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THE WISCONSIN Hα MAPPER: A NEW LOOK AT THE WARM IONIZED MEDIUM

L. M. Haffner, R. J. Reynolds

Department of Astronomy, University of Wisconsin–Madison, USA

and

S. L. Tufte

Department of Physics, Lewis & Clark College, USA

RESUMEN

El relevamiento en H-Alpha de Wisconsin (WHAM) ha cubierto todo el cielo del norte en Hα desde Kitt Peak, Arizona. Usando un espectrómetro Fabry-Perot de alta transmisividad, con etalón doble de 15 cm y un CCD de alta sensibilidad, el relevamiento WHAM ha obtenido el primer mapa con velocidades calibradas en Hα en emisión de nuestra Galaxia. Una zona amplia, que incluye el brazo Local (Orión) y el brazo de Perseo, también ha sido observada por el WHAM en las líneas de [S II] y [N II]. Estos nuevos datos muestrean directamente y por primera vez, las condiciones físicas a gran escala del medio ionizado tibio (WIM). Las tendencias de los cocientes de líneas sugieren que las variaciones en la temperatura son muestreadas por los mapas de [N II]/Hα y [S II]/Hα. Dado que estos cocientes se incrementan fuertemente en regiones alejadas del plano Galáctico, revelan un incremento sustancial en la temperatura del WIM del halo. Además de este resultado, los datos revelan una nueva region H II excitada por una estrella B, dan una medida de la escala de altura de los electrones del WIM y, del cociente [S II]/[N II], proveen nueva información sobre la ionización del WIM.

ABSTRACT

The Wisconsin H-Alpha Mapper (WHAM) has surveyed the entire northern sky in Hα from Kitt Peak, Arizona. Using a high-throughput, 15-cm diameter double-etalon Fabry-Perot spectrometer and a sensitive CCD detector, the WHAM survey provides the first calibrated, velocity-resolved map of Hα emission in our Galaxy. A large portion of the Galaxy, which samples regions of the Local (Orion) spiral arm and the more distant Perseus arm, has been also been observed with the WHAM in lines of [S II] and [N II]. These new data directly probe the physical conditions of the Warm Ionized Medium (WIM) on a global scale for the first time. Trends in these line ratios over this large region of the sky suggest that temperature variations are traced by the [N II]/Hα and [S II]/Hα maps. Since these ratios increase dramatically away from the Galactic plane, they reveal a substantial temperature rise in WIM halo gas. In addition to this striking new result, the data set also reveals new information about the ionization in the WIM through the [S II]/[N II] ratio, uncovers a previously undiscovered B-star H II region, and provides an accurate measurement of the electron scale height of the WIM.

Key Words: **GALAXY: HALO — H II REGIONS — ISM: ATOMS — ISM: STRUCTURE**

1. INTRODUCTION

With a scale height of 1 kpc, mass surface density equal to one-third that of H I, and power input requirement equal to the supernovae output rate of our Galaxy (Reynolds 1993), the Warm Ionized Medium (WIM) is justifiably a major component of the Interstellar Medium (ISM). Although, originally discovered in the 1960s through radio observations (Hoyle & Ellis 1963; Guèlin 1974), the WIM is typically studied through optical emission lines, particularly Hα, [S II] λ6716, and [N II] λ6583. Characterizing the details of the WIM is important not only for improving the picture of the ISM and the interaction among its components, but also for understanding the nature of the foreground gas through which all extra-galactic and cosmological observations are made.

Several authors have presented ideas for the source of the ionizing power of the WIM. Most recently, Miller & Cox (1993), Dove & Shull (1994), and Dove, Shull, & Ferrara (2000) present a picture of a pervasive, warm, (originally) neutral medium being ionized by radiation from early-type stars leaking between cold H I clouds or out of density bounded H II regions. This picture results in regions of fully ionized gas and "shadowed" neutral gas. Other theories suggest that the Hα emission should be positively correlated with H I features. Norman (1991) and Koo, Heiles, & Reach (1992) associate the pervasive Hα emission with the walls of superbubbles, "chimneys," and "worms," while McKee & Ostriker (1977) suggest that prominent Hα emission is confined to the surface of neutral clouds bathed in a hot medium. Alternatively, Spitzer & Fitzpatrick (1993) and Sciama (1990) have suggested that the H^+ should be well-mixed with the neutral material.

