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# THOR: The HI, OH, Recombination line survey of the Milky Way

## The pilot study: HI observations of the giant molecular cloud W43<sup>★</sup>

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### ABSTRACT

To study the atomic, molecular, and ionized emission of giant molecular clouds (GMCs) in the Milky Way, we initiated a large program with the *Karl G. Jansky* Very Large Array (VLA): “THOR: The HI, OH, Recombination line survey of the Milky Way”. We map the 21 cm HI line, 4 OH lines, up to 19 H $\alpha$  recombination lines and the continuum from 1 to 2 GHz of a significant fraction of the Milky Way ( $l = 15^\circ\text{--}67^\circ$ ,  $|b| \leq 1^\circ$ ) at an angular resolution of  $\sim 20''$ . Starting in 2012, as a pilot study we mapped 4 square degrees of the GMC associated with the W43 star formation complex. The rest of the THOR survey area was observed during 2013 and 2014. In this paper, we focus on the HI emission from the W43 GMC complex. Classically, the HI 21 cm line is treated as optically thin with properties such as the column density calculated under this assumption. This approach might yield reasonable results for regions of low-mass star formation, however, it is not sufficient to describe GMCs. We analyzed strong continuum sources to measure the optical depth along the line of sight, and thus correct the HI 21 cm emission for optical depth effects and weak diffuse continuum emission. Hence, we are able to measure the HI mass of this region more accurately and our analysis reveals a lower limit for the HI mass of  $M = 6.6_{-1.8} \times 10^6 M_\odot$  ( $v_{\text{LSR}} = 60\text{--}120 \text{ km s}^{-1}$ ), which is a factor of 2.4 larger than the mass estimated with the assumption of optically thin emission. The HI column densities are as high as  $N_{\text{HI}} \sim 150 M_\odot \text{ pc}^{-2} \approx 1.9 \times 10^{22} \text{ cm}^{-2}$ , which is an order of magnitude higher than for low-mass star formation regions. This result challenges theoretical models that predict a threshold for the HI column density of  $\sim 10 M_\odot \text{ pc}^{-2}$ , at which the formation of molecular hydrogen should set in. By assuming an elliptical layered structure for W43, we estimate the particle density profile. For the atomic gas particle density, we find a linear decrease toward the center of W43 with values decreasing from  $n_{\text{HI}} = 20 \text{ cm}^{-3}$  near the cloud edge to almost  $0 \text{ cm}^{-3}$  at its center. On the other hand, the molecular hydrogen, traced via dust observations with the *Herschel* Space Observatory, shows an exponential increase toward the center with densities increasing to  $n_{\text{H}_2} > 200 \text{ cm}^{-3}$ , averaged over a region of  $\sim 10 \text{ pc}$ . While atomic and molecular hydrogen are well mixed at the cloud edge, the center of the cloud is strongly dominated by H<sub>2</sub> emission. We do not identify a sharp transition between hydrogen in atomic and molecular form. Our results, which challenge current theoretical models, are an important characterization of the atomic to molecular hydrogen transition in an extreme environment.

**Key words.** ISM: clouds – ISM: structure – ISM: atoms – stars: formation – radio lines: ISM – surveys

## 1. Introduction

It is well known that stars form in giant molecular clouds (GMCs; Mac Low & Klessen 2004; McKee & Ostriker 2007; Dobbs et al. 2014; Offner et al. 2014), which primarily consist of molecular hydrogen. Yet it is still under debate whether molecular hydrogen is actually necessary for star formation or whether molecular hydrogen and stars only form under the same conditions side by side (Glover & Clark 2012). The density within these clouds is high enough (particle density:  $n > 1\text{--}100 \text{ cm}^{-3}$ , column density:  $N > 1\text{--}100 M_\odot \text{ pc}^{-2} \sim 10^{20}\text{--}10^{22} \text{ cm}^{-2}$ ) for molecular hydrogen to become self-shielded from the interstellar radiation field, which would otherwise dissociate the H<sub>2</sub> molecules (e.g., Dobbs et al. 2014). Hence, molecular clouds form in the interior of large clouds of neutral hydrogen, which

themselves are the environment of molecular clouds. Another open question is the fraction of neutral hydrogen within molecular clouds and how this affects physical conditions (Krčo & Goldsmith 2010; Goldsmith & Li 2005). Furthermore, the correlation between the transition between these two fundamental states of hydrogen and the corresponding physical conditions is also still unclear.

