



Ionized gas in the Smith Cloud

Alex S. Hill, L. Matthew Haffner, Ronald J. Reynolds (UW-Madison)



hill@astro.wisc.edu; haffner@astro.wisc.edu; reynolds@astro.wisc.edu

Introduction

The Smith Cloud is a high velocity cloud with a radial velocity near $+100 \text{ km s}^{-1}$ located at $(l, b) = (40^\circ, -14^\circ)$. Stellar absorption distance brackets place the cloud at a distance of $9.8 - 15.1 \text{ kpc}$ (Wakker et al. 2008). Lockman et al. (2008) presented an H I survey of the cloud using the Green Bank Telescope. They indicate that the cloud is interacting with gas in the Galactic disk. The cloud has a cometary morphology with a bright core and a diffuse, trailing tail. The velocity of the interacting gas yields a kinematic distance of $12.4 \pm 1.3 \text{ kpc}$, consistent with the stellar absorption distance constraint. This distance places the cloud 2.9 kpc below the plane and 7.6 kpc from the Galactic center, moving towards the plane at $73 \pm 26 \text{ km s}^{-1}$ with an H I mass of $> 10^6 M_{\text{sun}}$.

Bland-Hawthorn et al. (1998) obtained H α , [O III] $\lambda 5007$, and [N II] $\lambda 6548$ Fabry-Perot spectra of two $5'$ fields in the core of the cloud. They detected emission from the cloud in H α and [N II] and reported an elevated [N II] / H α ratio compared to the warm ionized medium (WIM). We present WHAM observations of ionized gas in the cloud, including the first H α map.

Observations

The Wisconsin H-Alpha Mapper (WHAM) is a dual-etalon Fabry-Perot spectrometer coupled to a siderostat. WHAM is designed to observe faint optical emission lines from diffuse gas. The instrument integrates all emission within its 1° field of view, sacrificing spatial information to obtain spectra with a resolution of 12 km s^{-1} over a 200 km s^{-1} -wide window with a sensitivity below 0.1 R in a 30 s exposure ($1 \text{ Rayleigh} = 10^6 / 4\pi \text{ photons s}^{-1} \text{ cm}^{-2} \text{ sr}^{-1}$). The instrument is described in detail by Haffner et al. (2003).

We obtained a map of the H α emission from the Smith Cloud region using WHAM with the "block" mapping technique described in Haffner et al. (2003). We observed each 1° pointing for 60 s . We integrate the observed spectrum at each pointing over the velocity range of the Smith Cloud, $+90 < v < +145$; the resulting map is shown in Figure 1. This velocity interval excludes some of the emission from the cloud but avoids contamination due to the warm ionized medium gas in the foreground Sagittarius Arm.

We also obtained deeper spectra towards the core of the cloud. Two-minute "on" observations (blue 'x' in Figure 1) were alternated with two-minute "off" observations (green 'x' in Figure 1) for a total of six minutes on source for H α and eight minutes on source each for [N II] and [S II]. We fit the off and on spectra of each line to a single atmospheric template, which we then subtracted from the on spectra. Summed, atmosphere-subtracted on spectra for each line are shown in Figure 2.

Four two-minute [O III] spectra were observed in the same fashion. Because no Galactic emission is obvious at low velocities, Figure 2 shows ON-OFF spectra with no atmospheric template for this line. Like Bland-Hawthorn et al. (1998), we do not detect [O III] emission.

Line ratios and temperature

We fit the atmosphere-subtracted spectra (Figure 2) with three Gaussians convolved with the instrument profile: one near $v_{\text{LSR}} = 0$, one near $v_{\text{LSR}} = 40 \text{ km s}^{-1}$ (corresponding to the Sagittarius Arm), and one for the Smith Cloud at 100 km s^{-1} . A fourth component not clearly associated with any gas structure was required to obtain a good fit to the H α data. Fit parameters and line intensities are shown in Table 1.

We find a line ratio $[\text{N II}] / \text{H}\alpha = 0.39 \pm 0.09$ in the Smith Cloud within the 1° beam of WHAM. This is considerably lower than the near-unity value reported by Bland-Hawthorn et al. (1998) within their $5'$ beams.