Major advances in detector technology have recently allowed breakthrough studies of the WIM. Direct measurement of extremely faint, optical diagnostic lines in the WIM, including He I λ5876 (Tufte 1997) and [O I] λ6300 (Reynolds et al. 1998), are beginning to place important constraints on the nature and source of the ionization and heating of this gas in our Galaxy. In addition to our project, several imaging surveys are now underway to map the details of the structure of faint Hα emission near the plane of the Milky Way (Dennison, Simonetti, & Topasna 1998; Gaustad, McCullough, & Van Buren 1996; Parker & Phillips 1998).

There have a been quite a few intensive studies on the nature of the WIM in other galaxies—often referred to in this context as "Diffuse Ionized Gas" (DIG). Recent optical emission line imaging studies of galaxies by Greenawalt et al. (1998) and Hoopes, Rand, & Walterbos (1999) explore the detailed relationship between the WIM and H II regions in the plane and show that the fraction of total Hα luminosity in spiral galaxies arising from the WIM is typically around 50%. The extended layer of WIM at large distances from the galactic plane often shows networks of shells and filaments as well as an overall diffuse component. The most comprehensive spectroscopic work on an edge-on spiral galaxy similar to the Milky Way has been undertaken by Rand (1997; 1998), who has measured numerous emission lines in the halo of NGC 891. Domgörgen & Dettmar (1997) and Golla, Dettmar, & Domgörgen (1996) have also probed similar lines in the edge-on galaxies NGC 2188 and NGC 4631. All found a pronounced increase in the intensity ratios [S II]/Hα and [N II]/Hα in regions with fainter Hα emission. For spectra obtained perpendicular to the galaxies, these ratios rise systematically with distance from the galactic plane. Ferguson, Wyse, & Gallagher (1996) and Otte & Dettmar (1999) studied the highly-inclined SBm galaxy NGC 55 and found a smooth transition in the emission-line ratios of [O I], [O II], [N II] and [S II] to Hα from bright H II regions to fainter WIM gas. In many of these studies, the emission line trends in the brighter regions of the WIM can be explained fairly well by photoionization models, but discrepancies often creep in at lower emission measures where [S II] and [N II] (most notably) emission becomes equal to that of Hα. Here current photoionization models have difficulty emulating the WIM.

To further our understanding of this phase of the ISM, we have designed and built a dedicated survey instrument, the Wisconsin H-Alpha Mapper (WHAM), to produce the first deep, velocity-resolved maps of the WIM in our Galaxy. Below we highlight the features of the Hα survey in §2, review current results derived from WHAM data in §3, and discuss future science to be explored with the instrument in §4.

2. THE WHAM SURVEY

Although the on-going Hα imaging surveys are starting to provide striking details of WIM features with their moderate angular resolution ($\sim 1'$) and deep coverage (~ 1 R; 1 R $= 10^6$ ph cm^{-2} s^{-1}), they lack velocity resolution. WHAM complements these imaging surveys nicely by providing a data set with 12 km s^{-1} spectral resolution and one-degree angular resolution. The addition of this capability allows the WHAM survey to add

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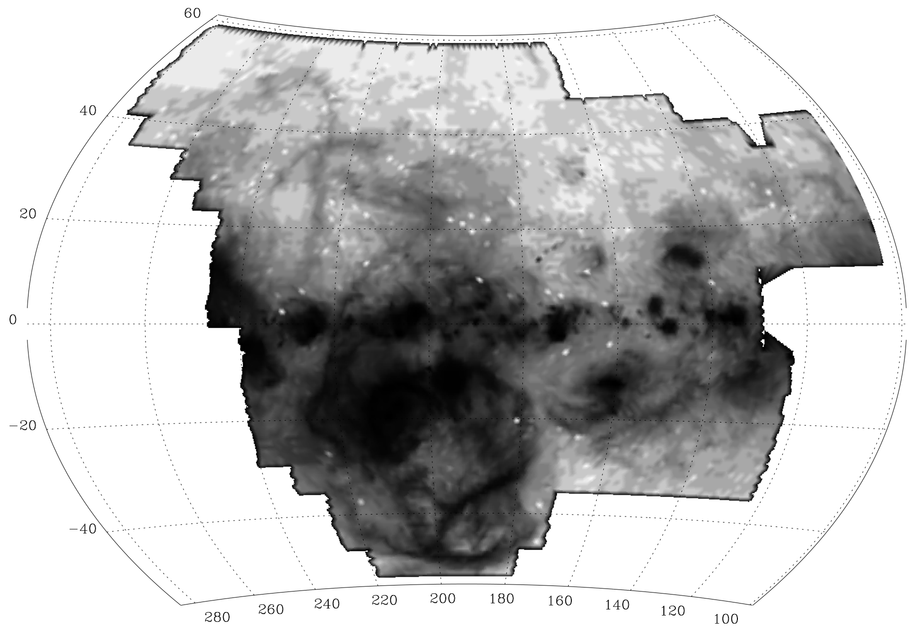

