

The Wisconsin H-Alpha Mapper Sky Survey

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Introduction

We present the first all-sky, kinematic survey of H α from the Milky Way, combining survey observations taken with the Wisconsin H-Alpha Mapper (WHAM) from Kitt Peak (1997–2007) and Cerro Tololo (2009–present). The WHAM Sky Survey (WHAM-SS; Figure 1, at right) reaches sensitivity levels of about 0.1 R (EM $\sim$ 0.2 pc cm⁻⁶) with emission detected toward every direction in the sky. WHAM was designed primarily to study the large-scale distribution and kinematics of the Warm Ionized Medium (WIM) component of the interstellar medium (ISM). Each pointing of the survey comprises a spatially integrated spectrum from a one-degree beam on the sky covering at least 200 km s⁻¹ around the Local Standard of Rest (LSR) with 12 km s⁻¹ spectral resolution. Aside from many large-scale, locally-ionized regions, much of this emission arises from the diffuse, thick WIM and extends several kiloparsecs into the Galactic halo with a kinematic signature that traces the gaseous spiral arms of the Galaxy.

First detected through the absorption of diffuse, low-frequency radio synchrotron radiation (Hoyle & Ellis 1963), the WIM has been studied primarily through optical emission lines over the past few decades. These observations show the WIM to be a pervasive component of the ISM with temperatures ranging 8,000 K to 12,000 K; ionization fractions (H⁺/H) typically > 90%; a scale height near the Sun and within the Perseus Arm of $\sim$ 1 kpc; and typical local electron densities of 0.01 cm⁻³ to 0.1 cm⁻³ (Haffner et al. 2009). Although denser, “classical” H II regions contribute a comparable fraction of the total Galactic H α luminosity, the WIM contains roughly 90% of the ionized mass of the Milky Way. The WHAM-SS now allows a deep study of the global distribution and kinematics of diffuse ionized gas throughout the Galaxy.

Observations

To fully map the extent and kinematics of the WIM, we designed and built a dedicated instrument that excels in observations of faint, diffuse optical emission. WHAM (Figure 2, below) consists of a steerable siderostat with a 0.6-m primary lens coupled to a 15-cm, dual-etalon Fabry-Perot spectrometer. This optical configuration (R $\sim$ 30,000) delivers a spatially integrated spectrum from a one-degree beam on the sky covering 200 km s⁻¹ with 12 km s⁻¹ spectral resolution. Optimized for H α , a 30-second exposure per pointing provides sensitivity to emission with $I \sim$ 0.1 R (EM $\sim$ 0.2 pc cm⁻⁶), allowing us to survey the observable sky with one velocity window in about two years. The spectrometer can be tuned to observe many other emission lines between about 4800Å and 7200Å. We use a combination of deep observations and large-scale mapping of optical transitions commonly used to study warm, ionized gas (e.g., H β , [N II], [S II], [O III], [O I], and He I) to examine the physical conditions of gas in a variety of regions (e.g., Madsen et al. 2006; Hausen et al. 2002a; Reynolds et al. 2001; Haffner et al. 1999).

Commissioned at Pine Bluff Observatory (PBO) in Wisconsin during 1996, we installed WHAM at Kitt Peak National Observatory (KPNO) in November, 1996 and began the Northern Sky Survey (WHAM-NSS; Haffner et al. 2003) in early 1997. Two years of H α survey observations were followed by an exploration of the physics of the WIM through other optical emission lines as well as observations of faint H α emission from high-velocity complexes. After eleven years at KPNO, we decommissioned WHAM and moved it back to PBO for a year of maintenance. In early 2009, WHAM was shipped to Chile and was installed at Cerro Tololo Inter-American Observatory (CTIO) to complete the Milky Way survey and begin study of ionized gas throughout the Magellanic System (e.g., Barger et al. 2013; Smart et al. 2016).

WHAM-SS data is obtained in “blocks” of 30–50 one-degree pointings organized into a roughly 7° $\times$ 7° grid. Trading full sampling for full sky coverage in a tractable span of time ($\sim$ 2 years), we use a beam spacing of $\Delta b = 0.85^\circ$, $\Delta l = 0.98 \times \cos b$. In each direction, WHAM integrates for 30s capturing a spectrum approximately $-100 \text{ km s}^{-1} \leq v_{\text{LSR}} \leq +100 \text{ km s}^{-1}$ around H α . Geocoronal H α emission distinct in all but the brightest Galactic regions provides a consistent, precise velocity reference calibration. Intensities are calibrated by frequent observations of standard nebular targets,



Figure 2: The Wisconsin H-Alpha Mapper. WHAM at the Cerro Tololo Inter-American Observatory in Chile.