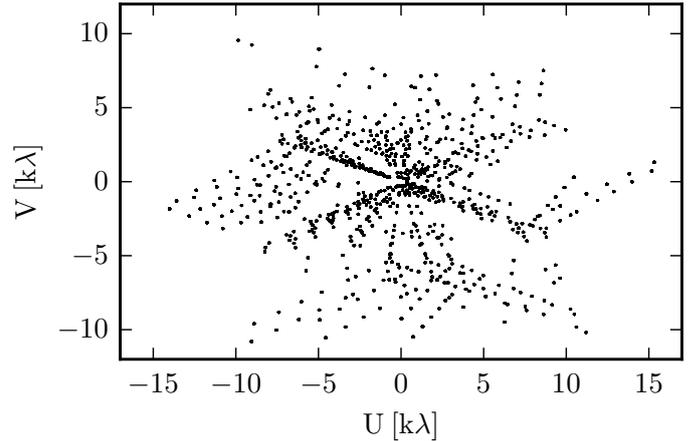
As cold molecular hydrogen is challenging to observe directly, it is difficult to study its distribution in detail. Classically, the low- $J$  rotational transitions of CO are used as a tracer for H<sub>2</sub>, however, recent simulations and observations show that a large amount ( $\sim 40\%$ ) of H<sub>2</sub> is CO-dark and therefore not well traced by CO (Pineda et al. 2013; Smith et al. 2014). Another approach to study molecular hydrogen is via observations of thermal dust emission or dust extinction (Lada et al. 2007; Molinari et al. 2010; Kainulainen & Tan 2013; Kainulainen et al. 2013). In contrast, the 21 cm spin-flip transition of hydrogen offers a well-known method to measure the atomic gas content. Even

<sup>★</sup> The HI data cubes are only available at the CDS via anonymous ftp to [cdsarc.u-strasbg.fr](http://cdsarc.u-strasbg.fr) (130.79.128.5) or via <http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/580/A112>

though the 21 cm line is well studied (e.g., Radhakrishnan et al. 1972; Gibson et al. 2000, 2005a; Taylor et al. 2003; Heiles & Troland 2003a,b; Strasser & Taylor 2004; Goldsmith & Li 2005; Stil et al. 2006; Kalberla & Kerp 2009; McClure-Griffiths et al. 2012; Roy et al. 2013a; Fukui et al. 2015; Murray et al. 2014; Motte et al. 2014), it is difficult to disentangle the different contributions of the cold and warm HI in emission and absorption for different spin temperatures and optical depths. In addition, radio continuum emission at the frequency of the HI emission line can also suppress the intensity of the observed HI emission, an effect that is especially significant for the Galactic plane.

To address cloud formation, HI to H<sub>2</sub> formation as well as many other issues in ISM studies of the Milky Way, we initiated the THOR project: the HI, OH, Recombination line survey of the Milky Way (Beuther et al., in prep.). We are using the *Karl G. Jansky* Very Large Array (VLA) in a large program to observe the HI line at 21 cm, four OH lines at 1612, 1665, 1667, and 1720 MHz, 19 H $\alpha$  radio recombination lines (RRL) and the continuum from 1–2 GHz, which is split in 8 sub-bands. These observations result in an angular resolution of 15–20". We were awarded more than 200 h observing time to map a significant fraction of the Milky Way (Galactic longitude  $l = 15\text{--}67^\circ$ , Galactic latitude  $|b| \leq 1^\circ$ ) for the semester 2013A and 2014B. To test our observing strategy and data reduction, we began with a pilot study of a  $2^\circ \times 2^\circ$  field around W43, which was completed in 10 h. In this paper, we describe the pilot study, which was observed in the semester 2012A. As the wealth of this data set is immense, we focus on the HI line here, but consecutive papers will focus on other aspects of the pilot study (e.g., Walsh et al. 2015; Johnston et al., in prep.). The full survey will be presented in Beuther et al. (in prep.).