Fig. 1. A preliminary portion of the WHAM Hα Sky Survey. Grayscale represents total integrated Hα emission within $v_{\rm LSR} = -100$ to $+100$ km s^{-1}. White 'point sources' are bright stellar absorption features that will be removed during the final survey reduction.

two important pieces to the diffuse Hα picture.

First, at this velocity resolution, Galactic emission is separated from Hα emission from the earth's upper atmosphere, the "geocoronal" Hα line. Since Galactic emission from most regions of the sky is shifted 20–30 km s^{-1} away from the atmospheric line at some time during the year (due to orbital motion of the earth), prudent observing tactics and accurate geocoronal subtraction make an absolute intensity calibration of the WHAM survey possible. Since the intensity of this foreground emission varies with both time and direction on the sky, normal filter imaging techniques cannot inherently provide a consistent zero-point reference for absolute calibration. The spectral separation of the two Hα lines also prevents the sky line from adding unwanted noise to the Galactic spectral region, allowing WHAM to unambiguously detect Galactic emission down to 0.1 R (EM $\sim$ 2 pc cm^{-6}).

More importantly, velocity resolution gives us the unique opportunity to explore the actual kinematics of the WIM and other extended diffuse Hα sources. Without this resolution, comparing structures found in the WIM with other surveys, particularly H I, is difficult (e.g., Reynolds et al. 1995). Our hope is that such comparisons will reveal the relationships between the WIM and other components of the interstellar medium and help discriminate among powering sources for the WIM.

The Hα survey consists of more than 37,000 pointings of the one-degree beam with $\Delta b = 0\overset{\circ}{.}85$ and $\Delta l = 0\overset{\circ}{.}98/\cos b$ with $\delta \geq -30°$. Each 30-second exposure results in a 200 km s^{-1} wide spectrum centered near the Local Standard of Rest (LSR). More details of the WHAM instrument and survey strategy can be found in Tufte (1997) and Haffner (1999). At the time of this writing, we are finishing the final data reduction pass and the survey is expected to be released in a few months. The data presented here are from a preliminary reduction which did not account for numerous faint (< 0.1 R) atmospheric lines that are being removed during the final pass.

Even without the full calibration planned for our final release, Figure 1 already shows the impressive complexity of Hα emission in our Galaxy. The region of the sky we show here was composed from over 13,400 spectra, about a third of the northern sky survey. The more obvious extra-planar emission features include the

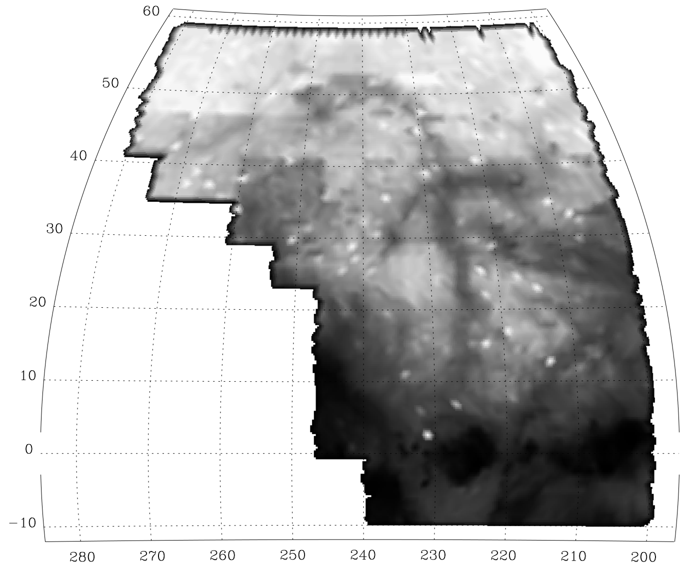

Fig. 2. A magnified view of a section of Figure 1 that focuses on two prominent Hα filaments discovered in the early survey reduction.