Line widths of H α and the relatively narrow [S II] line constrain the temperature of the gas, assuming the ionized hydrogen and sulfur are fully mixed (Reynolds 1985):

$$T = 10^4 \left(\left(\frac{W_H}{21.1 \text{ km s}^{-1}} \right)^2 - \left(\frac{W_S}{21.0 \text{ km s}^{-1}} \right)^2 - 0.072 \right) \text{ K}$$

With the widths in Table 1, $T = 11000 \pm 5000 \text{ K}$ in the core. The large uncertainty is primarily due to the blending of the lines.

Mass

To estimate the mass of the ionized gas in the cloud, we assume that the cloud consists of uniform-density neutral hydrogen with an ionized skin of the same density. We further assume that the depth along the line-of-sight is comparable to the projected width. In the 3 -square degree, high-column density core ($N_{\text{H I}} > 5 \times 10^{19} \text{ cm}^{-2}$, outlined by green contours in Figure 1), this yields an H α mass of $10^6 M_{\text{sun}}$.

Treating the entire $3 \times 1 \text{ kpc}$ cloud with $N_{\text{H I}} > 10^{19} \text{ cm}^{-2}$ (blue contours in Figure 1) gas as a single, uniform-density cloud in this manner, the emission measure is considerably larger than would be expected even if the H $^+$ and H 0 are fully mixed at the mean density of 0.003 cm^{-3} . The H I appears patchy, suggesting that the cloud is comprised of a number of smaller clumps which each have an ionized skin.

Assuming that the H $^+$ is evenly mixed throughout the cloud yields a density in the H α -emitting gas of 0.015 cm^{-3} . The H $^+$ mass in the low-column density region of the cloud would then be $\sim 6 \times 10^5 M_{\text{sun}}$. If the H $^+$ is an ionized "skin" with the same density as the H 0 , the neutral clouds fill $\sim 20\%$ of the volume of the Smith Cloud.

Nitrogen abundance

The line ratio $[\text{N II}] / \text{H}\alpha$ is sensitive primarily to the temperature and nitrogen abundance of the gas (Haffner et al. 1999):

$$\frac{[\text{N II}]}{\text{H}\alpha} = 1.63 \times 10^5 \left(\frac{N^+}{N} \frac{N}{H} \right) \left(\frac{H^+}{H} \right)^{-1} T_4^{0.427} e^{-2.18/T_4}$$

Because of the similar first ionization potentials of nitrogen (14.5 eV) and hydrogen (13.6 eV), $N^+ / N \approx H^+ / H$. The non-detection of [O III] supports our assumption that there is little N^{++} in this gas. Therefore, the detection of [N II] constrains the nitrogen abundance, shown in Figure 3. The highly uncertain temperature of the gas leads to an uncertain nitrogen abundance.

Conclusions

A map of H α emission from the Smith Cloud shows ionized gas coincident with the brightest H I emission, but equally bright H α in some regions with faint H I. The ionized mass of the cloud is at least as large as the neutral mass, $> 10^6 M_{\text{sun}}$. Ionized gas in the core of the Smith Cloud has an electron temperature $6000 < T(\text{K}) < 16000$. A detection of [N II] with $[\text{N II}] / \text{H}\alpha = 0.39 \pm 0.09$ shows that the cloud is not primordial, with N / H between 0.1 and $1 \times$ solar (Figure 3).