The field chosen for the pilot study is around the massive star-forming complex W43 ( $l = 29.2\text{--}31.5^\circ$ ,  $|b| \leq 1^\circ$ ). This region is situated at the intersection of the Galactic bar and the first spiral arm (Scutum-Centaurus Galactic arm, Nguyen Luong et al. 2011; Carlhoff et al. 2013), leading to complex kinematic structures and possibly high star formation activity. The complex W43 is referred to as a Galactic mini-starburst region (Motte et al. 2003; Bally et al. 2010) and shows a star formation rate of  $\sim 0.1 M_\odot \text{ yr}^{-1}$  (Nguyen Luong et al. 2011) or 5–10% of the star formation rate in the entire Milky Way. Motte et al. (2014) found velocity gradients in CO and HI 21 cm emission. These velocity gradients could indicate large scale velocity flows, which could cause vast star formation activity. Motte et al. (2014) also do not find a threshold for the HI column density, which is proposed by theoretical models (Krumholz et al. 2008, 2009). They argue that we see several transition layers of HI and H<sub>2</sub> along the line of sight and that the theoretical models are not suited to describe complicated molecular cloud complexes such as W43. The center of W43 harbors a large HII region, which is fueled by a Wolf-Rayet and OB star cluster (Liszt et al. 1993; Lester et al. 1985; Blum et al. 1999). Furthermore, W43 exhibits several high-mass starless molecular clumps, which are still in an early stage of star formation (Beuther et al. 2012; Louvet et al. 2014). Some massive dense clumps can potentially form young massive clusters, progenitors of globular clusters (Louvet et al. 2014; Nguyen-Lu'o'ng et al. 2013). The Bar and Spiral Structure Legacy survey (BeSSeL; Brunthaler et al. 2011; Reid et al. 2014) determined the distance to W43 to be  $5.5 \pm 0.4$  kpc from parallax measurements of methanol and water masers (Zhang et al. 2014). This result has to be treated cautiously, as none of the four masers used for the parallax measurements are spatially directly associated with W43-Main.



**Fig. 1.** UV coverage of one pointing (centered at RA 18:47:54.125746, Dec –03:28:42.90941, J2000) after  $4 \times 2$  min observing time.

## 2. Observations and data reduction

### 2.1. VLA Observations

We mapped a  $2^\circ \times 2^\circ$  field around W43 ( $l = 29.2\text{--}31.5^\circ$ ,  $|b| \leq 1^\circ$ ) during the 2012A semester with the *Karl G. Jansky* Very Large Array (VLA) in New Mexico in C-configuration (Project 12A-161). As we used Nyquist sampling at 1.42 GHz with a primary beam size of 32', we needed 59 pointings to cover the 4 square degree mosaic. We chose a hexagonal geometry for the mosaic, similar to the VGPS survey (Stil et al. 2006). This results in a smooth areal sensitivity function with fluctuations of less than 1% in the inner region and a decreasing sensitivity toward the edges of our field. We observed each pointing for  $4 \times 2$  min, which results in an overall observation time of ten hours, including  $\sim 2$  h overhead for flux, bandpass, and complex gain calibration. The resulting uv-coverage for one pointing, after  $4 \times 2$  min of observing time, is shown in Fig. 1. We performed the observations in two blocks each with 5 h observing time in April 2012. We chose the quasar 3C 286 as a flux and bandpass calibrator and the quasar J1822-0938 as a complex gain calibrator, which was observed every  $\sim 13$  min. Observing at L-band and using the new WIDAR correlator, we were able to simultaneously observe the HI 21 cm line, 4 OH lines (1612, 1665, 1667 and 1720 MHz) and 12 H $\alpha$  RRL. For the pilot field, we had the spectral capability to observe 12 H $\alpha$  RRL, however, for the full THOR survey we were able to observe 19 H $\alpha$  RRL. The continuum, consisting of eight spectral windows between 1 and 2 GHz, was observed in full polarization. For the HI 21 cm line, we used a bandwidth of 2 MHz with a channel width of 1.953 kHz. This results in a velocity range of  $\pm 200 \text{ km s}^{-1}$  and a channel spacing of  $\Delta v \approx 0.41 \text{ km s}^{-1}$ .

