Part 5

Galactic Surveys and Extended Emission

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Galactic Plane Surveys at Low Frequencies

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Abstract. Until recently, high angular resolution and high sensitivity surveys of the radio emission from the plane of our Galaxy were available only at frequencies of several GHz, where large single dish radio telescopes provide arcminute scale angular resolution. At these frequencies thermal radiation from HII regions and diffuse ionized gas comprise a major component of the Galactic emission. Advances in wide field interferometric imaging techniques now make it possible to carry out high sensitivity surveys of the Galaxy with arcminute scale angular resolution at 1.4 GHz and below. Over the past few years initial synthesis surveys have been made. More ambitious surveys that combined sensitive continuum observations with full polarimetry and images of the 3-dimensional structure of atomic hydrogen gas at pc scales are currently underway in the northern (DRAO) and southern (ATNF) hemispheres. The interstellar medium of the Galaxy contains structure on all spatial scales, and these surveys combined data from aperture synthesis telescopes and signal dish antennas to provide full spatial frequency coverage to the resolution limit. Preliminary results reveal wide-spread features and processes in the the interstellar medium that are not readily visible by other means, including, for example, unusual atomic hydrogen structures related to the vertical transfer of matter and radiation between the disk and halo of the Galaxy, Faraday rotation structures that allow study of the magnetic field and diffuse ionized component in the plane of the Galaxy, and a cold atomic phase of the neutral medium that may provide a link between global shock phenomena in the galaxy and the formation of molecular clouds.

1. Introduction

Surveys of the Milky Way Galaxy at low radio frequencies have been central to advancing our understanding of the structure of the Galaxy and the nature of the interstellar medium. Early radio continuum surveys, culminating in the 408 MHz, all-sky map of Haslam et al. (1982) with $\sim 1^\circ$ angular resolution, characterised the basic properties of the radio Galaxy, demonstrating, for example, that the low frequency continuum of the Galaxy is dominated by disk emission from synchrotron radiating electrons in the diffuse interstellar medium. Similarly, HI surveys in the 1960's and 1970's, (e.g. Weaver & Williams 1973; Cleary et al. 1979) delineated the global structure of the Galaxy within and beyond the stellar disk.

In the following decade, higher resolution observations of large sections of the plane were obtained using the largest available telescopes. Outstanding examples are the Bonn surveys at 1.4 GHz (Kallas & Reich 1980) and 2.7 GHz (Reich et al. 1985). This "golden age" of single-dish surveys allowed the separation of the discrete component of the Galactic radio emission from the background radiation, revealing and classifying large numbers of supernova remnants and HII regions. At the same time HI imaging provided data on atomic hydrogen in selected regions of the plane at $\sim 10'$ resolution (e.g. Braunsfurth 1983).

In the 1990's powerful radio interferometer arrays began to be utilized to carry out arcminute scale resolution surveys of the continuum radiation from the Galaxy. Surveys at 327 MHz (Taylor et al. 1997), 840 MHz (Green et al. 1999) have provided striking images of the diffuse ionized gas in the ISM and a more complete census of supernova remnants, that are unresolved or confused at lower resolution (Taylor et al. 1992).

These observations, and others at millimetre and infrared wavelengths have shown that the interstellar medium is a complex system. Yet, despite several decades of intense observations, our knowledge of this system is still very much in the formative stage. Fundamental questions that remain unanswered are numerous. What is the detailed evolutionary relationship between the phases of the ISM? What role does the disk-halo interaction play in the star formation history of the Galaxy? How can we characterise the topology and structure of the ISM? What are the main transport mechanisms for mass and energy among the components? Where and how are steady-state conditions achieved? Definitive answers to these questions require knowledge of the 3-dimensional structure and conditions of the ISM over the disk of the Galaxy and over the full range of spatial scales, from the parsec scale typical of stellar separations and clustering, to the kiloparsec scale of spiral arm patterns. Ambitious new surveys are now underway to address this need.