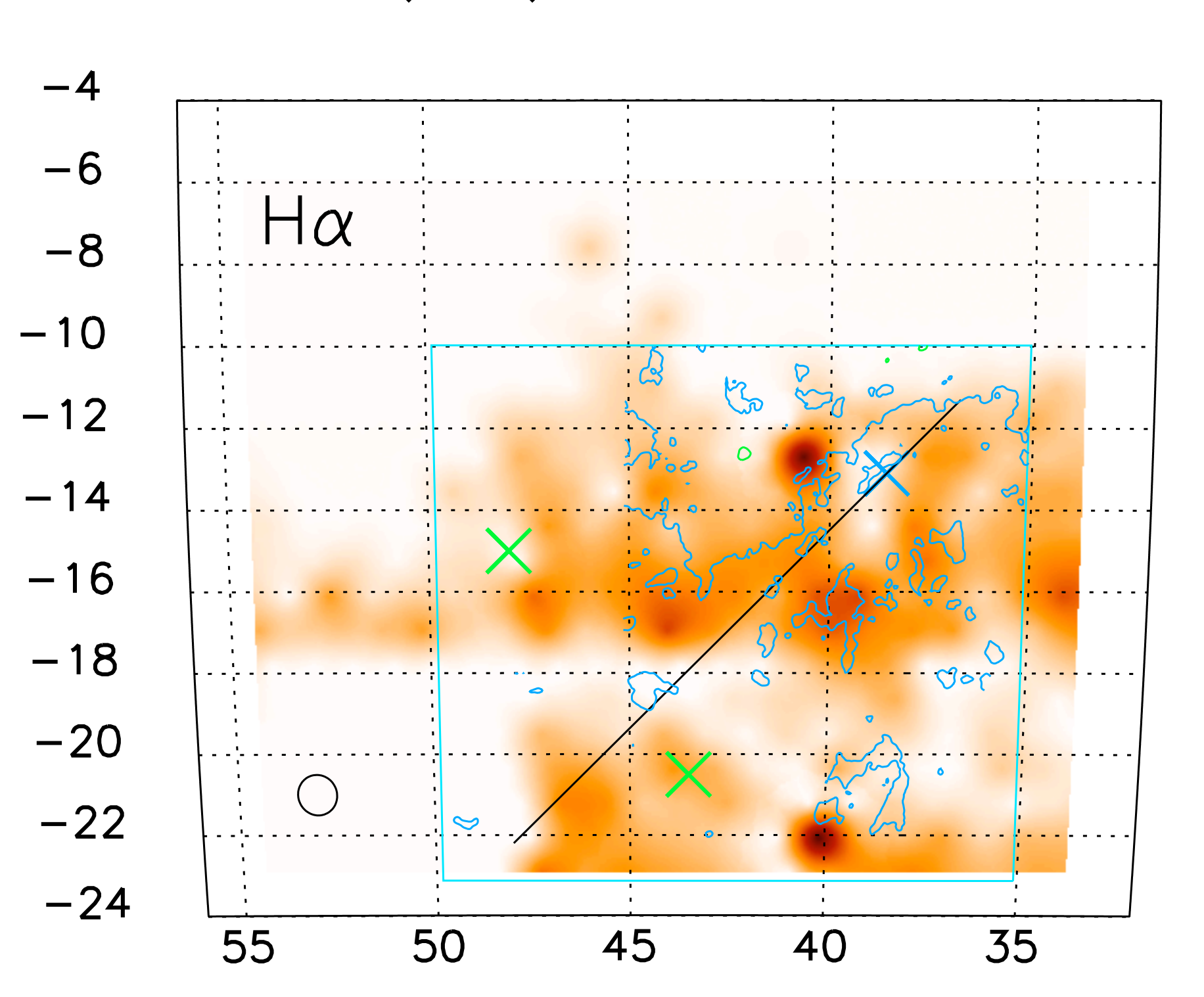
