Chapter 1

Introduction

A broad and ample rode, whose dust is Gold
And pavement Starrs, as Starrs to thee appeer,
Seen in the Galaxie, that Milkie way
Which nightly as a circling Zone thou seest
Pouderd with Starrs.

– John Milton (1608-1674)
Paradise Lost. Book vii.

There are few sights more impressive than the broad expanse of the Milky Way stretching across the Southern sky. Crossing from horizon to horizon, the astonishing number of stars, the dark clouds, and the stunning Galactic center will never cease to amaze even the most casual observer of the sky. Our name for this swath of sky, our home, comes from the Greek and Roman names for it: the Greeks named it *galaxies kuklos* – the milky circle, the Romans called it *via lactea* – milky road, or milky way. Despite early recognition of the magnitude of this Milky Way, surprisingly little is known about our Galaxy. Our position within it has hereto hindered efforts to understand its structure and dynamics.

1.1 Historical Perspective

Since the detection of the atomic hydrogen (H I) line in 1951 by Ewen and Purcell, H I in the Galaxy has been observed extensively. Throughout the 1950's and into the 1960's the first large-scale maps of the Galactic H I were made with telescopes in Australia and the Netherlands (Oort et al. 1958). Over the next ten years, focus was shifted towards the smaller scale distributions and physical properties of Galactic H I. Many of the questions addressed then remain unanswered today: how does the H I relate to the other ISM phases, particularly molecular gas and dust? what is the temperature of the warm H I? the cold H I? what determines the temperature? is there pressure equilibrium in the ISM? In the 1970's more attention was placed on the distribution of the H I at large galactocentric radii. Observations of the outer Galaxy demonstrated the warp and flare of the outer H I disk (Henderson et al. 1982). Throughout these early studies single dish telescopes grew larger, from the early Parkes 18 m to the larger 64 m, and as the resolution improved, the ability to efficiently map large areas slipped away. Spectral resolution also improved through the ever increasing capabilities of spectrometers. However, by the late 1970's Galactic H I studies had largely plateaued. With the advent of synthesis interferometer imaging techniques it became easier to observe H I in external galaxies with spatial resolution comparable to that used in our own. As a result, H I studies shifted focus to extragalactic sources where the advantage of perspective was favorable. Recently a technique of mapping large areas at high resolution with an interferometer, known as "mosaicing," has become feasible. This technique, and another that allows one to sample a larger range of angular scales by combining single dish and interferometer data, has allowed us once again to address the distribution of H I in the Milky Way. To this end, three surveys: the Southern Galactic Plane Survey (SGPS; McClure-Griffiths et al. 2001c), the Canadian Galactic Plane Survey (CGPS; Taylor 1999) and the VLA Galactic Plane Survey (VGPS; Dickey et al., in prep) have undertaken the task of mapping the Galactic plane in its entirety at angular resolution of ~ 1 arcminute, a spectral resolution of ~ 1 km s^{-1}, and to a sensitivity limit of ~ 1 K. This dissertation covers the SGPS and is one part of the large collaboration known as the International Galactic Plane Survey. Here we present the data from the SGPS and address questions about the large-scale structure and motions of hydrogen in the Milky Way.

1.2 The Southern Galactic Plane Survey (SGPS)

1.2.1 What is the SGPS?

The Southern Galactic Plane Survey (SGPS) is a survey of the H I spectral line and 21 cm continuum emission in the fourth quadrant of the Galactic plane. The survey provides a complete H I and 21 cm full polarization continuum (Stokes I, Q, U, & V) dataset of the area $253^\circ \leq l \leq 358^\circ$ and $-1\overset{\circ}{.}0 \leq b \leq +1\overset{\circ}{.}0$ as shown in Fig. 1.1. The data have an angular resolution of $2'$, a velocity resolution of $\Delta v = 0.82$ km s^{-1} and a sensitivity limit of ~ 2 K in the line and ~ 400 μJy Bm^{-1} in the continuum. The SGPS makes use of high spatial resolution data obtained with the Australia Telescope Compact Array (ATCA) and short spacing information obtained with the Parkes 64 m single dish[1] to provide a survey that is more than an order of magnitude more sensitive than previous surveys of this region. In addition to the main body of the survey, we have extended the single dish coverage to $b = \pm 10^\circ$ in order to study large scale structures that protrude from the Galactic plane.