2. Interferometric Surveys of Continuum and Atomic Hydrogen

2.1. The Canadian Galactic Plane Survey

The Dominion Radio Astrophysical Observatory (DRAO), in collaboration with a consortium of university astronomers, is engaged in the Canadian Galactic Plane Survey (CGPS), a project to map the atomic hydrogen and radio continuum emission within the region ($74° < l < 147°$, $-3.6° < b < +5.6°$).

The DRAO synthesis telescope is a seven-element, east-west array with maximum baseline of 604 metres. The array elements are 9-meter parabolic antennas, each equipped with receivers to simultaneously observe in the radio continuum at 408 MHz and 1420 MHz, and in 256 spectral line channels at HI. The basic parameters of the survey are list in Table 1. The synthesis field of view is 2.5° at 1420 MHz and 8° at 408 MHz. A complete synthesis of the field of view requires 144 hours of observations: twelve hours of observations at each of twelve configurations of the array. These combined observations provide regular sampling of baseline spacings from the maximum of 604 meters down to 12.9 meters. Image dynamic ranges of several thousand are achieved by self-calibration of the data and careful removal of the effects of strong source outside the primary field of view.

At 1420 MHz continuum, all polarisation products are observed. Since the array antennas have equatorial mounts, the parallactic angle of the feeds is constant during the course of a synthesis and instrumental polarisation terms are nearly constant. Observations of a strong unpolarised source (3C 295) over the field were used to derive the instrumental polarisation corrections for the full field of view. After correction, the instrumental polarisation in mosaic images of linearly polarised emission is less than 0.3% of Stokes I at the field centres and less than $\sim 1\%$ everywhere in the image.

Table 1. The Canadian Galactic Plane Survey

Frequency	Sensitivity (1σ)	Angular Resolution	Resolution Sampling
408 MHz	3 mJy beam^{-1}	$3.5' \times 3.5'$ cosec δ	
1420 MHz (I,Q,U,V)	0.20 mJy beam^{-1}	$1' \times 1'$ cosec δ	
HI line	3 K	$1' \times 1'$ cosec δ	0.82 km s^{-1}

Complete coverage of the survey region is achieved by a hexagonal grid of 190 synthesis fields. At 144 hours per field, the survey will take 5 years to complete. Observations are scheduled for completion in April 2000.

In the Galactic plane, emission is present on all spatial scales, and it is critical to fully sample the spatial frequency domain of the synthesis images. Synthesis information on spacing shorter than 12.9 m is obtained in the continuum for Stokes I from the surveys of Reich et al. (1997) for 1420 MHz and Haslam (1983) for 408 MHz. In the HI line, short spacing data is obtained by observations with the DRAO 26-m telescope.

2.2. The Southern Galactic Plane Survey

The Southern Galactic Plane Survey (SGPS) (Dickey et al. 1999) is a 21-cm line and continuum mapping project covering the Galactic plane over the region ($253° < l < 357°$, $-1° < b < 1°$). The survey combines data from the multi-beam system on the Parkes 64m single dish telescope with data from the Compact Array interferometer, which is an array of six 22m telescopes configurable on an east-west track. Both telescopes are part of the Australia Telescope National Facility (ATNF). The Compact Array observes simultaneously in line and continuum. The specifications of the survey are listed in Table 2. The sensitivity and HI line spectral resolution are almost identical to the CGPS project in the north.

Observations will be completed in early 2001. With the Compact Array, interferometer spacings are complete out to 375 m and some coverage is obtained between 375 and 750 m. This gives maximum brightness sensitivity when tapered to a $2'$ beam, but maps with resolution of $1'$ will also be made.

