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Surveys of the Milky Way and Magellanic System in the λ21-cm line of atomic hydrogen

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Abstract. In the next three years, surveys of the Northern and Southern skies using focal plane arrays on aperture synthesis radio telescopes will lead to a breakthrough in our knowledge of the warm and cool atomic phases of the interstellar medium and their relationship with the diffuse molecular gas. The sensitivity and resolution of these surveys will give an order of magnitude or more improvement over existing interstellar medium data. The GASKAP (South) and GAMES (North) projects together constitute a complete survey of the Milky Way plane and the Magellanic Clouds and Stream in both emission and absorption in the H I 21-cm line and the OH 18-cm lines. The overall goal of this project is to understand the mechanism of galaxy evolution, through a detailed tracing of the astrophysical processes that drive the cycle of star formation in very different environments. Comparison of 21-cm emission and absorption highlights the transition from the warm, diffuse medium to cool clouds. Tracing turbulence in the Magellanic Stream shows how extra-galactic gas makes the difficult passage through the halo to replenish the disk. Finally, high resolution images of OH masers trace outflows from evolved stars that enrich the medium with heavy elements. To understand how the Milky Way was assembled and how it has evolved since, the speed and efficiency of these processes must be measured, as functions of Galactic radius and height above the plane. Observations of similar processes in the Magellanic Clouds show how differently they might have worked in conditions typical of the early universe.

1. WHAT WE HAVE NOW

Surveys of the λ 21-cm emission of the Milky Way were begun in the early 1950's, Oort et al (1958) and made great progress through the 1960's and 1970's, (reviewed by Burton, 1988). But by about 1980 the insidious effects of stray radiation stopped further progress in Galactic emission surveys, Kalberla et al (1980), with a few notable exceptions, Lockman et al (2002). The stray radiation problem comes from the very low but widespread telescope response far off-axis, due in a large part to diffraction from the feed legs that block the aperture. Meticulous numerical correction for this effect, and the completely unblocked aperture design of the Green Bank Telescope, have made it possible in the last decade for H I surveys to achieve much more sensitive column density limits than were possible before. The column density of H I gas, N_H, is proportional to the brightness temperature, T_B, integrated over velocity in the spectrum:

$$\frac{N_H}{\mathrm{cm}^2} = 1.8\ 10^{18} \frac{\int_v T_B\ \mathrm{d}v}{\mathrm{K\ km\ s^{-1}}}$$

where the integral is taken over the entire emission spectrum, for a total column density, or over a single line component to get the column density of the corresponding cloud, or simply over one spectrometer channel to give the column density in the corresponding range of radial velocities. The uncertainty caused by the stray radiation, typically $T_B \sim 1$ K over a velocity range of $\sim 10\,\mathrm{km\,s^{-1}}$, leads to a lower

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Table 1. Recent Surveys of H I in the Milky Way.

name	longitude	latitude	resolution	noise T_{rms}
LAB	all	all	35′.	0.08 K
GASS	all	$\delta < +1°$	16′.	0.06 K
EBHIS	all	$\delta > -5°$	10′.	0.08 K
GALFA	all	$+38 > \delta > +4°$	4′.	0.08 K
CGPS	$65° < \ell < 180°$	$-3° < b < +5°$	1′.	3 K
SGPS	$255° < \ell < 360°$ $0° < \ell < 18°$	$-1° < b < +1°$ $-1° < b < +1°$	2′.	1.6 K
VGPS	$18° < \ell < 65°$	$-1.5° < b < +1.5°$	50″.	2 K

limit column density of $\sim 2\ 10^{19}$ cm^{-2}. After stray radiation correction, modern surveys can easily reach a factor of 20 to 100 deeper than this, to column density of a few $\times 10^{17}$ cm^{-2} in channels of width 1 km s^{-1}, with integration time per pointing of about one minute.

The most comprehensive surveys of the sky that have been fully stray-radiation corrected are the LAB survey, Kalberla et al (2005) with resolution 35′., and more recently the combined GASS and EBHIS surveys, McClure-Griffiths et al (2009); Kalberla et al (2010); Kerp et al (2011), which combine data from the Parkes (resolution 14′.) and Effelsburg (10′.) telescopes. These telescopes give the highest resolution possible for surveys of the entire sky, but the Arecibo telescope can give higher resolution over a significant portion of the sky ($36° > \delta > 4°$), and the GALFA survey has made very sensitive spectral line cubes of most of this area with beamwidth 3.5′. Stanimirovic et al (2006); Peek et al (2011). The Arecibo data has not been fully corrected for stray radiation to the same level as the LAB, GASS, and EBHIS surveys.

To achieve higher resolution than the largest single dish telescopes offer, aperture synthesis interferometer arrays are the only option. The technique of *mosaicking* many fields is a powerful way to study Galactic H I emission, because it enhances the sensitivity of the telescope to widespread emission that is mostly filtered out by the interferometer in normal data processing, Ekers and Rots (1979); Sault et al (1996). Interferometer mosaic surveys are generally supplemented by single dish maps, to restore the “zero spacing” emission, i.e. emission from gas very smoothly distributed on the sky.