### 2.2. Calibration

To edit and calibrate the data, we use CASA (version 4.1.0) with a modified VLA pipeline<sup>1</sup> (version 1.2.0). The pipeline does automatic flagging for, e.g., zeros or shadowing of antennas. We manually performed additional flagging for radio frequency interference (RFI) and bad antennas. The pipeline also applies the bandpass, flux, and complex gain calibrator to the data. We do not use Hanning smoothing and do not recalculate the data

<sup>1</sup> <https://science.nrao.edu/facilities/vla/data-processing/pipeline>

weights (“statwt”) at the end of the pipeline. The implemented modifications help to improve the quality check, and we do some flagging and editing by hand subsequently. A full description of our quality check method will be presented in our forthcoming overview paper (Beuther et al., in prep.).

### 2.3. Imaging and deconvolution

The HI emission and absorption covers a large range of angular scales, which is challenging for data reduction as the VLA C-Array filters out most of the large scale structure. Therefore, we combined our THOR data with the VGPS data (VLA D-Array and Green Bank Telescope data, [Stil et al. 2006](#)) to overcome missing flux problems and to reconstruct the large scale structure. We tested three different methods to combine the THOR and VGPS data. First, we tried to combine the visibility of the VGPS and THOR data and clean them together. Second, we tried the “feather” command in CASA and third, we used the images of the VGPS survey as a starting model (parameter “modelimage”) for the clean process in CASA. After testing these three methods, we choose the third method, as this method provides the best results considering noise, side lobes, and recovery of large scale structure. We compared point source peak fluxes of the combined images to the VGPS data to check for consistency. The difference is at the 10% level. The clean process was stopped at the  $5\sigma$  noise level.

We smoothed over three channels to reduce the noise, resulting in a velocity resolution of  $1.24 \text{ km s}^{-1}$ . This was the best compromise between computational time, noise, and a sufficient spectral resolution to distinguish absorption/emission features. The synthesized beam was set to  $20''$ , which is slightly larger than the best resolution achievable ( $\sim 16''$ ). The weighting parameter was set to  $\text{robust} = 0.5$ , which is a combination of natural and uniform weighting. These methods result in an rms of  $\sim 14 \text{ K}$  ( $9 \text{ mJy beam}^{-1}$ ) for emission free channels and up to a factor of 2 or 3 more in channels with strong emission due to systematic errors, such as side lobes. The dynamical range of our data set is  $\sim 100\text{--}200$ , depending on the region. In the following, the HI absorption and small scale structure is based on the THOR data, whereas the large scale emission is based on the VGPS data.

The 21 cm continuum data are taken from the HI data cube for high and low velocities ( $-80$  to  $-50$  and  $135$  to  $155 \text{ km s}^{-1}$ ), which are not affected by HI emission or absorption. Therefore the data reduction and imaging for the 21 cm continuum data is the same as for the HI data, and we can avoid systematic errors due to different data reduction methods.

### 2.4. $\text{H}_2$ column density

As we will compare the HI and  $\text{H}_2$  column density in Sect. 5.4, we need an estimate of the  $\text{H}_2$  content. We use dust observations from the *Herschel* Space Observatory to assess the  $\text{H}_2$  column density. These observations are based on the HiGal survey ([Molinari et al. 2010](#)). The  $\text{H}_2$  column density map is taken from Fig. 9 of [Nguyen-Lu’o’ng et al. \(2013\)](#), which was derived by SED fitting methods described by [Hill et al. \(2011\)](#). As the dust observations have no velocity resolution, we see all the dust and thus gas along the line of sight. [Carlhoff et al. \(2013\)](#) showed that the *Herschel* dust data are similar within the uncertainties to the CO data at the velocity range of W43 ( $v_{\text{LSR}} = 60\text{--}120 \text{ km s}^{-1}$ ). Hence, the *Herschel* dust observations are dominated by the emission from W43 and the contributions

of other regions along the line of sight can be neglected. We refrain from using CO data to estimate the molecular content of W43, as CO does not trace all molecular hydrogen (e.g., [Smith et al. 2014](#)) and CO becomes optically thick for the dense interior of W43 ([Carlhoff et al. 2013](#)).

