensitivity pattern, and **(3)** synoptic measures of variable sources, such as OH masers. In the design study phase, an optimal balance will be determined between this overlap/multi-visit approach and the need for adequate *uv* coverage within reasonable observing constraints.
  - **Scheduling of observations** can probably be anytime (day or night) and random as suits ASKAP operational needs. We will perform BETA tests during the design study phase to assess the effect of Solar interference on spectral baselines.
  - **Short spacing data:** For most H I, we will use the GASS, GALFA, and LAB surveys (McClure-Griffiths et al. 2009; Stanimirović et al. 2006; Kalberla et al. 2005). Depending on the exact ASKAP *uv* coverage, we may use Parkes + ATCA H I data for the Magellanic Clouds (Kim et al. 2003; Stanimirović et al. 1999). We do not expect that missing short spacings will be a problem for RRLs or diffuse molecular emission.
  - **Commensal observing:** GASKAP does not have formal commensal partners. However, it is the union of several EoI projects comprising multiple, simultaneous surveys of H I and OH emission and absorption, OH masers, and additional heavy molecule and recombination line observations.

- **Correlator configuration:** Spectral sub-band "zoom modes", numbers of channels, center frequencies, and other parameters are given in Table 3 in §5.

- **Polarization Purity:** Our primary science does not require polarimetry but can benefit greatly from it. Our OH maser science will benefit from a Stokes V purity of 3% of Stokes I, with 1% preferred. Our H I absorption science will benefit from similar purity in Stokes Q, U.

- **Dynamic range:** Most GASKAP science can be done with a spectral dynamic range of a few hundred to one. We will work on deconvolution schemes that may improve this to a few thousand to one for bright point sources (including OH masers).

- **Imaging requirements:**

  - **Angular resolution:** We prefer $20''$ resolution wide-field imaging but can tolerate larger beams if necessary. We prefer better than $20''$ resolution in postage stamps.
  - **Postage stamps/cubes:** We would like to have small cubes around strong sources for best angular resolution. We estimate $3-5$ extragalactic continuum sources per square degree will be bright enough to benefit from this treatment.
  - **Deconvolution:** We do not require deconvolution, but if available, it will be very useful in the postage-stamp cubes around strong sources.
  - **Continuum Subtraction:** Our line emission cubes require continuum subtraction for proper analysis. For H I absorption studies, we would like supplemental cubes with the continuum left in, so that we have *in situ* measurements of the background source brightness with identical *uv* coverage to the H I data.
  - **Weighting:** We plan to explore optimal weighting parameters for the weighting scheme.

- **Source finder:** We will develop algorithms to find OH maser emission and determine positions with high spatial precision, including finding maser emission in different spectral channels.

- **Extra processing:** We plan significant image-plane processing of our spectral line cubes to produce suitable data products at a range of angular resolutions, and also to analyze data sets to extract catalogs and other derived data products.

- **Data products:**

  - **Standard tile cubes:** A set of wide-field (ℓ, b, v) FITS cubes in Stokes I for a $20''$ beam with $8''$ pixel sampling and "raw" channel widths for H I + OH (1.14 kHz) and other molecules + RRLs (2.29 kHz). These will be designed to follow a Virtual Observatory "atlas tile" scheme covering our entire survey area and ready for extraction or analysis by GASKAP scientists and public users alike. We will develop tools to assemble arbitrary-sized images from subsets and supersets of atlas tile cubes, so the angular width of a given tile cube is not critical. If one tile is the size of one ASKAP $(5.5°)^2$ field, this will require 2475 pixels on each side. The cube depth for each spectral line will be dictated by the number of channels in the sub-band, ranging from 1024 to 6384 (see Table 3). Smoothing/binning in velocity for greater sensitivity will be provided on-the-fly by a Virtual Observatory tool we shall develop.
  - **Larger-beam cubes** for $30''$, $60''$, $90''$, and $180''$ will be derived from the standard $20''$ beam cubes above in post-processing. They should have sky areas matching those of the $20''$ beam cubes but will need proportionately fewer pixels for adequate sampling.
  - **Postage-stamp image cubes** around bright continuum sources with best ASKAP resolution ($\sim 8''$) in H I and OH are desired to reduce emission confusion noise in absorption analyses and obtain precise maser positions.
  - **Various 2-D projections** (moment maps, T_{max} maps, etc.) of the 3-D image cubes will be produced by the GASKAP team and tiled together for large-scale science and public outreach and education.
  - **Spectral catalogs** of OH masers, H I absorption, diffuse OH absorption, RRL detections (if discrete), and complex molecular detections (if discrete)
  - **Other derived data products:** diffuse OH column density, cubes of RRL emission measure vs. velocity, HISA absorption (ℓ, b, v) cubes, gas properties vs. (ℓ, b, v) and (R, θ, z) in the Galaxy and Magellanic system, and molecular cloud properties from diffuse OH, HISA, other molecules, and far-infrared emission.