1.2.2 Why do we need the SGPS?

Surveys of the Milky Way allow us to look at the energetics and structure of our own Galaxy with spatial resolution that is unattainable in other galaxies. The inner

[1] The Parkes telescope and the ATCA are part of the Australia Telescope, which is funded by the Commonwealth of Australia for operation as a national facility managed by the Commonwealth Scientific and Industrial Research Organisation.

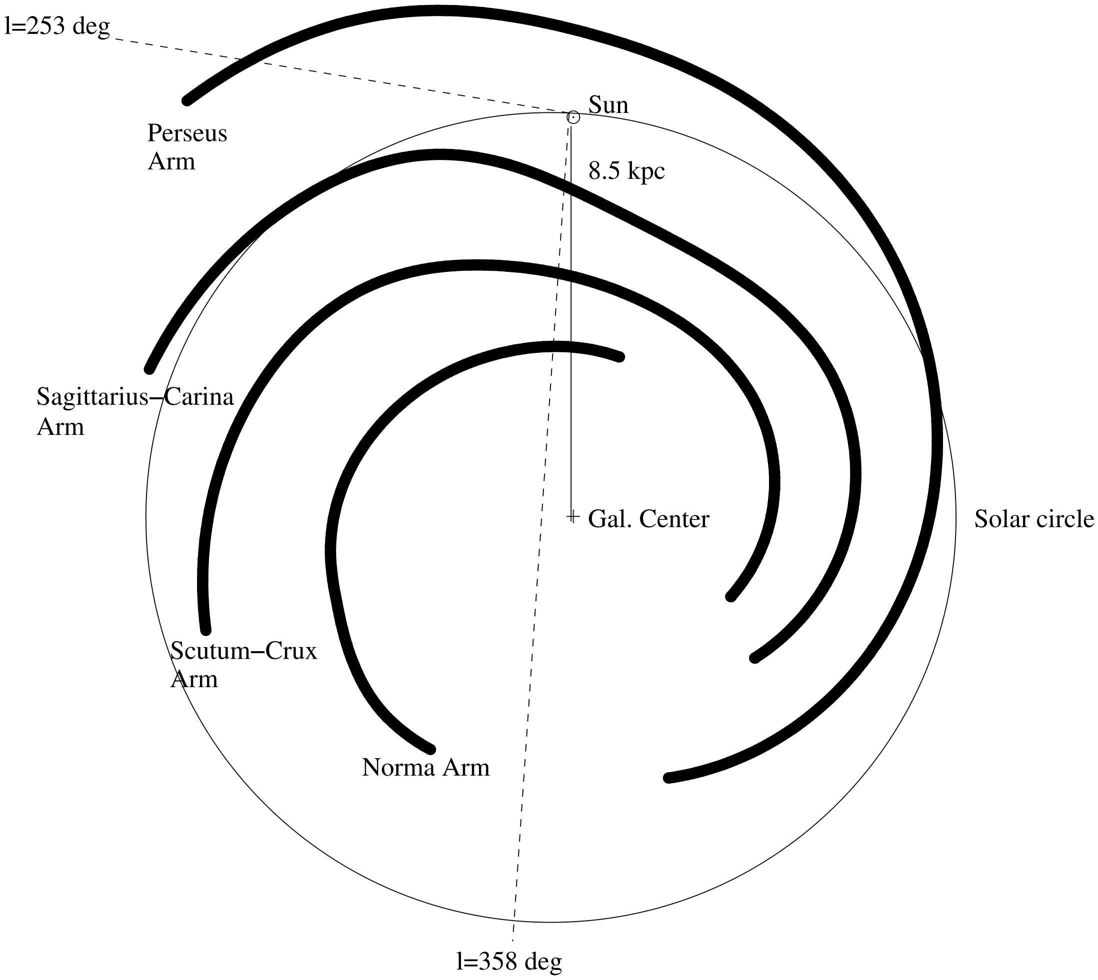

Figure 1.1: Diagram of the SGPS area. Approximate positions of the spiral arms are marked with heavy lines based on the Taylor & Cordes (1993) model. The solid circle marks the path of the Sun about the Galactic Center. The dashed lines mark the bounds of the survey.