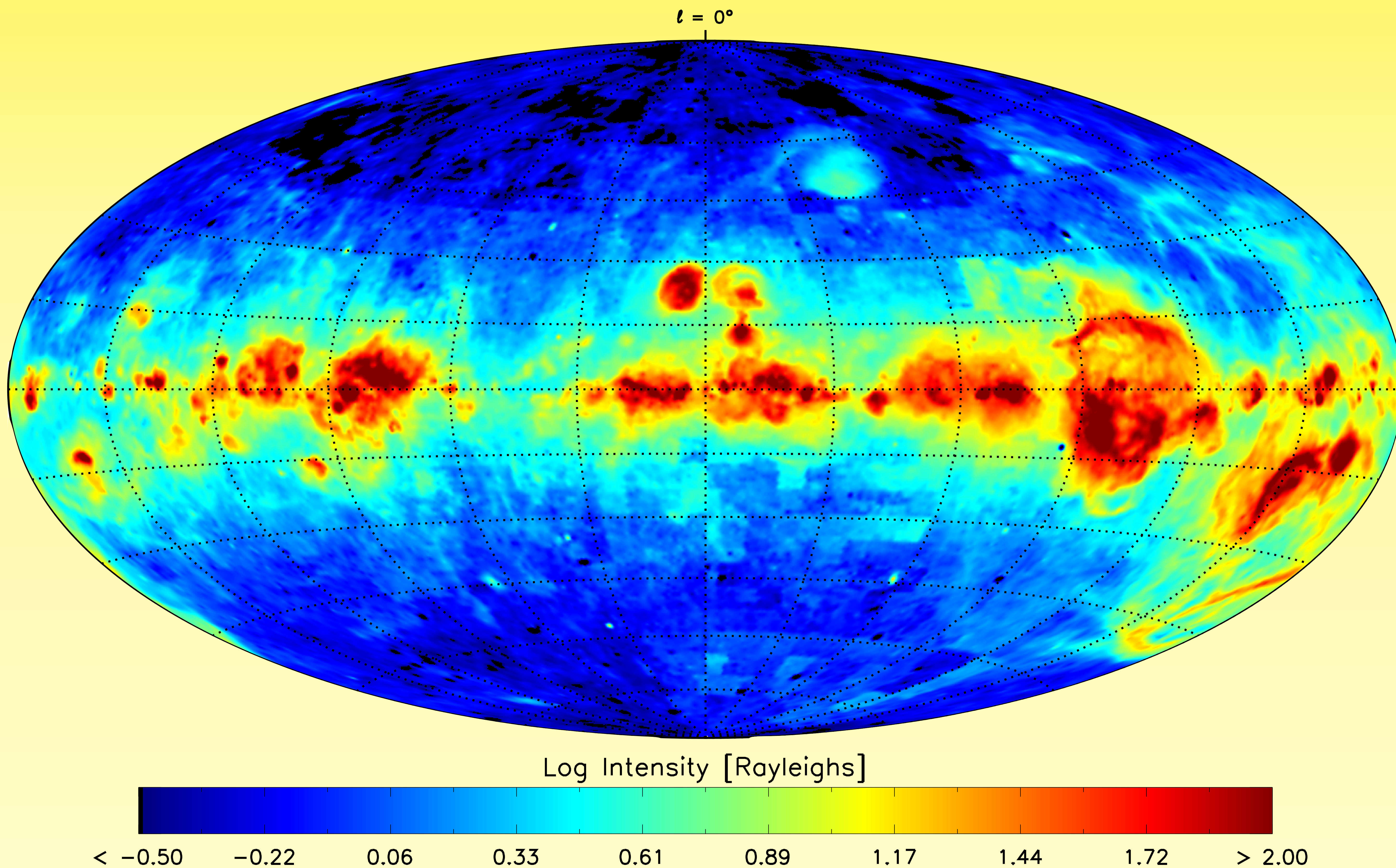


Figure 1: WHAM H α Sky Survey. Diffuse ionized gas in the Milky Way is displayed in a Hammer-Aitoff projection using Galactic coordinates. The map is centered at $l = 0^\circ$, $b = 0^\circ$. Color represents the logarithm of integrated H α intensity between $-150 \text{ km s}^{-1} \leq v_{\text{LSR}} \leq +150 \text{ km s}^{-1}$, although observations toward most directions do not span this full velocity range yet (see Figure 3). Grid lines are spaced every 30° in longitude and every 15° in latitude. H α emission has been detected throughout the Galaxy in every WHAM one-degree beam.

which not only track instrumental performance, but also measure atmospheric transmission from night to night.