Orion-Eridanus superbubble ($\ell = 180°$ to $230°$, $b = 0°$ to $-60°$), the ξ Per ($\ell = 140°$ to $180°$, $b = -10°$ to $-25°$) and α Cam ($\ell = 145°$, $b = +15°$) extended H II regions, the Monogem Ring supernova remnant ($\ell = 180°$ to $220°$, $b = 0°$ to $+40°$), and the vertical filament rising out of an H II region in the plane at $\ell = 225°$ ($b = 0°$ to $+50°$).

3. CURRENT RESULTS

3.1. *Hα Filaments*

Figure 2 is a magnified section of the upper-left corner of Figure 1. The long, vertical filament that rises out of the plane at $\ell = 225°$ and the shorter, horizontal arc between $b = +30°$ and $+40°$ do not appear to be associated with any other phase of the ISM traced by current all-sky surveys. They both have intensities which range from 0.5 to 1.0 R (EM $\sim 1.0 - 2.0$ pc cm^{-6}). The velocity at the base of the vertical filament coincides with the H II region near $\ell = 225°$, $b = 0°$, CMa OB1, which is located about 1 kpc from the sun. At this distance, the filament rises to 1.2 kpc above the plane before appearing to bend back down toward the plane. There is also a significant velocity gradient along its length, from $v_{\rm LSR} = +14$ km s^{-1} at the base to $v_{\rm LSR} = -25$ km s^{-1} at the apex. Much more detail on these Hα filaments can be found in Haffner, Reynolds, & Tufte (1998).

We present several possible scenarios in Haffner et al. (1998), but none has been specifically modeled. Since the published letter, we have become intrigued by the possibility that such filaments could be generated by large-scale magnetic fields. Observations of the stellar polarization from stars behind these structures should provide some information on the validity of such an idea. We hope to uncover more of these unique structures when the Hα survey is fully reduced!

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3.2. *Perseus Arm*

A taste of the rich spectroscopic information that is provided by the WHAM survey can be seen in Figure 3. Here a small portion of the Galaxy toward the Perseus arm ($\ell = 123°$ to $164°$, $b = -35°$ to $-5°$) is displayed in various integrated velocity bands. Due to Galactic rotation, the Perseus arm emission is well separated from Local emission in Figures 3*e* through 3*h* and can be studied with little contamination from nearby gas.

We exploited this velocity separation in Haffner et al. (1999) to make a new measurement of the vertical extent of the WIM layer. This new, high-quality data results in a measured exponential scale height of 1.0 ± 0.1 kpc if the Perseus arm is at a distance of 2.5 kpc from the sun. This new value is in excellent agreement with previous estimates (Reynolds 1991; Reynolds 1997).

As data taking for the Hα survey began to finish up near the end of 1997, we began mapping portions of the sky in [S II] and [N II] as well. This same region toward the Perseus arm was chosen as our first target. As described in Haffner et al. (1999), new information about the global properties of the WIM can be obtained by combining emission line observations. In particular, we find that S seems to be about 40–60% in the form of S^+ with notable coherent spatial variations and differences between the Local and Perseus arms. Such values are typically expected in a scenario where the WIM is predominantly photoionized, but the uncertain value of S abundance may come into play as noted by Sembach et al. (2000). However, the temperature trends of the Hα emitting gas do not seem to be explained well by current models (Reynolds, Haffner, & Tufte 1999; Reynolds, these proceedings).

In Haffner et al. (1999), we find that both the [N II]/Hα and [S II]/Hα ratios rise as the Hα intensity decreases. This trend, combined with the fact that the [S II]/[N II] ratio is remarkably constant, leads us to conclude that rising temperatures rather than changes in the ionization structure of the gas are producing elevated ratios in these fainter Hα regions. The most striking example of this effect is revealed when looking at the vertical structure of the Perseus arm where decreasing Hα intensity with height above the plane is simply due to the decreasing electron density. Our estimates suggest that at 1.75 kpc, the electron temperature is over 10,000 K.