Table 2. The Southern Galactic Plane Survey

Frequency	Sensitivity (1σ)	Angular Resolution	Resolution Sampling
1420 MHz (I,Q,U.V)	0.25 mJy	$2' \times 2'$ cosec δ	
HI line	2.6 K	$2' \times 2'$ cosec δ	0.82 km s^{-1}

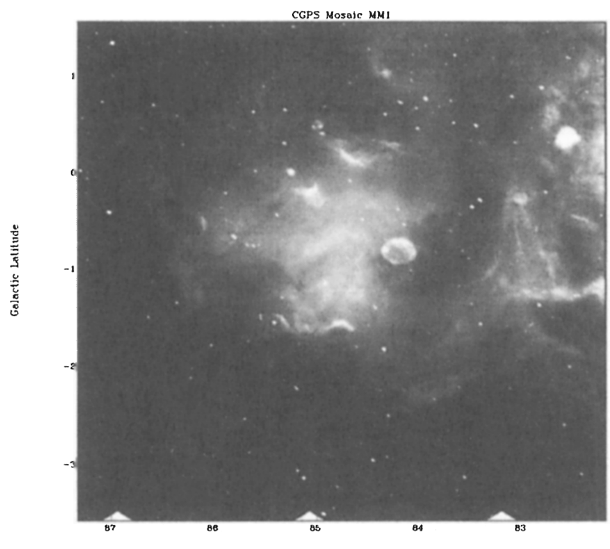

Figure 1. A sample image from the CGPS showing a $5.1° \times 5.1°$ area of the Cygnus-X region.

3. Radio Continuum Images

An example of a 1420 MHz continuum image from the CGPS is shown in figure 1. The image is dominated by bright filaments of diffuse ionized gas and supernova remnants. The image contains all spatial frequencies down to the $1'$ resolution limit, and is essentially artifact free. The dynamic range is limited by the thermal noise in the image of ~ 0.2 mJy $beam^{-1}$.

Figure 2 shows Stokes I and polarized intensity images from the CGPS of another area containing Lynds Bright Nebula 679. Outside of the region of the bright thermal filament visible in the Stokes I image, polarised emission is present with a wide range of spatial scales. This effect is ubiquitous in the CGPS images. Early results from other polarisation images were reported by Gray et al. (1998, 1999). In general, structures seen in polarised emission are not replicated in total intensity, leading to the conclusion that the polarised emission is an effect of a foreground Faraday screen comprised of the magneto-ionic com-

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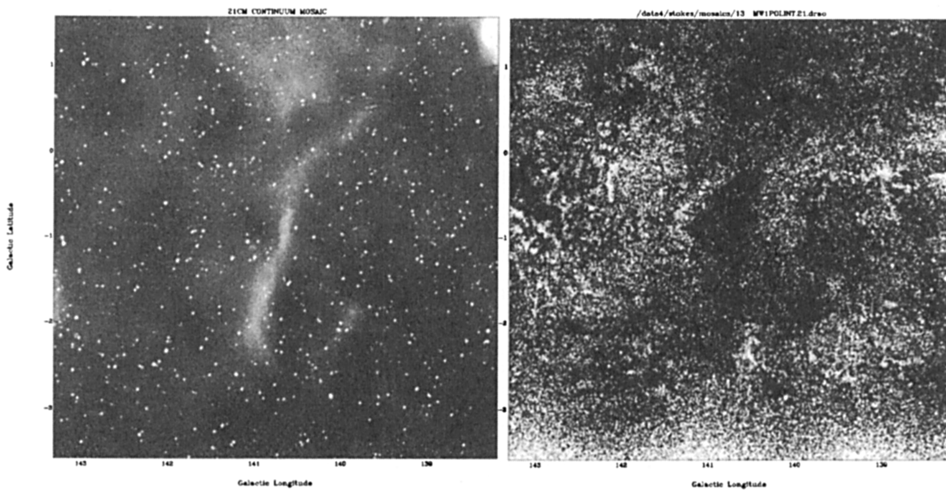

Figure 2. Polarised emission structures produced by differential Faraday rotation by the magneto-ionic component of the Interstellar Medium. The left image is a 5.1 × 5.1 degree map of the Stokes I, 1420 MHz emission from a region around the Lynds Bright nebula 679. The right image is the polarised intensity from the same region.

ponent of the ISM. Such structures have also been seen with the Westerbork Synthesis Radio Telescope at 327 MHz (Wieringa et al. 1993). Figure 3 illustrates how spatial changes in the polarisation angle of a uniform polarised background field can produce structures in polarised intensity. Rotation of the polarisation angle imposes intensity structure in Stokes Q and U that remains after the interferometer removes the spatially constant "background" emission.

