The Australian National University

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PhD Thesis Proposal

The Galactic Warm Partially Ionised Medium: A Hidden Phase of the ISM?

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Introduction

The interstellar medium (ISM) is the material from which stars form and to which stellar material returns when a star dies. The ISM is responsible for the transport of heat and matter through the Galaxy, driving its evolution. In the study of the ISM of the Milky Way lie the answers to vital questions about our Galaxy: What do the stars form from? What happens to the material that leaves the stars? What drives the evolution of our Galaxy as a whole?

The important role the ISM plays in the Galaxy is demonstrated in simulations such as EAGLE (Schaye et al., 2015). Segers et al. (2016) use these simulations to determine the importance of the recycling process of stellar ejecta. They determined that in Milky Way type galaxies recycled stellar mass constitutes 35% of the star formation rate and 20% of the stellar mass. These results demonstrate the importance of the ISM as a transporter of metals and heat throughout the Galaxy.

The material that forms the ISM is highly tenuous, representing only $\sim$ 10 - 15% of the total Galactic mass in the disk. It is highly inhomogeneous, however, forming great structures which exhibit tremendous variations in temperature and density. The ISM is also composed of many different constituents, namely atomic and ionised hydrogen, molecular gas, dust, cosmic rays, and magnetic fields (Ferrière, 2001). All the components play important roles in shaping the evolution the galaxy, and interact with each other on various scales.

The study of atomic hydrogen in the ISM has been ongoing since the first detection of the H I 21 cm line by Ewen and Purcell (1951). Since then our understanding of the composition and nature of gaseous ISM components has grown enormously. Currently, we understand interstellar atomic hydrogen to exist in many different 'phases'. Here a 'phase' refers to the broad properties that a region of gas will hold in common. In general, the gas will exist in cool molecular clouds where gravity is the prevailing force, or in diffuse regions where thermal, turbulent, and magnetic forces dominate (Heiles and Haverkorn, 2012). The diffuse ISM can again be classified into distinct phases; including both neutral and ionised phases (see Section 2.1 for details).

The phases of the ISM exist within and are often formed by structures within the Galaxy. These structures are as varied as the gas that forms them. They can be generally categorised as discrete, filamentary, and turbulent. Discrete structures include supernovae (SN) remnants, shells, and supershells. Structures such as supershells can break up over time and form into filamentary material (Heiles, 1979). Additionally, this process releases diffuse material into new areas of the Galaxy, which is then dominated by turbulent forces (Tomisaka, 1998; Heald, 2012).

1.1 Motivation

Despite huge gains in the understanding of the ISM and its components, much remains unknown regarding how the components interact with each other (Landecker, 2012; Heald, 2012; Heiles and Haverkorn, 2012).

This is particularly true of magnetic fields and how they interact with the ISM. It is understood, however, that magnetic fields play a vital role in the structure and formation of galaxies. This is due to most of the visible matter in the universe being ionised (Beck and Wielebinski, 2013). Even the material in the ISM that is classified as 'neutral' has an ionised component (McKee and Ostriker, 1977; Heiles, 2001; Heiles and Haverkorn, 2012). It has been recently argued by Heiles and Haverkorn (2012) that this partially ionised medium is likely very common, despite its lack of recognition in the literature. This is mostly due to the difficulty in directly observing this phase.

Despite the time over which the ISM has been studied, many of the surveys conducted in the past have not allowed for analysis of fine structure. This state is now changing rapidly as new surveys come online such as GASS for H I (McClure-Griffiths et al., 2009), GMIMS (Wolleben et al., 2009) and S-PASS (Carretti et al., 2006) for diffuse polarisation, and NVSS for rotation measure (Condon et al., 1998). These surveys allow for the study of structures within the ISM in fine detail, and the comparison of different components within these structures. H I surveys such as GASS trace the neutral hydrogen in the ISM as well as its kinematics. Diffuse polarisation surveys including GMIMS and S-PASS contain information on both the ionised ISM and magnetic fields. This is because polarised emissions are produced by synchrotron radiation from relativistic electrons. These emissions are also sensitive magnetic fields via Faraday rotation.

My thesis will study the warm ionised, the warm neutral, and partially ionised medium of the Galaxy and determine how they interact with Galactic magnetic fields. This will be done through comparison of the latest H I and diffuse polarisation data in combination with supporting observations such as NVSS rotation measure sources. The comparison will be focused through a series of case studies, each focusing on a different physical process within the ISM. As described above, these features include discrete objects such as supershells, filamentary structures, and turbulent material. Each of these different processes present a unique case in terms of interactions of ISM components.

