Chapter 1

Introduction

1.1 Why Study the Interstellar Medium?

The interstellar medium (ISM) plays a fundamental role in the process of Galactic evolution. This process involves a complex interplay between the interstellar matter and the stars. The stars are born from interstellar matter. During their lives, they deposit energy into the ISM in the form of electromagnetic radiation and stellar winds. When they die, the more massive stars return matter and energy back into the interstellar medium in dramatic supernova events. The matter returned to the ISM is enriched with heavy elements produced by nuclear burning in the stars' interiors and in processes occurring during the explosions. This enriched ejecta becomes the material of future generations of stars (which behave rather differently due to the presence of the "metals"). The process is not 100% efficient; some of the matter remains locked up forever in compact objects such as white dwarfs and neutron stars. Therefore, the composition of a galaxy slowly proceeds from all ISM to no ISM. The chemical evolution of a galaxy results from this cycle of stellar birth, death, and enriched rebirth.

The growth in quantity of these heavy elements allows for the possibility, along the way, of planets, rocks, and in at least one case living organisms.

The interstellar medium is arguably the least well understood player in this cycle. The main components of the interstellar medium have been identified, but the structure is still largely a mystery. The Galaxy is composed of primarily hydrogen (90% by number), some helium (10% by number), and only trace quantities of heavier elements. The gaseous component of the interstellar medium is known to contain regions of neutral atomic hydrogen (both in the form of clouds and in the form of a more diffuse component), molecular hydrogen, and ionized hydrogen (in the form of classical H II regions, a warm diffuse component, and a hot component). It is not known however, how these various components are distributed. For instance, it is still a matter of great controversy whether the hot component, thought to result from the ensemble of supernova remnants (SNR), fills most of the volume of the Galaxy, or is restricted to isolated SNR bubbles. Also, how the observed components fit together into an interacting physical system is poorly understood. One model (McKee & Ostriker 1977) contends that the diffuse ionized hydrogen in the ISM will be on the outer surfaces neutral hydrogen clouds. Other models (e.g. Miller & Cox 1993) speculate that the Hα emitting gas is part of a more diffuse intercloud medium. Clearly, before the process by which galaxies evolve can be understood, a better understanding of the interstellar medium needs to be acquired.

Interstellar studies are also very important to all astronomers because virtually all astrophysical observations must look through the material in the ISM. The interstellar matter subtracts from (e.g., dust absorption, H I and He I absorption of UV radiation and soft X-rays), adds to (e.g., free-free emission from ionized gas, light scattered into the beam by dust), and modifies (e.g., pulsar dispersions, Faraday rotation, polarization by aligned dust grains) the radiation on the way from the source to the observer. Detailed knowledge of the composition and distribution of interstellar matter is required to understand and remove the effects of this translucent screen. An obvious example is de-reddening of a stellar spectrum to correct for the bias introduced by interstellar dust. Another example, more closely related to the subject of this dissertation, is the removal of the free-free component of the microwave background using the WHAM survey of the diffuse ionized hydrogen.

1.2 The Warm Ionized Medium

The presence of ionized gas in the Galaxy has traditionally been associated with the bright ionized regions near hot stars called Strömgren spheres or classical H II regions. We now know that these classical H II regions contain only about 10% of the of the ionized hydrogen in the Galaxy. The remaining 90% is in the form of warm ($\sim 10^4$ K), low density (~ 0.1 cm^{-3}), fully ionized regions which fill approximately 20% of the volume within a 2 kpc thick layer about the Galactic plane. This warm ionized medium or WIM (sometimes also referred to as the Diffuse Ionized Gas or DIG), is now recognized as a major component of the interstellar medium.

The first evidence of widespread ionized hydrogen in the Galaxy came from peculiarities found in studies of the Galactic synchrotron background by Hoyle & Ellis (1963). More direct evidence of the presence of the diffuse component of H II came with the discovery of pulsars; the dispersion of the radio signals from these pulsars gives a direct measure of the column density of free electrons along the line of sight. Soon after this, Hα emission from the WIM was detected using a large aperture Fabry-

Perot spectrometer (Reynolds, Roesler, & Scherb 1973).