Galaxy, in particular, provides a number of scientific opportunities. Because of the low-resolution of early Galactic H I surveys (e.g. Goss & Shaver 1970; Weaver & Williams 1974), much of what we know about the structure of the Galactic H I is restricted to large scales. In other wave-bands Galactic surveys are much more up-to-date. In the infrared, X-ray, and Hα the inner Galaxy has been mapped extensively, while H I remains seriously under-sampled. Over the past five years the H I atlas of the Galaxy has been greatly improved by the Dominion Radio Astrophysical Observatory's (DRAO) Canadian Galactic Plane Survey (CGPS), which covers a longitude range of $l = 74°$ to $147°$ using a combination of interferometer and single dish data to image the Galaxy at a resolution of one arcminute (Taylor 1999). Despite the contributions of the CGPS to our knowledge of Galactic H I, the inner Galaxy remains neglected.

1.2.3 What can we do with the SGPS?

The overall goal of the Southern Galactic Plane Survey is to provide a dataset with which to study the structure and dynamics of the neutral hydrogen (H I) in the inner Galaxy. Previous studies of the inner Galaxy have lacked the sensitivity and resolution necessary to study the physical processes of the interstellar medium (ISM) over a large range of spatial scales. Though the goals of the SGPS are numerous, we will highlight a few below:

- The SGPS allows us to address questions about the spatial distributions and scale heights of the warm and cool components of the neutral medium in order to understand the thermal phases of the interstellar medium.
- Combining the Parkes and ATCA data, we are able to probe the interstellar medium through a broad range of spatial scales in order to develop a statistical interpretation of the neutral ISM throughout the inner Galaxy.
- H I emission data over the large range of spatial scales available in the SGPS

allows us to detect a full sample of H I shells with which to study not only the formation of shells - particularly of the largest, most enigmatic ones - but also their distribution in the Galaxy and global effect on Galactic structure.

- A number of H I self-absorption (HISA) features are apparent in the SGPS test region (McClure-Griffiths et al. 2001b). HISA, where cold H I clouds absorb the diffuse background H I emission, is an excellent probe of the distribution of the coldest, most compact H I clouds.

- The dataset provides H I absorption spectra for distance estimates of many Galactic objects and may be useful in identifying those extragalactic sources located close to the Galactic plane.

- The inclusion of full polarization information for the continuum data allows us to explore the polarization structure of individual objects, such as supernova remnants, and to investigate the Galactic magnetic field structure using the polarization of the diffuse background emission.

1.3 The Interstellar Medium in the Milky Way

The Milky Way, or the Galaxy, is a barred spiral Galaxy of mass on the order of 10^{11} $M_{\odot}$. Of this mass, about 5% is in the form of gas between the stars, or the interstellar medium (ISM). Of that, $\sim 40\%$ by mass (90% by number) is atomic hydrogen. The gas and stars of the Milky Way are largely confined to a thin disk and central bulge. The stellar disk has a scale height of 100 pc and radius 10 kpc, whereas the gas extends to a scale height of 1 kpc and radius 30 kpc. The Sun is located in the mid-plane, or Galactic plane, approximately 8.5 kpc from the Galactic Center.

In the simplest sense, the interstellar medium (ISM), is just that, the gas and dust between the stars. A wide range of elements, temperatures, densities, and physical states are represented in the ISM. Hydrogen, however, is by far the most pervasive.