Background

2.1 Components of the ISM

The ISM of the Milky Way is a diverse, bubbly, and cloudy place. In such a state it useful to classify different components of the ISM in order to guide both observations and analysis. Most broadly we can consider the ISM as composed of dust and gas. Whilst the dusty component of the ISM has a significant impact on the optical properties of the Galaxy, the focus of this review will be on the gaseous component. Gas represents roughly 99% of the mass of the ISM (Li and Draine, 2001). Thus, understanding the dynamics and interactions of this gas is key to a understanding the dynamics and evolution of the Galaxy as a whole.

Work regarding the classification of the components of interstellar gas has been under way for some time, and has evolved greatly (McKee and Ostriker, 1977; Cox and Reynolds, 1987; Heiles, 2001; Cox, 2005). Heiles and Haverkorn (2012) present the most recent and complete system of ISM classification in the form of a five phase model. As before, a 'phase' refers to the broad properties of gas in a given state. The model builds upon the system originally presented in McKee and Ostriker (1977). Heiles and Haverkorn review the 'classical' phases which are presented in previous work and argue for a new phase which may prove to be great relevance to this research.

2.1.1 A Five Phase ISM?

The four classical phases presented by Heiles and Haverkorn (2012) are the Cold Neutral Medium (CNM), the Warm Neutral Medium (WNM), the Warm Ionised Medium (WIM) and the Hot Ionised Medium (HIM). The difference between each phases arise from their distinct properties, which in turn causes appearance in different observational modes. The details of different observational methods are discussed later in this paper (see Section 2.4). These phases are described as 'classical' because their properties are well documented and studied in observational data and have a strong basis in theoretical models. Heiles and Haverkorn introduces the idea of a new phase; the Warm Partially Ionised Medium (WPIM). They argue the WPIM is deserving of its own category, despite a current lack of strong observational support. This is not due to this phase being unimportant. On the contrary, the WPIM is, due to ionised partially ionised nature, influenced by and has effects on magnetic fields. Therefore, the WPIM contains a significant fraction of the energy density of the ISM. Rather the difficulty lies in going about detecting it. Observations such as Hα trace electron density (n_e) as n_e^2, and thus the partially ionised medium does not have the free electron density to appear in Hα. This is somewhat indicative that new methods of observation are required to study this new phase. This thesis aims to develop the required method of observing the WPIM by combining multi-wavelength radio data. A summary of some the typical observed values for the WPIM and the other phases are given in Table 2.1.

Heiles (2001) outlines the classical ISM model presented in McKee and Ostriker (1977). In this model the CNM is found in outer shell of supernova remnants. More recent modelling, however, demonstrates that the CNM is likely to exist in a stable two-phase medium, with the WNM out to a galactocentric of $R \approx 16 - 18\,\mathrm{kpc}$ (Wolfire, 2004). The CNM can be heated from its typical temperature 50 K by soft X-rays which escape through the walls of a supernova remnant. These X-rays act on the CNM to produce the WMN, which has a typical temperature of around 6000 K. Additionally, the escaping X-rays also produce the WPIM by photoionisation. In the case described here the two neutral phases are in thermal equilibrium.

In order to form the WIM more input energy is needed than in the formation of the WNM. This extra energy is required to both photoionise and heat a given region of gas to a typical WIM temperature of 8000 K. This being the case, Heiles (2001) summarises that UV photons from starlight are the typical source of such energy. As such, the WIM typically forms in the outer parts of H II regions or 'H II -like' structures. The HIM, by contrast, is produced shocks from supernova explosions. The shock process yields far higher temperatures than the other phases; on the order of 10^6 K. Shocks are typical of supernova remnants and supershells, which is where the HIM is observed. Details and origins of these structures in the ISM are discussed in Section 2.3.

Property	CNM	WNM	WIM	WPIM	HIM
T (K)	50	6000	8000	7000	1.6×10^6
n_{H} (cm^{-3})	80	0.7	0.25	0.2	0.0034
$\frac{n_e}{n_{\mathrm{H}}}$	2×10^{-4}	1×10^{-3}	1	0.5	1

Table 2.1: Portion of Heiles and Haverkorn (2012): Table 1. Here T is the typical temperature, n_{H} is the number density of hydrogen nuclei and n_e is the number density of electrons.