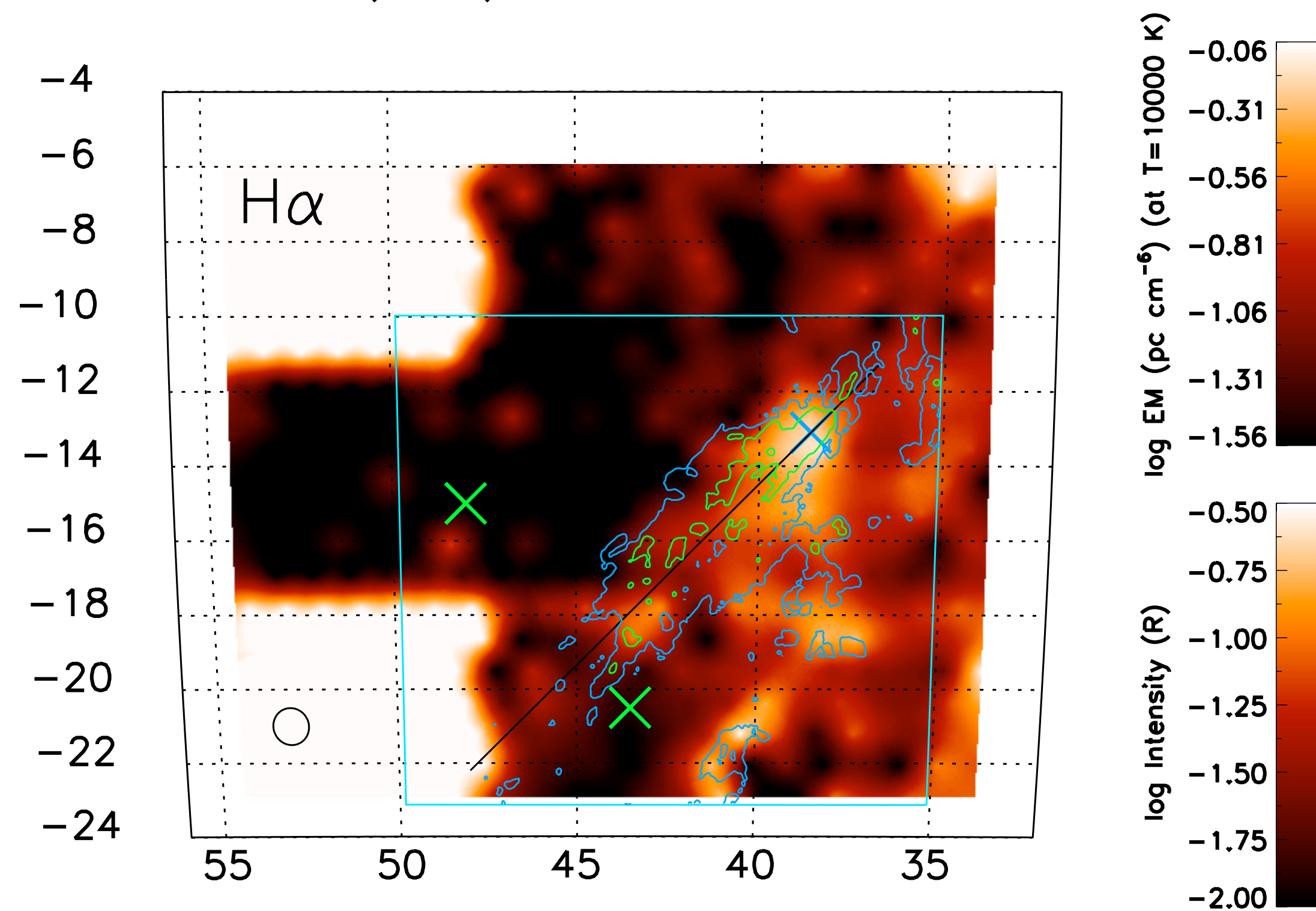