3.3. *Other WHAM Science*

Heiles has been studying the Orion-Eridanus superbubble in great detail for the last few years. The WHAM data has helped by allowing us to explore the full range of ISM phases present in the region and to start untangling the complex kinematics of the superbubble (Heiles, Haffner, & Reynolds 1999). The Hα emission from several diffuse structures in the region has also been combined with radio survey observations to measure temperatures and to derive the extinction of the Hα emission (Heiles et al. 2000).

A recent decomposition of FIRAS far-infrared emission implied that dust in the WIM is a substantial contributor (Lagache et al. 1999). The addition of WHAM data to this decomposition has indeed confirmed this fact in a few small regions of the sky (Lagache et al. 2000). Since there will be a substantial amount of WHAM Hα survey data from high Galactic latitudes, where molecular and H II regions are less abundant, future application of these correlation techniques should prove quite valuable in extracting details about dust in the WIM and the Cosmic Far-Infrared Background.

4. FUTURE WHAM SCIENCE

As multiwavelength observations in the Perseus arm show (§3.2; Haffner et al. 1999; Reynolds et al. 1998), the Hα survey is only a starting point for studies of diffuse emission with WHAM. We are continuing to collect data and have started several additional projects.

- Although even the brightest of the nebular [O III] lines at 5007Å is quite faint in the WIM, Rand (1998) has traced this emission out of the plane in NGC 891 and finds that [O III]/Hα increases at high $|z|$. We are investigating if this trend is similar in the Milky Way. With an ionization potential around 35 eV, O^{++} is an important tracer of ionization conditions in the WIM.

- In a joint STIS program with Jenkins & Tripp, we plan to combine the wealth of information from high signal-to-noise, high resolution absorption line spectra with multiwavelength WHAM emission spectra