- **Data volumes:** With $8''$ pixels, the volume of GASKAP data required to cover the 12,780 deg^2 and 16,384 channels (see Tables 1 and 3) with 4 bytes per record in Stokes I is 153 terabytes. Larger-beam versions of these same cubes require fewer pixels, and in sum will not more than double this number. 3-D postage stamps, 2-D projections, catalogs, and other derived data products are all far smaller than the main cube data sets. Thus the overall volume of GASKAP data products should be no more than ~ 300 TB. Hard disk storage capacity of this order is currently available on high-performance computing clusters and, depending on the slope of Moore's Law, may be in the desktop regime within 10 years. Similarly, if the standard tile cubes are 1 ASKAP field (5.5°) wide, they will be 145 GB in H I, which is awkward now but may be within reach of high-end desktop RAM by 2017.

7. Response to EoI Evaluation Committee

There were ten Expressions of Interest submitted for various aspects of this project, from seven principal investigators (PIs) each with a group of co-investigators (co-Is). Some of these were for H I 21-cm surveys, some for OH 18-cm surveys, some for recombination lines, some for other molecular lines, and some for combinations of these. Some of the EoIs were to survey the Galactic plane over various longitude and latitude ranges, some the Magellanic Clouds, some the Magellanic Stream, some various combinations of these, and one was to cover the entire sky! The substantive comments on these EoIs had to do with the size of the telescope time requests, the ambitious correlator configurations, the specifications for the angular resolution, and the expectations for deconvolution and dynamic range. After the PIs received the evaluations of their individual EoIs by the committee, we were strongly encouraged to join together to submit a single proposal. After considerable discussion on how to combine the survey specifications to accommodate all our major science goals, we settled on the parameters given in §§5 and 6 of this proposal. These constitute several different surveys rolled into one, with a single theme: to cover all the important areas of the Milky Way and the Magellanic Clouds, Bridge, and Stream, including all significant spectral lines between 21-cm and 18-cm wavelengths. This will give a coherent picture of the role of gas in galaxy evolution, from accretion to star formation.

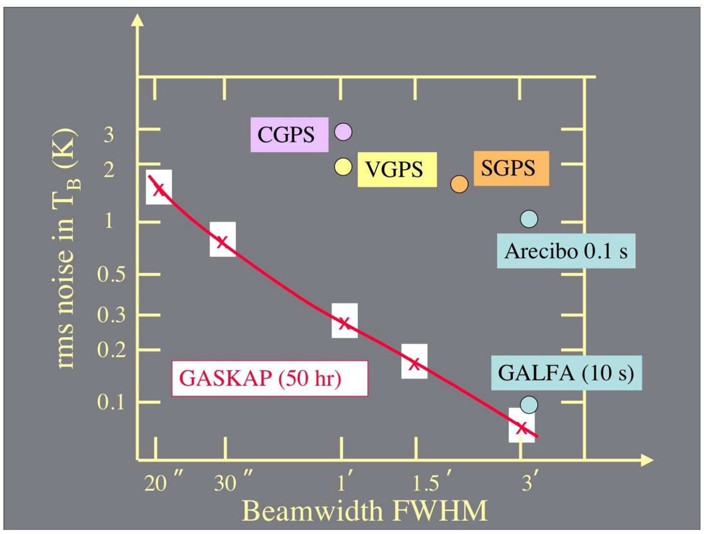


Figure 5. The sensitivity vs. resolution for various beamwidths. On the left (20″ and 30″) are combinations appropriate for HISA and HICA at low latitudes, on the right (1′ to 3′) are combinations appropriate for H I in the Magellanic Stream and diffuse OH emission at low latitudes. The numbers are for the middle survey speed, 0.6 square degrees per hour. The other two speeds give sensitivities a factor of two higher or lower (see Table 2 in §5).

The survey parameters described in this proposal take account of all technical limitations discussed in the evaluations of the EoIs. The total telescope time now fits the recommended target of one year (∼ 9000 hours). The three different survey speeds are chosen to give sensitivity in different regions matched to the brightness of the diffuse H I and OH emission at different resolutions between 20″ and 3′. The spectral resolution and sub-bands assume a limited flexibility for the correlator. Of the different survey components on Table 1, the first six are done simultaneously; only the last requires reobservation of a small fraction of the survey area to cover more lines. One of the most important features of this proposal is its simultaneous coverage of several different gas tracers: emission and absorption in the H I line and in three of the four OH lines.

The distribution of baselines in the ASKAP aperture plane is very well suited to a Galactic spectroscopy survey. The possibility of mapping simultaneously with the beam sizes from 20″ to 3′, by smoothing the accumulated cubes, gives a range of brightness sensitivity, as needed for the strong H I emission in the Galactic plane, and for the much fainter diffuse OH emission (Table 2). The possibility of "postage stamp" cubes at high resolution (7″ to 10″) allows for precision mapping of bright OH masers, and for interpolation and removal of H I emission from in front of compact continuum sources, to get high sensitivity absorption spectra. We will use as many such small cubes as we can get, particularly in the low and intermediate latitude parts of the survey. The sensitivity vs. resolution that will result is illustrated on Figure 5.