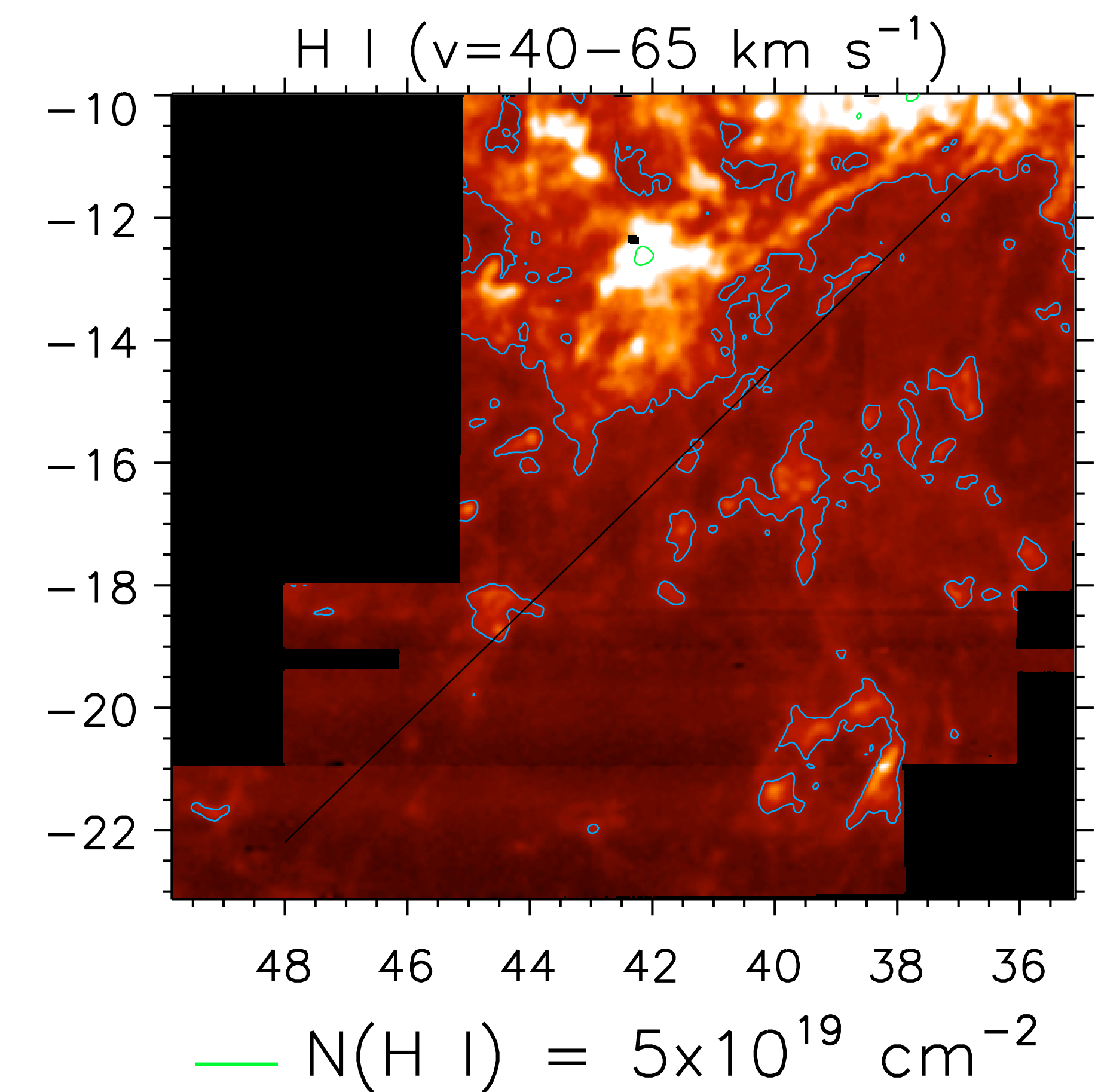