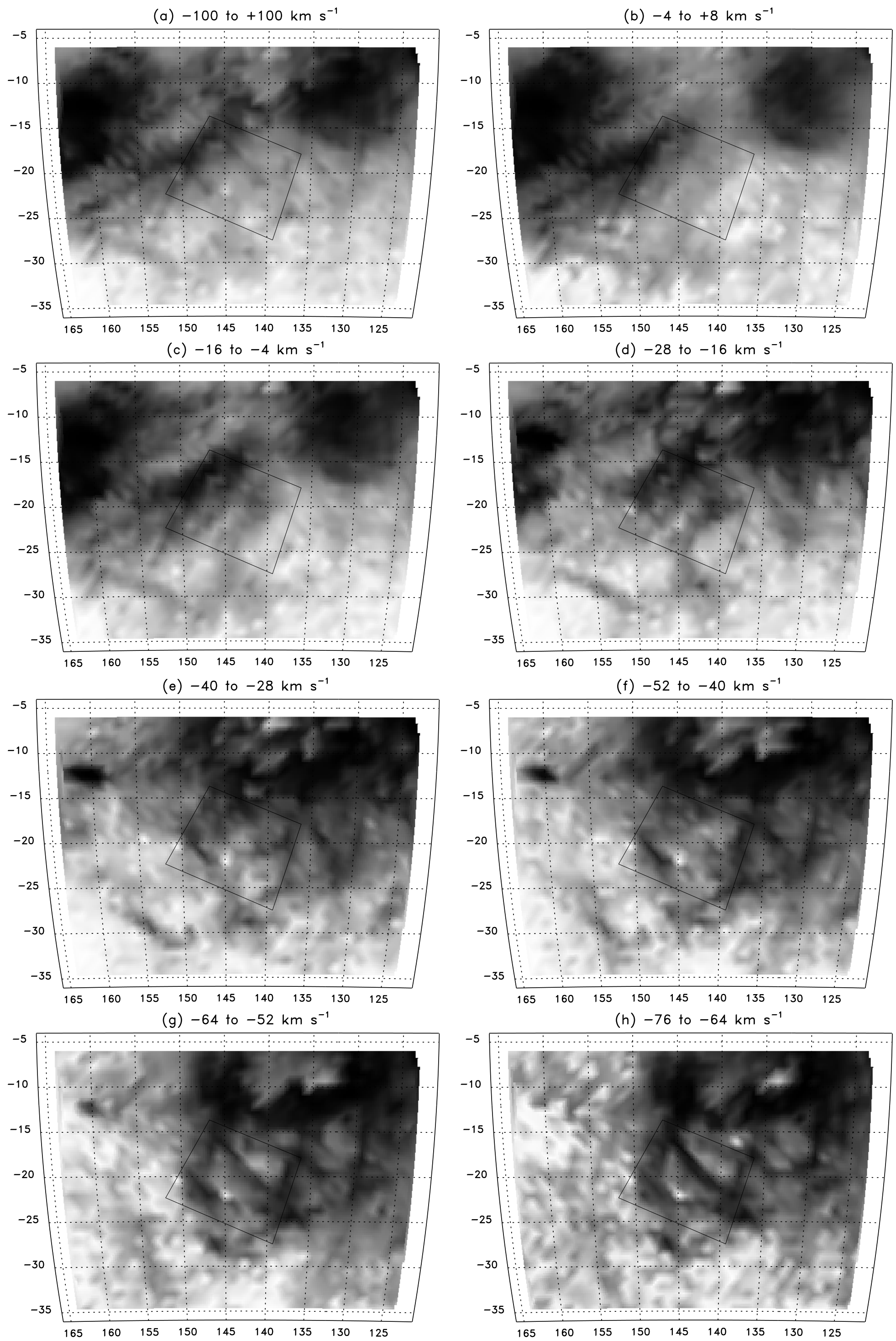

Fig. 3. These images show the integrated Hα emission (dark) in eight selected velocity bands. The axes are Galactic longitude and latitude. The overplotted box shows the location of a previous Hα survey in this region (Reynolds 1980; Reynolds et al. 1995). (*a*) shows the total intensity of Hα from the region by integrating over $v_{\rm LSR} = -100$ to $+100$ km s^{-1}. (*b*) through (*h*) show 12 km s^{-1} integration slices as labeled in the figure.

toward a select group of stars in and behind the Perseus arm. In addition to deriving further constraints on the physical conditions in WIM gas, we hope this technique will be useful in decoupling the contribution of the WIM and Warm Neutral Medium for certain species that are prevalent in both phases (Sembach et al. 2000).

- In early 2000 we plan to begin a survey of Hβ emission near the Galactic Plane (perhaps up to $|b| = 20$–$30°$) and toward brighter diffuse targets such as the Orion-Eridanus superbubble. Combining Hβ spectra with the Hα survey should provide interesting information about the extinction toward these Hα emitting regions.
- Since O and early B stars are able to provide a substantial amount of the ionization for the WIM, we have collected multiwavelength data on several fainter, extended H II regions away from the Galactic plane. At least one new H II has been found in the Hα survey (Haffner 1999). The B0.5e + sdO binary system ϕ Per located at $\ell = 131.°3$, $b = -11.°3$ is surrounded by a faint (< 10 R), circular ($d \sim 50$ pc) Hα nebula (Figures 3b and 3c). The line ratios are much different than the nearby O-star H II region created by ξ Per. We plan to use these observations to help the understanding of UV emission from such stars.
- As shown in Haffner et al. (1999), [S II] and [N II] emission are bright enough to be traced to high Galactic latitudes and seem to provide significant information on the ionization and temperature of the WIM. We plan to extend the maps of these other emission lines to further explore the global properties of the WIM.
- Finally, WHAM has an imaging mode which can provide one-degree, few-arcminute resolution images with a very narrow spectral bandpass (12–200 km s^{-1}). Although time consuming, we can use this mode to explore features smaller than the one-degree survey resolution. With multiwavelength capability and velocity-resolution, this observing mode may open up a whole new area of WHAM science.

We encourage the reader to visit the WHAM website at http://www.astro.wisc.edu/wham/ for information about these projects as well as the status of the WHAM Hα survey, which will be released in early 2000.

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L. M. Haffner and R. J. Reynolds: Department of Astronomy, University of Wisconsin–Madison, 475 North Charter Street, Madison, WI 53703 (haffner, reynolds@astro.wisc.edu).
S. L. Tufte: Department of Physics, Lewis & Clark College, 0615 SW Palatine Hill Road, Portland, OR 97219 (tufte@lclark.edu).