Though the ISM is complex, its temperatures, densities and phases are often modeled with the comparatively simple three-phase McKee & Ostriker (1977) model. In this model interstellar hydrogen is found in three main phases: the hot ionized medium (HIM), cool neutral medium (CNM) and warm neutral medium (WNM), all three of which are in pressure equilibrium. The hot, ionized medium is created by supernovae. On the edges of these bubbles of HIM are atomic clouds. The clouds are multi-layered, with cold, neutral gas (CNM) at the interior and a layer of warm neutral (WNM) gas on the exterior. The 21 cm line of hydrogen directly traces the warm neutral phase in emission and the cold neutral phase in absorption. The ionized gas, on the other hand, is traced by Hα and thermal X-ray emission, pulsar scintillation and dispersion measure. Cold, molecular hydrogen, from which stars form, is inferred from the presence of other molecular species, most often carbon monoxide (CO), and is detected in emission. Overall the gas density of the ISM is about 1 particle cm^{-3}, but the density and temperature vary greatly with environment. Though global pressure equilibrium may exist, local deviations from pressure equilibrium allow star formation to occur. The distribution, temperatures, densities and interrelation of these phases are some questions that drive the SGPS.

It is from the interstellar medium that stars are born and it is to the interstellar medium they return when they die. This delicate process of stellar life and death is controlled by the physical conditions in the ISM. The medium is continually replenished and enriched by massive stars as they eject gas and processed elements back into the ISM. Simultaneously, much of the dynamics of the ISM are driven by interactions with massive stars. On the small scales, the dynamics are dominated by these effects. The 21 cm line of neutral hydrogen acts as an excellent tracer of all these dynamics.

1.3.1 Neutral Hydrogen as a Probe

Neutral hydrogen (H I) emits a narrow emission line at a wavelength of $\lambda = 21.1$ cm ($\nu = 1420.405752$ MHz) through a hyperfine transition in which spins of the ground state electron and the proton switch from parallel to anti-parallel. The probability for this transition is given by the Einstein A coefficient, $A_{21} = 2.85 \times 10^{-15}$ s^{-1}. Therefore, under normal circumstances a given atom will make this transition once every 12 million years. Because of the long timescale involved in this transition, collisions and radiative processes have a long time to establish equilibrium.

The very small probability of transition requires that the H I line has a very narrow natural linewidth, $\Delta\nu_N = A_{21}/2\pi = 4.5 \times 10^{-16}$ Hz. In practice the linewidth for a single atom is determined by collisions, for typical ISM density and thermal velocity parameters of $n \sim 1$ cm^{-3} and $v \sim 1$ km s^{-1}, the linewidth is $\Delta\nu_N \sim 10^{-11}$ Hz. Because of the narrow width of the H I line, linewidths from a finite volume are due exclusively to Doppler broadening. The line therefore makes an excellent probe of the thermal properties and motions of the ISM.

At centimeter wavelengths, where the Rayleigh-Jeans limit ($h\nu \ll kT$) applies, the radiative transfer equation can be written in terms of brightness temperature, T_b, as

$$\frac{dT_b(\nu)}{d\tau(\nu)} = T_s - T_b(\nu), \tag{1.1}$$

where τ is the opacity along the line of sight, T_b is the brightness temperature and T_s is the spin or excitation temperature. In order to develop an intuitive feel for the H I radiation mechanism, we consider a single, isothermal gas cloud, in which case the radiative transfer equation is solved in terms of the velocity with

$$T_b(v) = T_s\left[1 - e^{-\tau(v)}\right] + T_{bg}e^{-\tau(v)}, \tag{1.2}$$

where T_{bg} is the background radiation incident on the cloud. The H I line is either seen in absorption, if $T_s < T_{bg}$, or emission, if $T_s > T_{bg}$. If there is no background source and the gas is optically thin ($\tau(v) \ll 1$) then $T_b(v) = T_s\,\tau(v)$. Alternately, if the gas is optically thick ($\tau(v) \gg 1$), then $T_b = T_s$. However, in the real ISM T_s and τ vary along the line of sight making equation 1.1 difficult to solve. If we instead consider just an integration along the line of sight (or over velocity) we find that $\int T_b(v)dv \propto N_H$, where N_H is the column density of neutral hydrogen along the line of sight. It is therefore clear that $\tau(v) = N(v)/(C \times T_s)$, where $C = 1.8 \times 10^{18}$ cm^{-2} K^{-1} (km s^{-1})$^{-1}$ for low values of τ.