The most ambitious mosaic surveys of the Galactic plane done so far are the three components of the International Galactic Plane Survey: the CGPS, Taylor et al (2003), the SGPS, McClure-Griffiths et al (2005), and the VGPS, Stil et al (2005). Their parameters are shown on table 1. These surveys have sufficient resolution to show structures with sizes of tens to hundreds of pc at distances of 5 to 10 kpc.

Most recent surveys of the H I emission of the Magellanic Clouds (MCs), Bridge (MB), and Stream (MS) also use the observing technique of interferometer mosaicking plus single dish maps. Some recent Magellanic surveys are summarized on table 2. Most of these surveys have velocity resolution of about 1 km s^{-1}, similar to the Galactic surveys on table 1, with the exception of the HIPASS survey of the full MS area, Putman et al (2003), for which the velocity channel spacing is 26.4 km s^{-1}. For comparison, the noise level on table 2 has been scaled to the equivalent 1 km s^{-1} resolution value from its actual value of $T_{rms} = 0.035$ K. Stray radiation removal in the single dish data is not an issue for extragalactic objects because their radial velocity is well separated from that of the Galactic emission that covers the sky and leaks into the spectrum through the distant sidelobes of the telescope beam. The gas in the MCs has high enough column density that it shows brightness temperatures as high as 135 K, Kim et al (2003), but in the MS typical column densities are a factor ten to 100 lower, so high sensitivity is required to map the Stream ($T_{rms} < 0.5$ K).

2. HI STRUCTURE OF THE DISK AND HALO

On the scales probed with 1′. resolution in our Galaxy ($\sim$3 pc) the atomic ISM shows dramatic shells and chimneys, that stand out by their empty interiors, McClure-Griffiths et al (2002), as well as populations

Table 2. Recent Surveys of the Magellanic Clouds, Bridge, and Stream.

region	resolution	noise T_{rms}	reference
LMC	1′	2.4 K	Kim et al (2003)
SMC	1.6′	1.4 K	Stanimirović et al (1999)
MB	1.6′	0.9 K	Muller et al (2003)
MB&MS	15.5′	0.2 K[1]	Putman et al (2003)
MS	16′	0.05 K	Brüns et al (2005)
MS	3.5′	0.03 K	Stanimirović et al (2008)
MS	9′	0.05 K	Nidever et al (2010)

[1]Reduced to 1 km s^{-1} velocity resolution.

of clouds in the disk and lower halo, Ford et al (2010). Analysis of the IGPS data by many groups has led to progress on all scales, from tracing spiral arms, (e.g. Dame and Thaddeus 2008, 2011; McClure-Griffiths et al 2004) and precise measurement of the rotation curve, McClure-Griffiths and Dickey (2007); Levine et al (2008), down to mapping cold atomic gas through its absorption of the bright H I emission behind, Gibson et al (2005); Kavars et al (2005). On the smallest scales, the cold gas often shows surprisingly linear, filamentary structure, McClure-Griffiths et al (2006).

One of the most important themes to emerge from mapping Galactic H I with spatial resolution of a few pc is the dominance of gas flow between the disk and the lower halo. The Galactic Fountain process, proposed some 35 years ago to explain the statistics of the high velocity clouds, (HVCs Shapiro and Field, 1976), is based on the ejection of hot gas from the disk due to the collective effect of supernova explosions in a region of active star formation. The hot gas eventually cools in the lower halo, and as its density increases it falls rapidly back into the plane. More sensitive surveys of HVCs and the neutral gas in the lower halo will show different stages of the fountain process in better detail.

Surveys of H I emission show the ISM structure more clearly than other tracers like molecular lines or Hα emission because the H I is so widespread throughout the disk and lower halo. The regions that are empty of H I are as striking in the maps as those that are full. These empty regions form a network of holes, tunnels, and chimneys that have been described mathematically as porosity by theorists since the pioneering work of McKee and Ostriker (1977), updated by Wolfire et al (2003). The network of bubbles and chimneys links the disk with the halo, as predicted by theoretical treatments of expanding shells, (e.g. Norman and Ikeuchi 1989). Modern simulations of the evolution of the ISM show similar structure on large and intermediate scales, de Avillez and Breitschwerdt (2005).

Structure in the diffuse ISM is an indicator of the flow of dynamical and thermal energy from the disk to the halo. Gas also flows from the halo into the disk, including both returning fountain material and accreted matter tidally stripped from satellite galaxies. The Magellanic Stream is the most prominent example of the latter type of gas infall. Even though most gas in the halo is ionized, it is easier to trace the small fraction that is neutral by its 21-cm emission than to use Hα to trace the dominant ionized component. This is because the density, n, is very low in the halo, and the emission coefficient of the Hα line goes as n^2 whereas that of the H I line goes as n, (e.g. Draine, 2011). Thus H I surveys of the MS are one of the best ways to trace the process of accretion of gas through the outer halo and down to the Galactic plane, Nidever et al (2010).