## 3. HI radiative transfer

In this section, we explain the methodology we used to determine the spin temperature, optical depth and column density of the neutral hydrogen. Even though the HI 21 cm line is a well-known probe of these quantities, the arrangement of different HI components with different temperatures along the line of sight can complicate these measurements. First we explain the classical methods to determine the column density via optically thin emission and HI continuum absorption (HICA). Subsequently, we outline the limitations of these methods and describe our approach to correct for optical depth and weak continuum emission. Although the basics of this approach are discussed in the literature (e.g., [Wilson et al. 2010](#)), we modified the classical approach to account for the continuum emission and optical depth. Therefore, we outline the calculations in more detail.

All following values are frequency dependent. To keep the equations and description simple, we drop the frequency dependencies in the equations. We emphasize, however, that the following emission/absorption mechanisms only works for identical frequencies and, therefore, identical velocities.

### 3.1. Column density

The classical approach to determine the HI column density is given by [Wilson et al. \(2010\)](#) as

$$\frac{N_{\text{H}}}{\text{cm}^{-2}} = 1.8224 \times 10^{18} \frac{T_{\text{S}}}{\text{K}} \int_{-\infty}^{\infty} \tau(v) d\left(\frac{v}{\text{km s}^{-1}}\right), \quad (1)$$

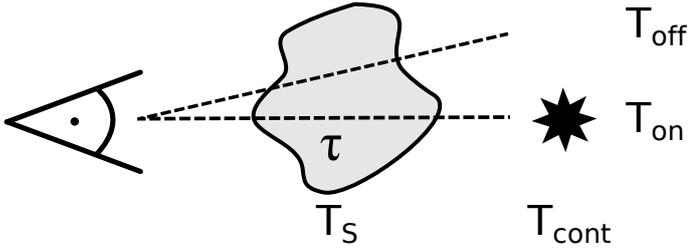
where  $N_{\text{H}}$ ,  $T_{\text{S}}$  and  $\tau$  are the column density, the spin temperature, and the velocity dependent opacity, respectively. The spin temperature  $T_{\text{S}}$  describes the relative population of the spin states of the hydrogen atom ([Wilson et al. 2010](#)). As  $T_{\text{S}}$  is the equivalent of the excitation temperature for molecules, it is only equal to the kinetic temperature in local thermodynamic equilibrium (i.e., when there are enough collisions to thermalize the gas). We assume in the following that the spin temperature  $T_{\text{S}}$  does not vary significantly within one velocity channel. In most cases, neither  $T_{\text{S}}$  nor the optical depth are known. The simplest assumption is that the HI emission is optically thin (see Sect. 3.2).

### 3.2. Optically thin HI emission

Under the optically thin assumption, without background continuum emission, the expression for the brightness temperature  $T_{\text{B}}$  simplifies to the following:

$$T_{\text{B}} = T_{\text{S}} (1 - \exp(-\tau)) \approx T_{\text{S}} \tau. \quad (2)$$

This simplification provides a linear relation between the column density (Eq. (1)) and the brightness temperature. Hence, we can estimate the column density directly from the measured brightness temperature  $T_{\text{B}}$ . This method is used in several studies and is well described in the literature (e.g., [Lee et al. 2012](#); [Motte et al. 2014](#); [Wilson et al. 2010](#)). Below, we discuss its limitations and describe a procedure to overcome them.



**Fig. 2.** Sketch of the arrangement of the HI cloud with spin temperature  $T_S$  and optical depth  $\tau$  and the continuum source in the background. The on and off positions are marked.

### 3.3. HI optical depth

The HI continuum absorption method is the classical method to determine properties of the cold neutral medium (Strasser & Taylor 2004; Heiles & Troland 2003a,b; Strasser et al. 2007). This method is based on strong continuum sources ( $T_B > 300$  K), such as Galactic HII regions, active galactic nuclei (AGNs), or extragalactic jets. As the brightness temperature of these continuum sources is larger than the typical spin temperature of the HI clouds ( $T_S \sim 100$  K), we observe the HI cloud in absorption. In addition, the absorption spectrum is dominated by the cold neutral medium, as the HI absorption coefficient is proportional to  $T^{-1}$ .