1.3.2 Large Scale Structure

On the large scale, interstellar gas moves within the Galaxy in a manner that is dictated by the gravitational potential of the stars and dark matter. At the Solar circle gas orbits the Galactic Center with a velocity of 220 km s^{-1}. Surprisingly little is known about the spiral structure of the Galaxy. We believe that it is a four arm spiral, though evidence suggests that it may be a two arm spiral, or a four-two composite (Englmaier & Gerhard 1999; Fux 1999). Resolving this question is complicated by our lack of perspective.

The rotation curve of the Galaxy is a crucial item to studies of Galactic structure as it is used to determine kinematic distances to Galactic objects. The dynamics of the rotation are governed by the following set of equations. The Galactic coordinate system defines Galactic longitude, l, and Galactic latitude, b, measured with respect to the Sun. Longitude of zero is in the direction of the Galactic center and $l = 180°$ is the anti-center. Latitude $b = 0°$ defines the mid-plane of the disk at the position of the Sun. Galactocentric radius, R_g, is the radius with respect to the Galactic Center defined as:

$$R_g = (R_0^2 + d^2 - 2R_0 d \cos l)^{1/2}, \tag{1.3}$$

where R_0 is the distance of the Sun from the Galactic center, accepted by the IAU as 8.5 kpc, and d is the distance of the object from the Sun. An object with a circular orbit about the Galactic center has an angular velocity, ω defined as

$$\omega = \frac{V_r}{R_0 \sin l \cos b} + \omega_0, \tag{1.4}$$

where V_r is the radial velocity of the object and ω_0 is the angular velocity of the Sun about the Galactic center such that $\omega_0 R_0 = 220$ km s^{-1}. Fich et al. (1989) fit the rotation curve using H I tangent point velocities and CO emission line velocities with associated spectrophotometric distances to H II regions. The result is a linear fit given by:

$$\frac{\omega}{\omega_0} = 1.00746 \left(\frac{R_0}{R}\right) - 0.017112. \tag{1.5}$$

Throughout this work we employ the Fich et al. (1989) curve for kinematic distances.

1.4 H I Shells

H I shells, as a class of objects, significantly impact the structure and evolution of the ISM and may drive interstellar turbulence. By injecting large quantities of energy into the ISM, these shells reshape galaxies on size scales of tens to thousands of parsecs and may trigger new star formation. H I shells and supershells have long been studied in external galaxies, as well as in our own Milky Way, as a probe of the star formation feedback processes in the interstellar medium (e.g. Westerlund & Matthewson 1966; Heiles 1979). Studies of external galaxies, in particular, recent studies of the Large and Small Magellanic Clouds, indicate large populations of shells and supershells, which dominate the structure of the ISM (Staveley-Smith et al. 1997; Kim et al. 1998). Unfortunately, much less is known about H I shells in the Milky Way. The population of known Galactic H I shells is extremely varied, few shells are circular and none are "typical." There are many shells with radii on the order of a few tens of parsecs, while others have radii up to a kiloparsec. Shells are also observed in all stages of their evolution, from small and rapidly expanding, to large and stalled. Because the shell walls often contain $\sim 10^6$ M$_\odot$ of swept-up mass, the kinetic energy of expanding shells can be of the order of 10^{51} ergs.