Figure 2 also illustrates that where the thermal emission measure is high, the background radiation is completely depolarised. This arises from "beam depolarisation", when the scale over which the polarisation angle varies becomes smaller than the beam. This result suggests that the characteristic size of the Faraday rotation "cells" decrease near regions of bright diffuse HII; further suggesting that the homogeneity of the Faraday screen is related to the average electron density of the ISM, or that HII regions have diffuse halos that energize and disturb a larger surrounding region of the ISM.

Since the rotation measure of the Faraday screen is given by the product of electron density and magnetic field along the line of sight, knowledge of the average electron density from the bremmstrahlung emissivity allows information to be extracted on the interstellar magnetic field. The excess rotation of the polarisation angle by passage through a region of uniform electron density and magnetic field is given by $\Delta\psi = 46\lambda^2 n_e B_{||} L$ degrees, where n_e has units of cm^{-3}, $B_{||}$ μG and L pc. The interstellar magnetic field is characterised by a uniform component and a random component with roughly equal magnitude of a few μG. Setting n_e and $B_{||}$ to typical ISM values and $\lambda = 21$ cm yields

$$\Delta\psi = 105° \cdot \left(\frac{n_e}{0.1\mathrm{cm}^{-3}}\right)\left(\frac{B_{||}}{5\mu\mathrm{G}}\right)\left(\frac{L}{100\mathrm{pc}}\right).$$

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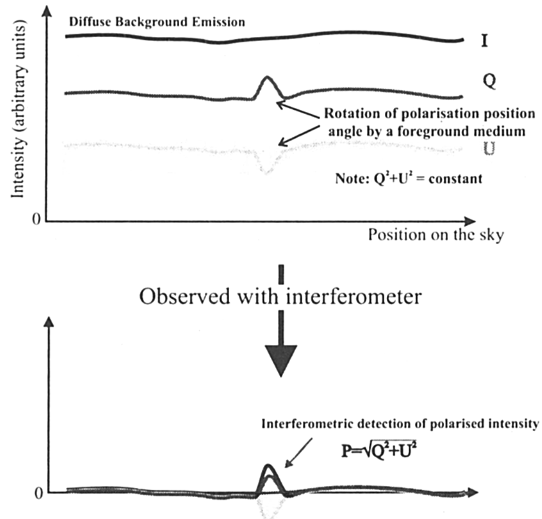

Figure 3. When observing with an interferometer, structure in polarised intensity, with no corresponding Stokes I counterpart, can be produced by spatial structure in the polarisation angle of a background polarised radiation field.

This equations demonstrates that observations with resolution $\sim 1'$ at $\lambda 21$ cm are ideally suited for studies of the random component of the magnetic field in the disk of the Galaxy. At typical distances of a few kpc, $1'$ corresponds to a linear dimension of a few pc, and regions with dimension of 10s of pc will produce incremental rotation angles of a few 10s of degrees. Because of the λ^2 dependence, at shorter wavelengths the effect is much reduced and difficult to measure. At longer wavelengths rotation is so large that differential effects within the beam and along the line of sight leads to depolarisation of signals.

3.1. Atomic Hydrogen

The arcminute resolution HI images are revealing previously undetected features that are shaped by the vertical ejection of material and radiation from the Galactic disk. Examples are the Galactic Chimney (Normandeau et al. 1996) and the Galactic Mushroom (English et al. 1999). Such phenomena cannot be detected in observations of even the most nearby external galaxies, due to lack of spatial resolution.