The intention of this thesis is to study the WNM, the WPIM, and how they interact with magnetic fields. The classification of the WPIM as a distinct phase is new, and as such detailed observations of its properties and interactions are yet to be conducted.

2.2 Influence of Magnetic fields on the ISM

Magnetic fields are known to play an important role in the ISM, and yet much is still unknown regarding their interactions within the ISM (Beck, 2001; Han, 2001; Landecker, 2012). As established previously, much of the ISM is ionised, with even the neutral medium containing a partially ionised component. The ionised fraction of the WNM has been found between 2% and 8% (Foster, Kothes, and Brown, 2013). The former value was derived by Wolfire et al. (1995) from a two-phase neutral ISM model, whereas the latter was found by Jenkins (2013) from measurement of electron column density. The fact that much of the ISM is ionised means that magnetic fields play a pivotal role in governing the ISM. This occurs through both magnetic locking and Lorenz forces. Magnetic fields are known to contribute to a number of ISM processes including total gas pressure, flow along spiral arms, cosmic ray acceleration, and star formation conditions (Beck, 2004; Landecker, 2012). It is typical to consider Galactic magnetic fields on two broad scales. There exist large-scale fields on the same size scale as the spiral arms of the Galaxy, and small-scale fields whose interactions are on the scale of stars and other intra-arm processes.

Landecker (2012) reviews the Galactic magnetic fields by way of observations in diffuse polarisation (see Section 2.4). Landecker notes that despite the theoretical 'promise' of diffuse polarisation observations, the technical difficulty of measuring Galactic magnetics fields has proved to be a challenge. Much progress has still been made, however, which now opens up new avenues of investigation. Sun et al. (2008) were able to constrain both the ordered (large-scale) and a random (small-scale) field values at the solar radius to $2\,\mu\mathrm{G}$ and $3\,\mu\mathrm{G}$, respectively. These observed values are somewhat lower then expected when assuming equipartition of energy (Beck, 2004). Magnetic fields are also observed to have far higher values within certain dense regions the ISM, with magnitudes as reaching $30\,\mu\mathrm{G}$. The areas that contain such high values indicate that the field is being compressed along with the plasma. This too is true of the local random field, whose magnitude exceeds the ordered field value. Structures that could drive such compression are discussed in Section 2.3.

A key message from both reviews and research papers on the Galactic magnetic field is that it should be considered an important component of the ISM, and not distinct from it. Much like the phases of the ISM, the magnetic field interacts, influences, and is influenced by the other components in the ISM. This is well demonstrated in Figure 2.1 (Heiles and Haverkorn, 2012). This figure shows that approximate energy density of the Galactic magnetic fields are on order of magnitude equivalence with other components of the ISM. It is possible to conclude from this that the energy density from magnetic fields is on rough equipartition with pressure from turbulent and thermal gas (Heiles and Haverkorn, 2012). It is important, then, to analyse Galactic magnetic fields in the context of their interactions with various parts of the ISM (Landecker, 2012).

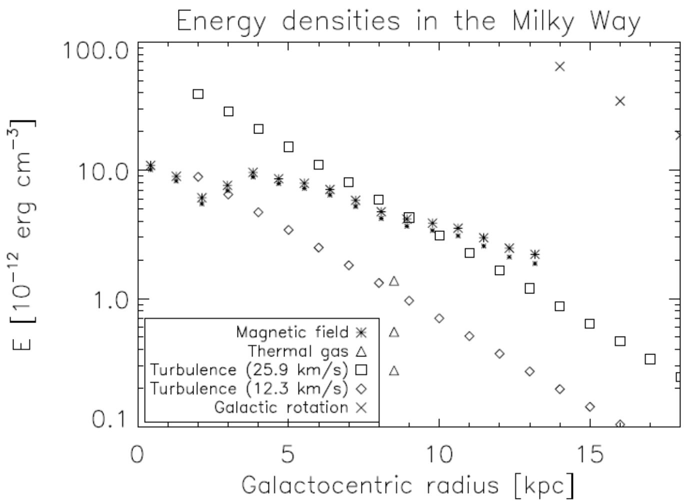

FIGURE 2.1: Heiles and Haverkorn (2012): Figure 1. Energy density in the Milky Way, by component: "...magnetic field according to the revised (large asterisks) and the classical equipartition formula (small asterisks); gas with a velocity dispersion of 25.9 km/s (boxes) and of 12.3 km/s (diamonds); thermal gas at the solar radius for the WPIM, CNM/WNM/WIM and HIM components (triangles); and Galactic rotation (crosses)"