3. THE FUTURE: GASKAP AND GAMES

Radio astronomy technology is advancing more rapidly, notably with the development of focal plane array (FPA) receivers that can be used on each element of a conventional aperture synthesis telescope array. Such arrays have been successfully tested for use on the Australian Square Kilometre Array

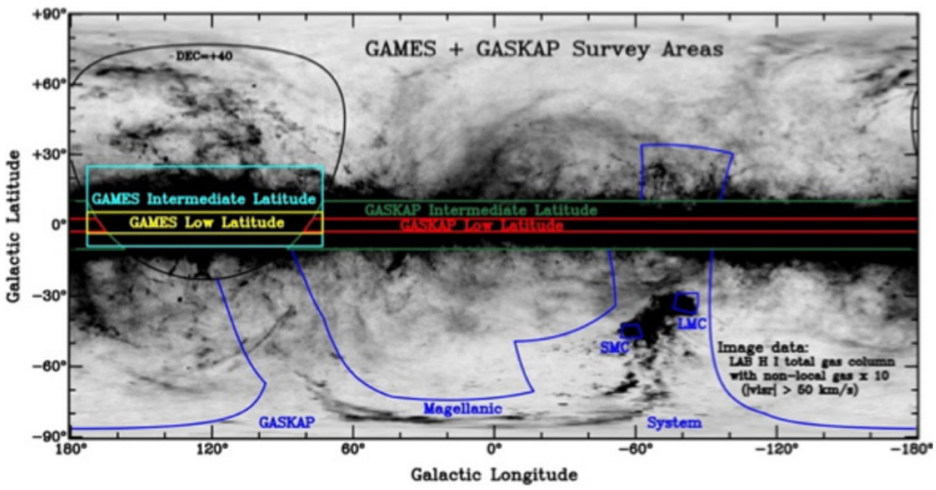

Figure 1. The survey area for the GASKAP and GAMES surveys (courtesy S. Gibson). The background shows column densities from the LAB survey, with HVCs and the MS gas enhanced by a factor of ten relative to the disk.

Pathfinder, (ASKAP, Johnston et al 2007) and Westerbork Synthesis Radio Telescope, (WSRT Apertif, Verheijen et al, 2008). When these FPA receivers are installed and optimised for λ 21-cm surveys, it will be possible to improve the combination of sensitivity and resolution by an order of magnitude over the surveys described in section 1. To exploit this technical breakthrough, a large international team has proposed a pair of surveys of the Milky Way disk and the MCs and MS, called GASKAP (Galactic ASKAP Survey) and GAMES (the Galactic and Magellanic Emission Survey). The frequency range will cover both the λ 21-cm H I and $\lambda\lambda$ 18-cm lines of OH, thus detecting masers that trace both star forming regions (at 1665 and 1667 MHz) and post-AGB stars (at 1612 MHz). The velocity resolution will be $0.2\,\mathrm{km\,s^{-1}}$. At low latitudes ($|b|$ <2.5 °) the brightness sensitivity (for a $1\,\mathrm{km\,s^{-1}}$ velocity width) will be 0.8 K rms in a beam with width 30.″, or 0.08 K for a beam width of 3.′ ($N_{rms} = 1.4\ 10^{17}\,\mathrm{cm^{-2}}$). One of the features of an aperture synthesis survey is that the brightness sensitivity varies with the resolution, which is selected when the Fourier inversion is done on the data to make the maps and spectral line cubes. The GASKAP survey will make maps with a variety of resolutions and sensitivities, from 20.″ to 180.″, plus small, "postage stamp" cubes around OH masers and bright continuum sources showing H I absorption.

The area to be covered by GASKAP and GAMES together is shown on figure 1. The ASKAP portion covers everything south of $\delta = 40°$, including most of the MS and all of the MCs. The WSRT-Apertif survey fills in the portion with $79° < \ell < 167°$ where the plane is north of $\delta = 40°$. The survey parameters will be matched to give a continuous, smooth set of data products. The GASKAP survey is described in more detail by Dickey et al (2012). Currently simulations are being carried out to help plan the data reduction and survey strategies. In early 2012 the first six antennas of the ASKAP telescope will be fitted with FPA receivers and tested as an array. Test observations for GASKAP will begin later in 2012 and early 2013, with a goal of having the survey well underway by 2015.

4. SUMMARY

In the past decade there have been many very ambitious surveys of H I in the Milky Way and MCs, MB, and MS. These surveys have broken new ground in sensitivity, resolution, and in the elimination of the effects of stray radiation. The new data has led to advances in our understanding of the dynamics of the

Galaxy, the mixture of phases in the interstellar medium, the rotation and structure of the MCs. The next five years will bring an even more exciting advance, as the new FPA technology on aperture synthesis radio telescopes will lead to much more sensitive surveys with resolution of 30.″ or less.

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