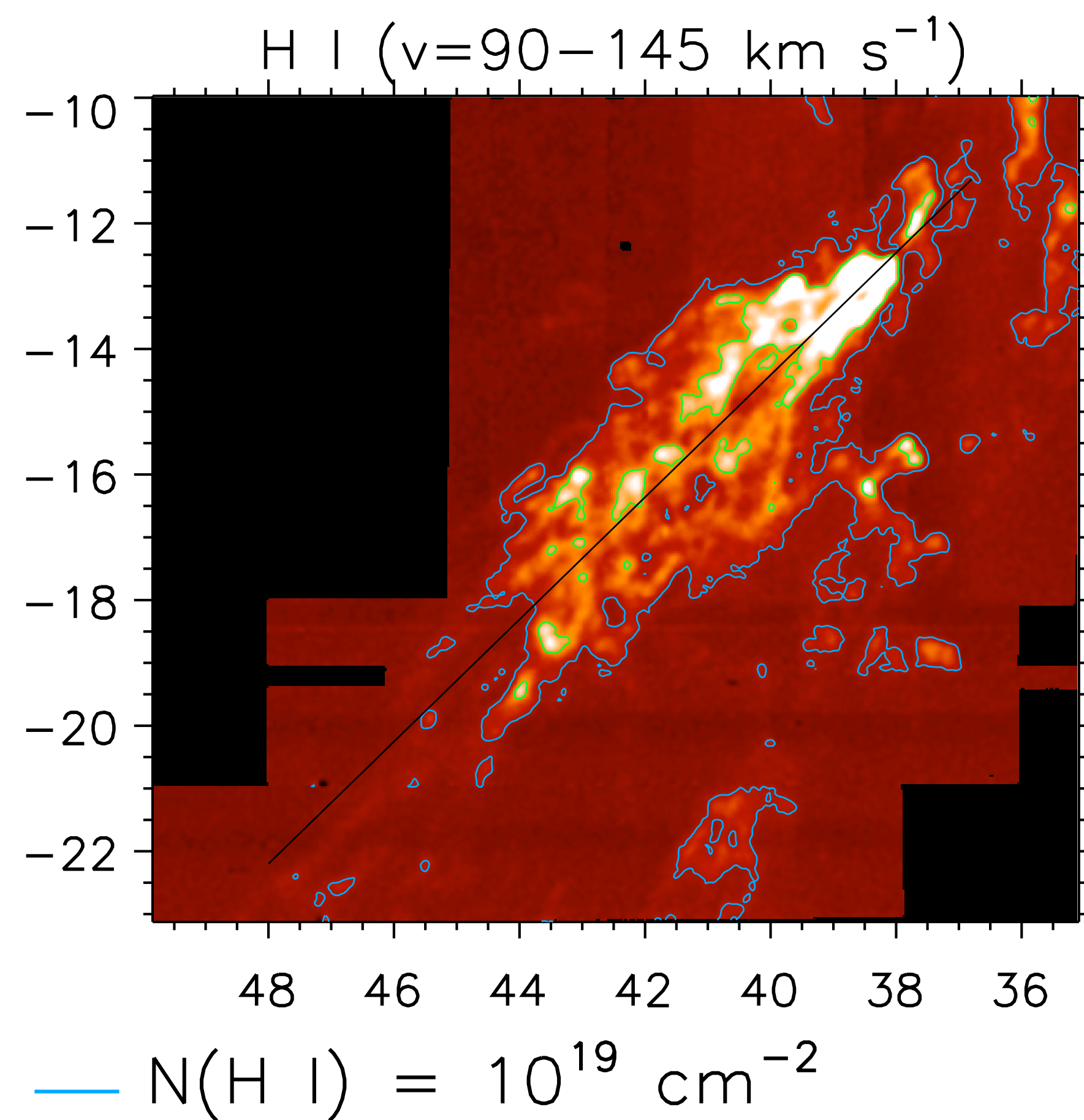