2.3 Structures Within the ISM

2.3.1 Discrete Structures

The ISM is far from a static and idle environment. It is pervaded by bubbly and turbulent structures which are in the process of breaking, fragmenting and interacting with each other. Many of these structures, however, are deterministic in origin. Heiles (1979) outlined the observed structures of H I and the sources driving them. Much of this structure is driven by injections of energy by hot OB stars and supernovae explosions. Such sources are at least partially isotropic there therefore they blow out spherical bubble-like structures. These structures grow in size over time as more energy is injected into them. They also break apart as they interact with other components of the ISM. Studying these structures is an excellent way of performing Galactic archaeology as the processes that formed them leave their trace in the morphology of the shells (McClure-Griffiths et al., 2002).

H I shells are driven by a combinations of hot OB stellar winds and supernovae explosions, which provide energies on the order of 10^{51}-10^{53} ergs (McClure-Griffiths et al., 2002). The term 'supershell' is used to describe objects with input energies greater than about 3×10^{52} ergs (Heiles, 1979). McClure-Griffiths et al.

outline, that despite H I shells being valuable method of analysing and quantifying the structure ISM past H I surveys have lacked the sensitivity, resolution and coverage needed for a complete picture. However, as the latest H I emission surveys are being analysed more of these structures are being discovered which opens up a great resource for studying the ISM.

Work on the H II region W4 provides examples of the results that can be obtained by studying these structures. The morphology of the superbubble was analysed by West et al. (2007) and its magnetic properties were determined by Gao et al. (2015). In their morphological analysis West et al. (2007) found this structure to be a superbubble in the process of fragmenting into a chimney structure. Galactic chimneys are formed by the breaking of a bubble's wall, which allows the release of the hot ionised material within into upper parts of the Galaxy. In the follow up to this work Gao et al., 2015 used polarised radio data to determine the magnetic field properties of the shell. Using a Faraday screen model they found strong regular fields along the walls of the shell. By analysing the signs of the derived RM values they also concluded that the field matched the hypothesis that the field in the shell had been dragged and compressed out of the Perseus arm. Additionally, they determined that the magnetic and thermal pressures were roughly equal in the upper parts of the shell. Results such as these are useful for putting constraints on modelling of supershell formation.

Another type of continuum structure worthy of consideration are the continuum loops. These structures are some of the largest seen in the radio sky and have been the subject of investigation for some time. Berkhuijsen, Haslam, and Salter (1971) classified the largest of these loops, including what is now known as the North Polar Spur (NPS). More recently Sun et al. (2015) performed high detail Faraday tomography on the NPS, deducing the magnetic fields associated with the structure. The origin of structures such as the NPS are likely to be blown out H I supershells, which have expanded creating the great loop-like structures (Sofue and Nakai, 1983; Sun et al., 2015).

2.3.1.1 GSH 006-15+7

There are many hundreds of H I supershells that have been discovered in the Milky Way. Galactic supershell GSH $006-15+7$ was discovered only recently by Moss et al. (2012), who discovered this feature in the H I emission as part of the GASS data set (McClure-Griffiths et al., 2009, see Section 2.4.1.1). This supershell appears close to the Galactic plane with central a location at $l \approx 6^\circ$ and $b \approx -15^\circ$ in Galactic coordinates. The shell spans longitudes of $l = [356, 16]^\circ$ and latitudes of $b = [-28, 2]^\circ$. The shell also extends over a velocity range of $v_{\mathrm{LSR}} \approx [5, 11]\,\mathrm{km\,s^{-1}}$, with a central velocity of $7\,\mathrm{km\,s^{-1}}$. Moss et al., 2012 find with a distance to the shell of $\sim 1.5\,\mathrm{kpc}$ the shell has a physical size of 780 pc by 580 pc. This puts this supershell as one of the largest ever discovered. Additionally, the shell has a total energy budget of approximately 10^{52} ergs, a total mass of $(3 \pm 2) \times 10^6\,M_\odot$ and an estimated age of $15 \pm 5\,\mathrm{Myr}$ The shell is likely powered by the OB stars of Sgr OB 1 and open clusters NGC6514, 6530, and 6531. In total these regions provide approximately 5×10^{51} ergs, which is short of the shell's total energy requirement. Moss et al. suggest that the remainder of this budget was likely provided by supernovae explosions from the associated stellar clusters. Finally, due to the shell's irregular morphology it is likely that it is in the process of fragmenting and becoming a chimney structure. The proximity of this structure to the Galactic plane means that it is covered by a wide variety of surveys, allowing for the further probing of its magneto-ionic properties. The first part of my thesis will be an examination of this shell in H I and diffuse polarisation (see Section 3.2).