We believe that most shells are formed by the combined effects of stellar winds and supernovae. This explanation is particularly convincing for smaller shells, with diameters of a few tens of parsecs. In some cases shells can even be directly associated with individual H II regions, supernova remnants or stellar complexes (Normandeau et al. 1996; Rizzo & Arnal 1998). The larger shells, however, are much more enigmatic. They seem to require unreasonably large ($> 10^{53}$ ergs) formation energies in order to maintain large expansion velocities of $v_{\rm exp} \sim 20$ km s^{-1} at radii in excess of a few hundred parsecs. If these shells were indeed formed by stellar winds and supernovae, as many as a few thousand massive stars must have lived and died within a radius of several tens of parsecs to create the supershells. While that is possible, it requires several generations of star formation. Other, more energetic phenomena, have been suggested to account for the seemingly unreasonable formation energies, including impacts of high velocity clouds (HVCs) with the Galactic disk (Tenorio-Tagle et al. 1987) or hypernovae and/or gamma ray bursts (Loeb & Perna 1998). However, with the relatively small sample of known shells in the Milky Way it is difficult to determine which formation mechanisms are at work.

For the largest, and therefore the oldest, shells, expansion can exceed the scale height of the H I layer of the Galaxy. Such expansion will elongate along the axis perpendicular to the Galactic plane, as predicted by theories of expansion into a stratified medium (e.g. Kompaneets 1960). In this case, at the interface between the dense, thin and diffuse disks the shell will become Rayleigh-Taylor unstable and break-out into the Galactic halo. These so-called "chimneys" provide a source of gas, thermal support and chemical enrichment for the halo and therefore play a potentially crucial, though poorly understood, role in the exchange of matter between the disk and halo. There are two separate theories on the process of disk-halo mass exchange: the classic Fountain model (Shapiro & Field 1976; Bregman 1980) and the chimney model (Tomisaka & Ikeuchi 1986; Norman & Ikeuchi 1989). The models differ in the process that supplies gas to the halo - the Fountain model relying on buoyantly rising gas and the chimney model relying on gas expelled through many, clustered supernovae - but the fate of the gas is the same in both models. In both cases the hot gas expelled to the halo cools and condenses into clouds that are expected to descend onto the disk in the form of high or intermediate velocity clouds. Despite these theories there is little evidence of the Galactic Fountain and very few chimneys have been found.

1.4.1 Why study H I shells?

With lifetimes on the order of tens of millions of years, H I shells survive much longer than the radiative lifetimes of their parent H II regions and supernova remnants (SNRs). The ultimate destruction of an H I shell occurs when the shell dissipates as a result of turbulent motions in the interstellar medium and shear due to differential rotation in the Galaxy (Tenorio-Tagle et al. 1987; Dove et al. 2000). These processes, which operate on timescales of 20-40 million years, slowly erase shells from view. The shell therefore provides a lasting fossil of stellar life and death with which we can attempt to understand the impact of massive stars on the ISM.

The new high resolution surveys of H I in the Galactic Plane, such as the CGPS and SGPS, offer us the chance to study the dynamics, density and distribution of H I shells in the Milky Way and address their impact on the ISM and Galactic structure. Unfortunately, in the inner Galaxy, where they are most likely to occur because of high star formation rates, they prove difficult to detect due to distance ambiguities. As a result, our knowledge of how dramatically the Galaxy has been shaped by shells is limited.

1.5 Structure of this Work

This work presents the SGPS and focuses primarily on H I shells in the Southern Galactic Plane. The text is organized into two main sections, the Parkes portion of the survey and the Australia Telescope Compact Array (ATCA) portion of the survey. In the first section we describe the data taking and analysis procedures for the Parkes survey. These are followed with results derived directly from that data set, in particular, studies of large H I shells. Here we hope to address questions about how large, energetic H I shells form and what effect H I shells have on the global ISM. We will present a new H I shell catalog for the SGPS region and explore several examples within it.

The second section describes the ATCA survey and results. In that section we explain the observations and analysis procedures with particular attention to problems encountered and solutions developed. We discuss the basics of mosaicing and single dish-interferometer data combination. The full survey data are presented. We also present an analysis of the SGPS test region, where we demonstrate several different studies that can be accomplished with the survey data. We conclude with an analysis of the distribution of H I shells in the Galaxy and address plausible explanations for some of the more energetic shells.