The space averaged midplane density of the WIM was determined to be $< n_e >_o \simeq 0.03\ cm^{-3}$ by determining the dispersion measure ($DM \equiv \int n_e dl$) toward a collection of pulsars with known distances. The discovery of pulsars in high latitude globular clusters provided the first measurement of the total column density of free electrons along high latitude sightlines. The result is that $N_{HII} = 0.8 - 1.4 \times 10^{20}\ cm^{-2}$ from the midplane to the location of the globular clusters (Reynolds 1989a). Combining this with the midplane density gives the scale height $H \simeq N_{HII}\ /\ < n_e >_o \simeq 1$ kpc. Measuring the emission measure ($EM \equiv \int n_e^2\ dl$) toward the same pulsar directions provided the first measurement of the volume filling fraction of the WIM with the result that $f_{WIM} \gtrsim 0.2$ (Reynolds 1991), implying that the diffuse ionized gas is clumped into regions with local densities $n_e \simeq 0.1\ cm^{-3}$. While the space averaged midplane density of ionized hydrogen is only 5% of that of the neutral hydrogen, the much larger scale height of the diffuse H II means that the total column density of ionized hydrogen through the disk of the galaxy is 1/4 to 1/2 that of the H I, and also implies that at $z \sim 1$ kpc the ionized gas may predominate.

The study of faint optical emission lines at high spectral resolution from the WIM has provided a great deal of valuable information about the distribution, kinematics, physical state, and energy requirements of this newly recognized major component of the ISM (see Table 1.1 for a summary of known properties). Fabry-Perot spectrometers are ideally suited to this type of study due to their ability to have high light throughput (high etendue) for diffuse sources at high spectral resolution (see Section 2.2.3). For example, Fabry-Perot measurements of the Hα intensity at high Galactic latitudes imply a hydrogen recombination rate equal to 5×10^6 H-ionizations s^{-1} per cm^2 of

Galactic disk (Reynolds 1993). Each ionization costs 13.6 eV, and therefore, this high ionization rate leads to a substantial power requirement for the ionizing source (see below).

Faint optical emission lines also provide constraints on the temperature and ionization fraction in the WIM. A lower limit on the temperature $\mathrm{T}_{WIM} \gtrsim 5400$ K results from measurements of the [O I] $\lambda 6300$ / Hα ratio in combination with a measurement of the [S II] $\lambda 6716$ / Hα ratio (Reynolds 1989b). An upper limit $\mathrm{T}_{WIM} \lesssim 20{,}000$ K is derived from comparing line widths measured for the [S II] $\lambda 6716$ line to the widths of the corresponding Hα line (Reynolds 1985). The generally adopted temperature is $\mathrm{T}_{WIM} \simeq 8000$ K. A lower limit to the hydrogen ionization fraction χ_H within the ionized regions has been calculated from the upper limit [O I] $\lambda 6300$ / H$\alpha \leq 0.02$. This upper limit implies $\chi_H \geq 0.70$ for $\mathrm{T}_{WIM} \geq 5400$ K, and if $\mathrm{T}_{WIM} = 8000$ K, the lower limit becomes $\chi_H \geq 0.94$.

Another active area of research into the physical state of the WIM using faint optical emission lines is determining and understanding the helium ionization fraction χ_{He}. A recent measurement by Reynolds and Tufte (1995) of the He I $\lambda 5876$ recombination line from the WIM placed upper limits on the He I $\lambda 5876$ / Hα ratio which lead to the conclusion that the helium in the WIM is significantly less ionized than the hydrogen. In Chapter 5, I present actual detections of this line at a level that is slightly higher than was suggested by the previous data.

The WIM also has distinctive spectral characteristics. Various emission lines from the WIM have been measured, and their strengths with respect to Hα differ from the classical O star H II region line ratios. For example, the [S II] $\lambda 6716$ / Hα ratios has been found to be much higher in the WIM than in the O star H II regions.

The [N II] $\lambda6584$ / Hα from the WIM is about the same as that from H II regions, while the [O III]$\lambda5007$ / Hα is low. Many of the spectral features found in the WIM can be explained in the context of an O star ionization model in which the stellar radiation field is very dilute. Models have been constructed by Mathis (1986) and by Domgörgen and Mathis (1994) attempting to explain these line ratios using O stars as the source of ionization. These models are fairly successful, but only work for certain distributions of the hydrogen in the ISM.

Since ionized hydrogen will naturally recombine to form neutral hydrogen, its presence requires an active source of ionization. The average recombination rate per cm^2 of Galactic disk is $<$ r$_G$ $> \simeq 5 \times 10^6$ s^{-1} cm^{-2}, which sets the required ionizing photon production rate, or at 13.6 eV per ionization a power requirement of $<$ W $> \simeq$ 1.0×10^{-4} ergs s^{-1} per cm^2 of Galactic disk. Of the known sources of ionization, only the Lyman continuum flux of O stars comfortably exceeds this energy requirement. Other possible sources include supernovae (100% of the energy injected by supernova is required to maintain the ionization), cosmic rays, turbulent mixing layers, Galactic flares, etc...