2.3.2 Filamentary Structures

A great deal of H I observations reveal filamentary structures within the ISM. Heiles (1989) found in their investigation of H I shells, that many of the structures they observed were filaments, and not sheet-like. Structures associated with shells are typically sheet-like as they are swept up in shocks. Filaments are examples of ordered structure in the ISM that do not originate from stellar outflow or SN shocks. In such filaments Heiles (1989) found that magnetic fields are the primary source of pressure over thermal and turbulent sources. In fact, thermal and turbulent pressures are exceeded by magnetic pressures by factors of 67 and 10, respectively. These structures are driven out of the WNM and WIM by magnetic forces. Presumably, the WPIM also lurks in the formations of these structures. Analysing their formation, morphology, and dynamics should prove to be an excellent method of studying the WPIM.

2.3.3 Turbulent Structures

Not all structure observed in the ISM has a deterministic origin. On the contrary, turbulent structure dominates in the diffuse ISM. Small scale structure driven by turbulence has recently been detected in fine detail using the 'polarisation gradient' method outlined by Gaensler et al. (2011). This new technique employs the deceptively simple polarisation gradient:

$$|\nabla \mathbf{P}| = \sqrt{\left(\frac{\partial Q}{\partial x}\right)^2 + \left(\frac{\partial U}{\partial x}\right)^2 + \left(\frac{\partial Q}{\partial y}\right)^2 + \left(\frac{\partial U}{\partial y}\right)^2} \tag{2.1}$$

Where $\mathbf{P} \equiv (Q, U)$, x and y are the image coordinates, and Q and U are linear polarisation Stokes parameters. The structures that appear from this technique often have no direct counterpart in other emission methods. What they trace is turbulence in diffuse, magnetised and ionised gas.

Iacobelli et al. (2014) provide the first polarisation gradient map of the Southern sky, tracing magnetised turbulence in the magneto-ionic medium. These data allow for the study of turbulence in high detail, revealing new elongated structures. Not only is variations in electron density traced by this technique, but also variations in magnetic fields. Thus, the turbulent ISM provides another case for the study of magneto-ionic interactions. Iacobelli et al. found the structure they observed to consistent with the WIM. However, we expect that the WPIM will also play a role in these magneto-ionic interactions, therefore it can be studied using this technique.

2.4 Observational Methods and Surveys

2.4.1 The 21cm Line

Neutral hydrogen (H I) pervades the Galactic ISM. We are able to measure the amount of atomic hydrogen and gain kinematic information through observation of the 21 cm line ($\nu \approx 1420\,\mathrm{MHz}$). This spectral line arises from the hyperfine transition of the electron of the H I atom from one spin state to the other. Since its first detection by Ewen and Purcell (1951) the line has been used to trace Galactic H I and form our view of the composition of the Galaxy (McClure-Griffiths et al., 2009). Doppler shift of the transition is used to gain kinematic information of the gas. Once the relative motion of the Sun is accounted for this information can be used a variety of ways; not least of which is computing the rotation curve of the Milky Way. In addition, the intensity of the transition line can be used to infer the abundance of H I for a given velocity. This is done by the following relation (Dickey and Lockman, 1990):

$$N_{\mathrm{H}} = 1.823 \times 10^{18} \int T_{\mathrm{b}} dv \,\mathrm{cm}^{-2} \tag{2.2}$$

Where N_{H} is the column density of H I , T_{b} is the brightness temperature of the 21 cm emission which is integrated across velocity (v) space. This function only holds, however, at low optical depth. In the optically thick case it is not possible to determine a unique $N_{\mathrm{H}}(v)$ (Dickey and Lockman, 1990). In the absence of strong optical depth H I emission correlates to H I density. Thus, with surveys of emission with great enough resolution and sensitivity, structures of neutral hydrogen can be revealed. Luckily for us the Milky Way on the whole has low optical depth in H I (Dickey and Lockman, 1990), which allows for the study of structure and kinematics throughout the entire Galaxy.