Apart from the geocorona, faint ($l < 0.1 \text{ R}$) atmospheric emission lines are present throughout the 200 km s⁻¹ window (Hausen et al. 2002b). In most directions above $|b| = 20^\circ$, accurate removal of these lines is essential to recover Galactic intensities and trace structures in the faint background. Haffner et al. (2003) details the procedure we followed for the Northern Sky Survey to clean and calibrate that data. The pattern of these faint lines around H α is the same at CTIO, allowing us to use the same methods to subtract atmospheric lines from the southern portion of the survey.

We attempt to observe blocks at a time of the year that gives us the best chance to extract accurate Galactic emission. In particular, we try to: (1) maximize the separation between the geocorona and expected Galactic emission, particularly near $v_{\text{LSR}} = 0 \text{ km s}^{-1}$; (2) minimize the zenith distance of the observation; and, for directions near the ecliptic plane, (3) maximize the angular distance of the target from the sun. This final requirement helps to minimize the level of background contamination by zodiacal light, which adds the H α Fraunhofer absorption line to the spectrum and complicates data reduction. These survey requirements lead to an LSR velocity range that varies with position and observing date, as evident in Figure 3. With some Galactic emission missed by a single pass of WHAM’s 200 km s⁻¹ coverage, we are beginning observations to extend the survey range to at least $\pm 150 \text{ km s}^{-1}$. The extent of emission in the first and fourth quadrants ($l = 90^\circ$ – 0° ; 360° – 270°) has been surprising and particularly impressive. In some directions, WHAM is tracing diffuse ionized gas structures beyond the solar circle with distances approaching 10–12 kpc.

The H α Sky Survey

The wealth of spectral information contained in the WHAM-SS is only touched on by Figure 1 (above), a full integration map that highlights structure to emission well below 1 R. In Figure 3 (at right), four slices of the velocity-longitude plane at specific Galactic latitudes are shown. Intensities are logarithmically scaled to show the full extent of detected emission. The oscillation of the intensity-weighted center of each column around 0 km s⁻¹ as a function of longitude is the imprint of Galactic rotation on distant ($d > 1 \text{ kpc}$) gas components and traces spiral arms. A component at