There are several difficulties associated with the idea of O stars ionizing the interstellar medium. The first is a spatial problem. The O stars reside in the Galactic plane and are few and far between. The WIM is a very thick layer and is in large part far from the O stars. It takes very little H I gas to absorb the Lyman continuum flux from the O stars on its way to the WIM gas and there is considerable H I in the Galaxy. Hence, a very special arrangement of the H I is necessary to match simultaneously the distribution of column density of H I on the sky, known from 21 cm maps, and the constraint that the O star photons can reach the WIM. Models have been constructed by Miller & Cox (1993) and by Dove & Shull (1994) to investigate the feasibility of this. Both find that it can be done if the H I distribution satisfies certain constraints, constraints which may or may not exist in the real ISM. The other problem with the O star ionization model is a spectral problem. The He I λ5876 / Hα line has been measured to be quite low compared to classical H II regions. This indicates a softer spectrum than is known to be emitted by the ensemble of O stars in the solar neighborhood (see Chapter 5).

In summary, although the average properties of the WIM are now known, detailed information is not yet available about the distribution and relation to the H I, ionization state, temperature, and relationship to known sources of ionization such as O stars.

1.3 The Wisconsin H-Alpha Mapper (WHAM)

The WHAM facility is a recently completed dual-etalon Fabry-Perot spectrometer coupled to a 0.6 m siderostat designed to study faint optical emission lines from diffuse sources at high spectral resolution. The WHAM system is 100 times more sensitive than the previously most sensitive instrument of its type, and therefore opens up new opportunities for exploration. The primary purpose of the WHAM instrument is to conduct a sensitive kinematic survey of the northern sky ($\delta >$ -30°) in the Balmer-α line of hydrogen (Hα), analogous to the surveys of H I in 21 cm. The survey will have 1° spatial resolution and 12 km s^{-1} spectral resolution. The 30 second integration time per beam will provide a signal to noise ratio of 20 for a 0.5 R line having a width of 20 km s^{-1} (FWHM). The WHAM instrument is now operating at its Kitt Peak site, and the survey will begin in January of 1997. We expect the approximately 40,000 spectra will take about 2 years to gather, and that the calibrated spectra and velocity interval maps will be available within a year after the data is collected. The WHAM Hα survey will provide the first detailed look at the distribution and kinematics of the ionized gas in the Galaxy. This data set will also be compared to already existing H I surveys, which will allow study of the detailed inter-relationship between the neutral and ionized gas in the interstellar medium.

In the first part of this dissertation, I present a description of the design of the WHAM spectrometer, and measurements of the performance characteristics. In Chapter 2, after reviewing the basic theory of Fabry-Perot systems, I describe our specific technique for utilizing them, which involves the use of dual-etalons in series, pressure tuning, and imaging of the ring pattern passed by the etalons onto a CCD detector. A description of the optical system is also included. Measurements of the performance characteristics relevant to producing a calibrated spectrum with the WHAM spectrometer are presented in Chapter 3. I include studies of the instrument profile function, linearity, wavelength and intensity calibrations, the imaging performance of the optical system, sensitivity, the CCD detector properties, and noise.

By using long exposures (e.g., 900 seconds), the WHAM instrument is capable of studying very faint ($\lesssim 0.1$ R) optical emission lines. This capability was exploited while the instrument was located at its Pine Bluff Observatory site west of Madison (January 1996 – November 1996). In one study, we observed Hα emission from high velocity clouds (HVCs) in the M complex. The results include a number of first detections of such emission and are presented in Chapter 4 of this dissertation. Another study obtained the first detections of the He I $\lambda5876$ recombination line from the WIM. The intensity of this line compared to the Hα intensity probes the degree of helium ionization in the WIM, which is related to the hardness of the ionizing spectrum. The results of this study are presented in Chapter 5.

References

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	Parameter	Value
Geometry	Scale height, H_e	910 (-320, +400) pc
	Average volume filling fraction, $\langle f_e \rangle$	$> 20\%$
	Average local density, n_e	0.08[a] ± 0.02 cm^{-3}
	Midplane local density[b], $(n_e)_{z=0}$	~ 0.16 cm^{-3}
	Surface density	$1.4 \pm 0.2 \times 10^{20}$ cm^{-2}
		1.6[c] M$_\odot$ pc^{-2}
Energy	Temperature, T_e	~ 8000 K
	Non-thermal speeds	12–30 km s^{-1}
	Ionization rate, $\langle r_G \rangle$	$4.8 \pm 0.4 \times 10^6$ s^{-1} cm^{-2}
Ionization	H$^+$ fraction, $n(\mathrm{H}^+)/n(\mathrm{H}^0)$	> 2 (if $T_e \sim 5400$ K)
		> 15 (if $T_e \sim 8000$ K)
	He$^+$ fraction, $n(\mathrm{He}^+)/n(\mathrm{He}^0)$	$\lesssim 0.27$

Table 1.1: Properties of the Warm Ionized Medium

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[a] Within $z \sim \pm 1$ kpc.

[b] Assuming an exponential distribution and H_e above.

[c] H + He.