2.4.1.1 GASS

The Parkes Galactic All-Sky Survey (GASS) is the highest resolution, highest sensitivity H I survey of the Southern sky to date (McClure-Griffiths et al., 2009). GASS measured H I emission across the Southern sky below a declination of $\delta = 1°$ using the Parkes 64 m Telescope. The survey boasts an angular resolution of 16', a velocity resolution of $1.0\,\mathrm{km\,s^{-1}}$, and a noise floor of 57 mK in brightness temperature. The velocity space covered is $-400\,\mathrm{km\,s^{-1}}$ to $500\,\mathrm{km\,s^{-1}}$, which encompasses the range of H I velocity in the Southern sky. Work has already begun on making use of these data including identifying new H I structures (Moss et al., 2012) and other projects of importance to Galactic structure (McClure-Griffiths et al., 2009).

2.4.2 Diffuse Polarisation and Rotation Measure Synthesis

Synchrotron emission produces diffuse polarised emissions which are visible across the entire sky (Landecker, 2012). Diffuse polarisation provides a unique view of the sky, revealing features not observed in any other observational mode. This linearly polarised emission is an excellent probe of the magneto-ionic medium of the Galaxy, due in large part to the Faraday rotation effect. Faraday rotation is quantified via Faraday depth (ϕ), as defined by Burn (1966), as follows:

$$\frac{\Delta\theta}{\lambda^2} = \phi \equiv 0.812 \int_{\text{observer}}^{\text{source}} n_e \mathbf{B} \cdot d\mathbf{r}\,\mathrm{rad\,m^{-2}} \tag{2.3}$$

Here $\Delta\theta$ is the angle through which the radiation is rotated, λ is the wavelength of the emission, n_e is the electron density, and $\mathbf{B}$ is the magnetic field strength integrated out long the line of sight $\mathbf{r}$. Note that the Faraday depth (ϕ) is distinct from the rotation measure (RM) as defined in Equation 2.4. Often these two parameters are used interchangeably in the literature, despite their different derivations and meanings. RM is the gradient of polarisation angle (χ) against wavelength squared (Brentjens and de Bruyn, 2005).

$$\mathrm{RM} = \frac{d\chi(\lambda^2)}{d\lambda^2} \tag{2.4}$$

For a Faraday simple source these parameters these values will be the same, but in reality there will be some mix of emission and rotation along the line of sight. Additionally, sources may become 'depolarised'. This can occur by two primary mechanisms; bandwidth and beam depolarisation. In each case the superposition of two opposing (π rad out of phase) polarised waves act destructively. In bandwidth depolarisation this occurs when strong rotation sources along the line of sight cause $n\pi$ ambiguities in the measurement of χ. In beam depolarisation this effect occurs when two opposing emission sources are unresolved on the sky by the telescope in question.

Following the work of Burn (1966), Brentjens and de Bruyn (2005) derive a method of 'rotation measure synthesis' to solve the problem of depolarisation. This process involves taking the Fourier transform of a broadband emission, which results in the Faraday dispersion function ($F(\phi)$). This is a function of Faraday depth against polarised emission for a given line of sight. The resulting profile of this function allows for a characteristic Faraday depth to be determined for a line of sight. The profile also carries with it additional information about emission and rotation along the line of sight, which can be resolved given enough spectral information in observing. The result of this technique is that the magneto-ionic properties of a region can be determined, in principle, from polarised broadband observations.

Synchrotron radiation has an additional benefit to observing the WIM/WPIM. Unlike Hα which traces n_e^2, synchrotron traces n_e. This means that diffuse polarisation is the ideal method of observing the WIM and WPIM, as Hα is often dominated by H II regions which blow out the detail need to detect a phase such as the WPIM.

2.4.2.1 GMIMS

The Global Magneto-Ionic Medium Survey (GMIMS) (Wolleben et al., 2009) is a project whose purpose is to bring together the best diffuse polarisation surveys to map the entire sky. It aims to do this over a frequency range from 300 MHz to 1.8 GHz in intervals of 1 MHz (or smaller) and with an angular resolution of 30 - 60 arcmin. The overarching purpose of such a survey is to provide high quality data for use in rotation measure synthesis.