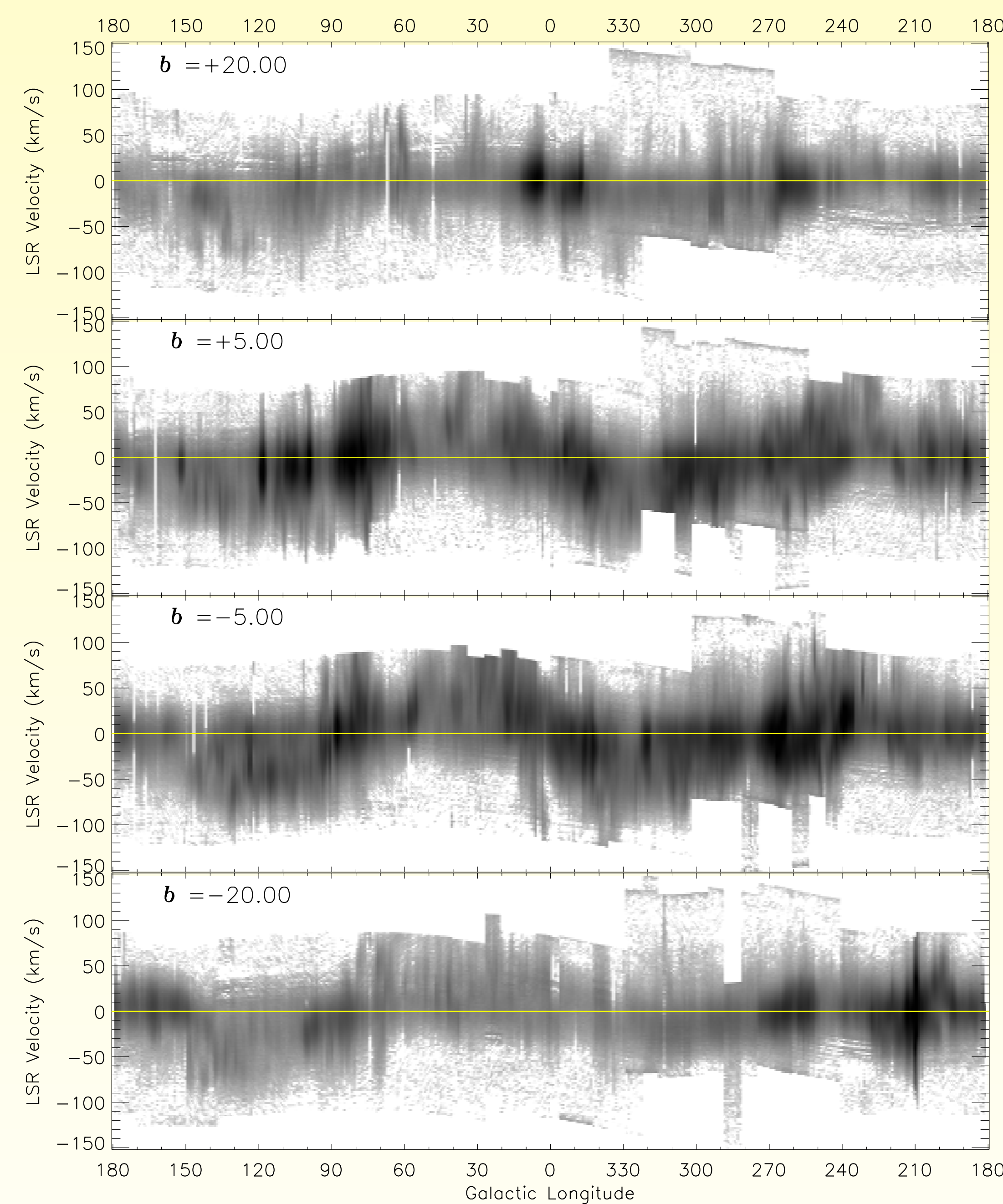


Figure 3: Velocity-Longitude Plots: Several examples of the rich kinematics present in the WHAM-SS at four different Galactic latitudes. Each column in a plot displays the H α spectrum for a given longitude as a reverse grayscale slice. Intensities are logarithmically scaled. Most spectra are limited to a single exposure extent of 200 km s⁻¹ in this release of the WHAM-SS; the v_{LSR} range shifts with position due to our survey strategy that minimizes atmospheric contamination.

0 km s⁻¹ is detected in every direction of the survey. At low and moderate latitudes a second component is detected toward most longitudes where rotation contributes significantly to radial velocity at $|v_{\text{LSR}}| = 40$ –50 km s⁻¹ from gas typically 2–4 kpc distant. This velocity component can often be traced beyond $|b| = 30^\circ$ —heights of 1–2 kpc from the plane. Higher velocity components from more distant gas participating in Galactic rotation are also occasionally present, especially at lower latitudes toward the inner Galaxy, as highlighted in Figure 3. The ionized component of gas *not* participating in rotation, intermediate- and high-velocity clouds, is also regularly detected by WHAM (e.g., Tufte, et al. 1998; Haffner et al. 2003; Barger et al. 2012).

Data from the northern portion of the survey are available from our site (<http://www.astro.wisc.edu/wham/>). The first release of the fully calibrated, all-sky WHAM-SS will be submitted for publication and publicly available in early 2016.

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Acknowledgments

The move from KPNO to CTIO and ongoing WHAM operations have been supported by NSF awards AST-0607512 and AST-1108911. WHAM was built with the help of the Wisconsin Graduate School, Physical Sciences Lab, and Space Astronomy Lab. Sam Gabett and Don Michalski provided much needed technical and design expertise during the 2008 upgrade in Wisconsin. The relocation south was made smooth due to the excellent staff at KPNO and CTIO. Without them we would not be able to remotely observe under such fine skies, collecting nearly two decades of fantastic data!