Figure 1: Top: GBT H I image (Lockman et al. 2008) of the Smith Cloud (left) and lower velocity gas (right). Contours show column densities of 10^{19} (blue) and 5×10^{19} (green) cm^{-2} integrated over the corresponding velocity intervals.

Bottom: Corresponding WHAM H α maps, with H I contours at the same column densities. The region observed in H I is outlined in cyan.

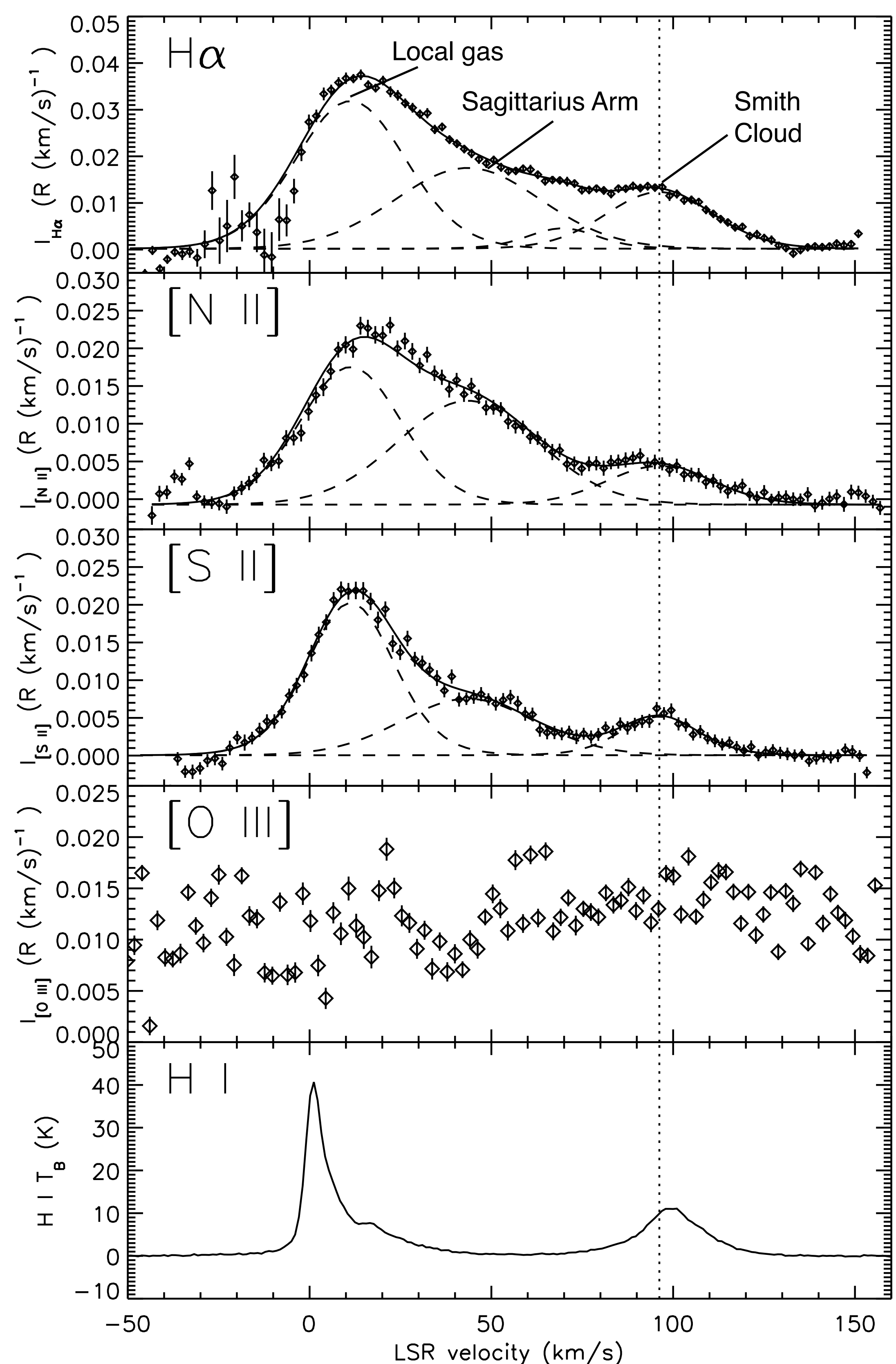


Figure 2: Spectra of the core region of the Smith Cloud. H α , [N II], and [S II] WHAM spectra were fit to an atmospheric template. The [O III] WHAM spectrum is ON-OFF. The H I spectrum is from Lockman et al. (2008). A dashed line at 96.2 km s^{-1} is shown for reference.

References

- Bland-Hawthorn, J., et al. 1998, MNRAS, 299, 611
Haffner, L. M., et al. 2003, ApJS, 149, 405
Lockman, F. J., et al. 2008, ApJ, 679, L21
Meyer, D. M., Cardelli, J. A., & Sofia, U. J. 1997, ApJ, 490, L103
Reynolds, R. J. 1985, ApJ, 294, 256
Wakker, B. P., et al. 2008, ApJ, 672, 298

Table 1.

Line	Mean (km s^{-1})	Width (km s^{-1})	Intensity (R)
H α	96.1 ± 1.1	30.2 ± 2.8	0.45 ± 0.04
H α	96.2	30.1 ± 2.1	0.46 ± 0.03
[N II]	92.8 ± 2.3	28.7 ± 5.8	0.17 ± 0.03
[N II]	96.2	29.8 ± 4.2	0.19 ± 0.03
[S II]	96.2 ± 1.1	19.7 ± 3.3	0.14 ± 0.02

Table 1: Three-component Gaussian fits to the spectra in Figure 2; parameters of the Smith Cloud component are shown. Values with no uncertainty were fixed in the fit. In H α and [N II] fits where the mean velocity was not fixed, the width of the Sagittarius Arm component was fixed to 30 km s^{-1} .