GMIMS plans to bring six surveys together to cover its goal sky coverage and frequency range. These six surveys will be comprised of low-, mid-, and high-band surveys in both the Northern and Southern skies. The high-band North survey, a.k.a. the DRAO 26 m Rotation Measure Synthesis Survey (Wolleben et al., 2010), is now complete. I analysed these data for my Honours thesis in the North and South Galactic Poles. The low-band South component is due to be ready for analysis in the coming months; this survey is being conducted by the Parkes 26 m from 300-480 MHz. The high-band South survey is covered by the Southern Twenty-centimeter All-sky Polarisation Survey (STAPS) (Haverkorn et al., 2008). The work on STAPS is now at a stage where scientific analysis can begin. The other GMIMS survey components are currently in the planning stage (Wolleben et al., 2009).

2.4.2.2 S-PASS

A powerful complimentary survey to GMIMS is the S-band Polarisation All Sky Survey (S-PASS) (Carretti et al., 2006). SPASS is a whole southern sky survey of diffuse polarisation at 2.3 GHz. Currently high quality single frequency maps are available through this survey. The advantage of this frequency channel is that there are fewer depolarisation effects than with 1.4 GHz surveys (Iacobelli et al., 2014). There is the possibility that the broadband component of this survey will become available in the future.

2.4.2.3 ASKAP - POSSUM

The Australian Square Kilometre Array Pathfinder (ASKAP) is widely viewed as the next major iteration of interferometric observation in the Southern sky. ASKAP has just begun to receive its first commissioning data this year and promises to provide a new level sensitivity and resolution for radio surveys. Survey Science with ASKAP: Polarisation Sky Survey of the Universe's Magnetism (POSSUM) (Gaensler et al., 2010) is the diffuse polarisation arm of ASKAP. As these data come online they are sure to be an invaluable resource for studying the WIM, the WPIM, and the magneto-ionic medium as a whole.

2.4.2.4 Discrete Rotation Measure Surveys - NVSS

In order to obtain a value for Faraday depth it can be useful to use an extra-Galactic source. In such a case the limits of Equation 2.3 become effectively 0 to ∞, which removes the need to know the distance to the source. Additionally, it can be assumed that variations in emission/rotation from source to source will average out given a large enough sample size Mao et al. (2010).

With this in mind the the NRAO VLA Sky Survey (NVSS) (Condon et al., 1998) has been processed by Taylor, Stil, and Sunstrum (2009) to produce a RM catalogue covering the entire North sky down to declination of $\delta = -40°$. This survey includes some 37543 polarised sources, which allows for RM analysis and magnetic field computation across most of the sky.

2.4.3 Polarised Emission from *Planck*

The *Planck* satellite was launched in 2009 with the purpose of measuring the Cosmic Microwave Background (CMB) (Planck Collaboration et al., 2015a). Unavoidably, this mission also measured the Galactic foreground. This by-product of sorts has proven to be rich source of diffuse polarised emission data. Planck Collaboration et al. (2015b) present the Galactic foreground results from 200 to 100 GHz. Within this range three primary emission modes are present: synchrotron, free-free and 'anomalous microwave emission' (AME) from spinning dust grains. The team reduced these data to synchrotron-only map, whose frequency range allows for Faraday rotation to be disregarded. In this map new filamentary and spur-like structures are present. These unique structures in combination with the high signal-to-noise ratio mean that these data presented here a rich source of information on the WIM/WPIM structure.

Research Proposal

3.1 Overall Aim

The idea of the WPIM is a relatively new one, presently without robust observational evidence. If the WPIM does exist it should play an important role in the interactions between the ISM and Galactic magnetic fields. Furthermore, interactions between the Galactic magnetic fields and the ISM are not fully understood. The WIM is known to interact with magnetic fields and so should the WNM, because of its non-negligible ionisation fraction. It follows that the WPIM must also interact with magnetic fields. The magnetic signature left by the WPIM may prove to be the best way to study it. I propose to investigate the existence and properties of the WPIM as traced by the magneto-ionic medium and magnetised WNM. This will be accomplished through employing the latest H I surveys which trace neutral hydrogen and comparing these data with surveys of diffuse polarisation, which trace the magneto-ionic medium.

This is a very broad goal and as such we will break it down into series of case studies. Each case study will provide unique information and perspective. Specifically what each case will be is still to be determined. The surveys we propose to use, as given in Section 2.4, provide broad scope for potential comparisons and interactions.

3.2 H I Shell Comparisons

Perhaps the most obvious case is to begin with discrete structures such as H I supershells. These are structures formed by swept up neutral hydrogen which are filled up by the WNM. We expect that WPIM could lie within the walls of these structures.