The HI Galactic Chimney, also traceable in Hα and CO, is a striking confirmation of certain aspects of the "chimney model" in which hot gas from supernovae and stellar winds is expelled into the halo though conduits which form above massive star forming regions. In the case of the Galactic Chimney, the outflow can be explained by stellar winds alone from the hot stars associated with the W4 HII complex below it. In contrast, the 340 pc high Galactic Mushroom (Figure 4) resembles the mushroom cloud of an atomic bomb blast, and can be described by similar physics.

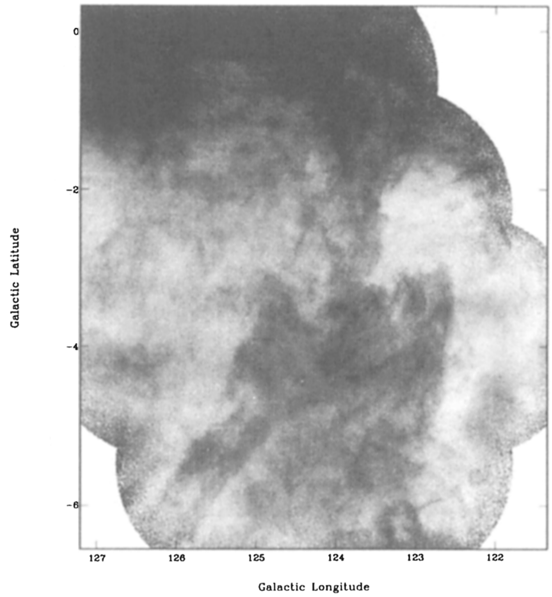

Figure 4. The "Mushroom Cloud" HI feature extending vertically downward several hundred parsecs out of the Galactic Plane (English et al. 1999).

New HI supershells are also being discovered, which shows tentative evidence for breakout on both sides of the disk (McClure-Griffiths et al. 1999).

HI self-absorption by cold atomic hydrogen has emerged from the CGPS and SGPS data as a striking feature of the 21-cm channel maps, with complex wispy and filamentary shapes ranging in size from one degree down to the arcminute limits of resolution (Figure 5). High angular and spectral resolution is critical to this study. The population revealed at $1'$ resolution is far richer and more diverse than expected from single dish surveys, whose large beams dilute most features into invisibility. Surprisingly, many of the strongest absorbing features in the CGPS, which are found in the Perseus arm (Gibson et al. 1999), lack clear associations with CO or dust emission, in contrast to the traditional equilibrium picture of cold atomic hydrogen as a trace constituent of molecular clouds. Since these strong features occur predominantly at velocities expected for the spiral wave shock, they may represent HI cooling and condensing into molecular gas downstream of the shock in the first step toward star formation.

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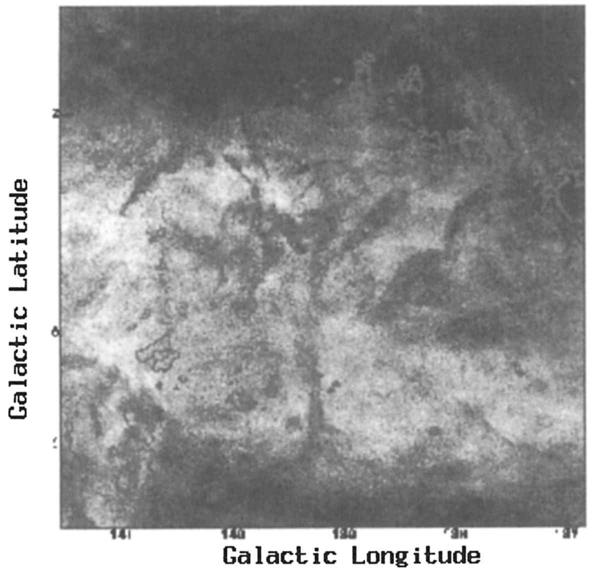

Figure 5. HI 21cm channel map of a CGPS field rich in self-absorption features. This LSR velocity of $-41\,\mathrm{km\,s^{-1}}$ is characteristic of gas in the Perseus spiral arm.

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