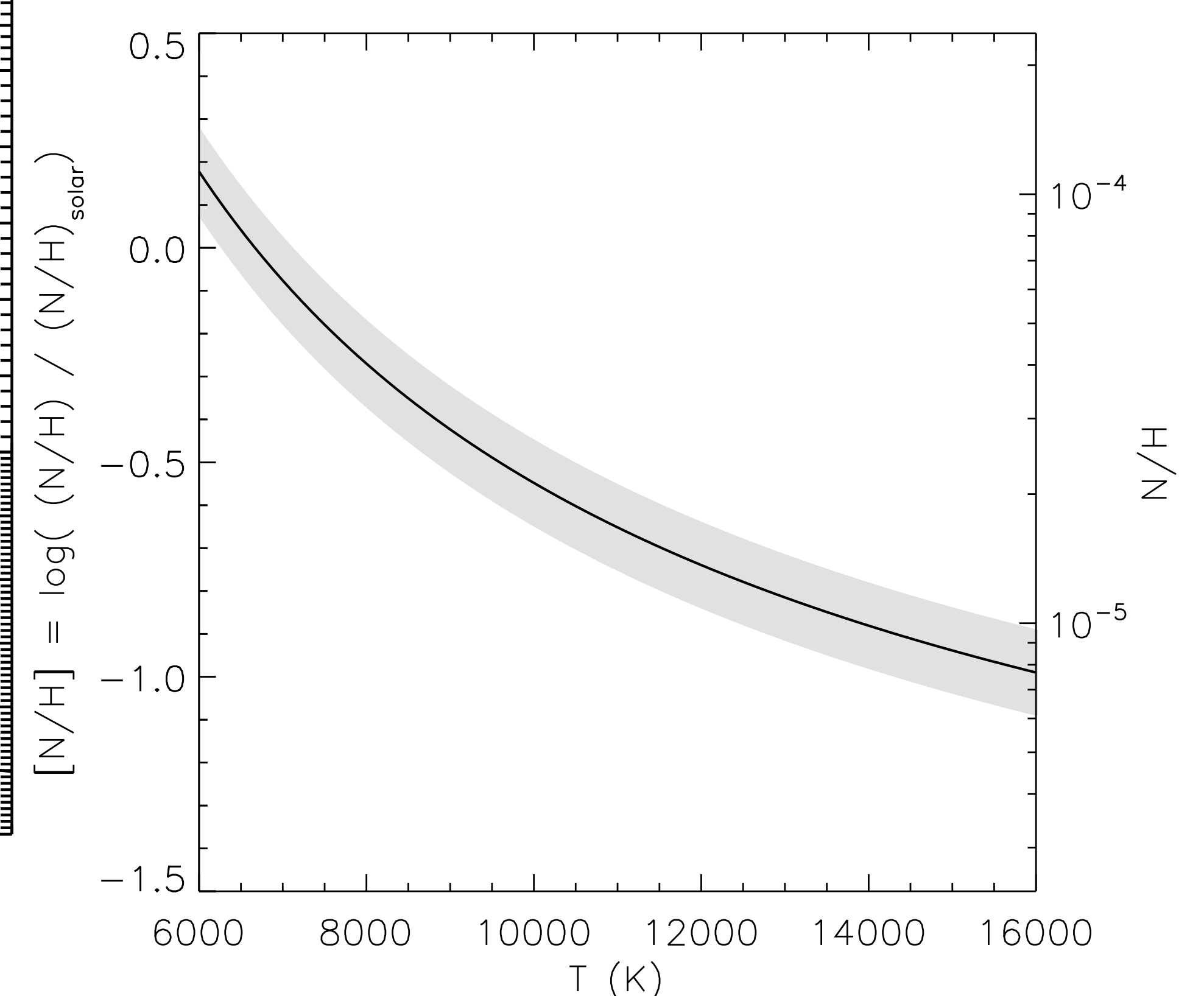


Figure 3: Nitrogen abundance as a function of temperature, given the observed $[\text{N II}] / \text{H}\alpha$ line ratio of 0.39 ± 0.09 , assuming $N^+ / N = H^+ / H$. We use $(N/H)_{\text{solar}} = 7.5 \times 10^{-5}$ (Meyer et al. 1997).

Acknowledgements

WHAM is supported by the National Science Foundation through grants AST 0204973 and AST 0607512. An American Astronomical Society International Travel Grant provided support for ASH to attend this meeting. We thank Jay Lockman for a helpful discussion and for providing the H I data cube presented in Lockman et al. (2008).