I have commenced work on analysing the supershell GSH $006-15+7$. We are comparing the shell as it appears in H I from GASS (McClure-Griffiths et al., 2009) with diffuse polarisation from S-PASS (Carretti et al., 2006). There almost certainly is a 'shadow' in the polarisation image that correlates with the H I shell. Additionally, the region is well covered by the NVSS rotation measure sources (Taylor, Stil, and Sunstrum, 2009). We aim to analyse the magnetic fields associated with the shell using both the RM sources and a Faraday screen model, such as the model used by Gao et al. (2015). These results can then be compared the work of Stil et al. (2009), who model the Faraday signatures of H I shells, and Tomisaka (1998) who model the evolution of H I shells in a magnetised medium. We also aim to provide modelling of the expected signature of a magnetised shell in polarisation images and compare with observations. This analysis will comprise the first paper of this thesis. The title of this paper will be along the lines of "The Warm Partially Ionised Medium and Magnetic Fields of GSH $006-15+7$".

3.3 Other Structures and Future Work

The data reduction of STAPS and GMIMS low-band surveys are in the final stages and we will have the data within a month. The initial task we will commence, following the supershell analysis, will be to identify the regions we wish study by comparing the H I and diffuse polarisation data.

As discussed there are many other structures that pervade the ISM. These include H I filaments (Heiles, 1989) and loops (Berkhuijsen, Haslam, and Salter, 1971; Sun et al., 2015). Within the loops and filaments we aim to measure the ordered and random magnetic field strengths both within and outside of the structure as they appear in H I emission. Additionally, turbulent structure can be identified using the polarisation gradient technique (Gaensler et al., 2010; Iacobelli et al., 2014). Using this technique we aim to find associations between weak shock structures and H I emission features. The second paper that we will produce for this thesis will be initial results from the comparison of the GMIMS south diffuse polarisation surveys and GASS H I .

Looking further ahead we hope to make use of ASKAP POSSUM (Gaensler et al., 2010) to greatly increase the sensitivity and resolution of the data available. We hope that the third publication we produce will make use of these data in combination with further comparison results from comparison of GMIMS diffuse polarisation surveys and GASS H I .

Lastly, we are aiming to investigate the nature of the WPIM and interaction with magneto-ionic medium. The first three publications we produce will be case studies of these interactions. With the final paper produced from this thesis we will aim to compare the properties of the WPIM in turbulent regions against deterministic structures. These properties include magnetic field strength, estimate of pressures, and kinematic properties. The result of such analysis will address under what conditions the WPIM is dominant in the ISM.

Timeline

4.1 2016 - Semester 1

Coursework

- Astrophysical Gas Dynamics - Prof. Geoffrey Bicknell

Thesis Work

- Familiarise myself with background material
- Familiarise myself with data - GASS H I (McClure-Griffiths et al., 2009) and SPASS single frequency maps (Carretti et al., 2006)
- Prepare thesis proposal
- Give thesis proposal talk at MSO
- Commence work on first research project - Comparison of H I and diffuse polarisation in the supershell GSH $006-15+7$

4.2 2016 - Semester 2

Coursework

- Astronomical Computing - Dr. Christoph Federrath

Thesis Work

- Start work with full GMIMS RM data

    Preliminary analysis of data set
- Identify first GMIMS/H I test case
- Identify which additional data sources will be used in comparison
- First paper (draft) complete on GSH $006-15+7$ research project by end of October
- Submit first paper by end of 2016

4.3 2017 - Semester 1

- Begin full analysis of GMIMS RM cubes with GASS H I cubes
- Present ASA talk in mid-year meeting
- Annual thesis report and talk at MSO
- Attend mid-year ASKAP/POSSUM meeting

4.4 2017 - Semester 2

- International collaborative visit/meeting - TBD
- Second paper complete - GMIMS RM and GASS H I initial comparison results (part I)

4.5 2018 - Semester 1

- Incorporate early ASKAP data into analysis
- Submit third paper by mid-year - the GMIMS RM and GASS H I further comparison results (part II)
- Annual thesis report and talk at MSO
- Attend mid-year ASKAP/POSSUM meeting
- International collaborative visit/meeting - TBD

4.6 2018 - Semester 2

- Fourth paper complete - Aiming to answer questions on the nature of the WPIM
- Job applications - October/November
- Begin thesis compilation before end of 2018

4.7 2019 - Semester 1

- Continue thesis compilation
- Submit thesis by May 1^{st}

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