The classical observing strategy is the ‘‘on-off’’ observation (see Fig. 2). The ‘‘on-source’’ points toward the continuum source and reveals the absorption spectrum ( $T_{\text{on}}$ ), whereas the ‘‘off-source’’ points slightly offset from the continuum source and reveals the emission spectrum ( $T_{\text{off}}$ ). During data reduction, the continuum is not subtracted from the HI spectrum. Hence, we can measure  $T_{\text{cont}}$  for channels that are not affected by the HI line. The general assumption is that the on-source and off-source spectra originate from the same cloud with the same properties. Therefore, it is important to have these two positions as close together as possible.

The measured on-source and off-source brightness temperatures are

$$\begin{aligned} T_{\text{on}} &= T_S (1 - \exp(-\tau)) + T_{\text{cont}} \exp(-\tau), \\ T_{\text{off}} &= T_S (1 - \exp(-\tau)). \end{aligned} \quad (3)$$

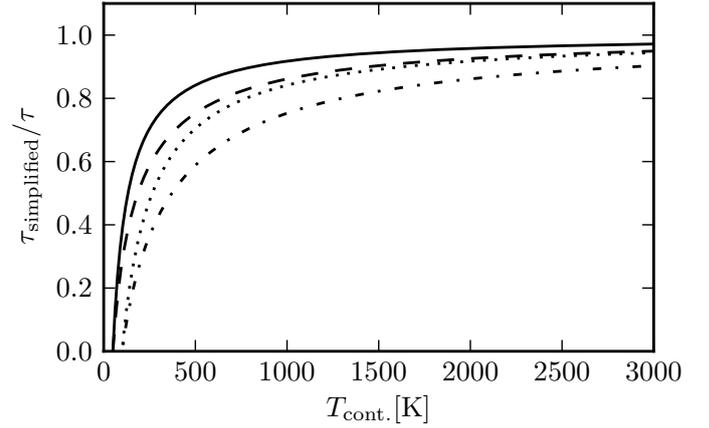
Hence, the optical depth is

$$\tau = -\ln\left(\frac{T_{\text{on}} - T_{\text{off}}}{T_{\text{cont}}}\right). \quad (4)$$

The spin temperature can then be determined from

$$T_S = \frac{T_{\text{off}}}{1 - e^{-\tau}}. \quad (5)$$

The advantage of the HICA method is the direct measurement of the optical depth and the spin temperature. The challenge of the HICA method is the need for strong continuum sources. Since most of the strong continuum sources are point sources, it is not possible to map the entire Milky Way, but instead the result is an incomplete grid of measurements. This way, it is not possible to map the intrinsic structure of individual clouds. Furthermore, the spin temperature does not describe the actual temperature of the cloud, but is a mean of the cold and warm component, weighted by their column densities (Strasser & Taylor 2004). Consequently, the derived spin temperature is an upper limit for the cold component.



**Fig. 3.** Optical depth simplification. The simplified optical depth is calculated by neglecting the spin temperature of the cloud. The solid and dashed lines represent a spin temperature of 50 K with optical depths of 1 and 2, respectively. The dotted and dash-dotted lines represent a spin temperature of 100 K with optical depths of 1 and 2, respectively.

As some Galactic continuum sources, such as W43-Main, are extended, it is difficult to determine a proper off position. Nevertheless, it is still possible to determine the optical depth. As we use the VLA C+D array observations, including the continuum without the GBT data, we filter out most smooth large scale structure. The VLA C+D array data show HI emission of less than 30 K. Therefore, we can neglect the emission of the HI cloud in Eq. (3) and set  $T_{\text{off}} = T_S (1 - \exp(-\tau)) = 0$  and calculate the optical depth without any off position as

$$\tau_{\text{simplified}} = -\ln\left(\frac{T_{\text{on}}}{T_{\text{cont}}}\right). \quad (6)$$

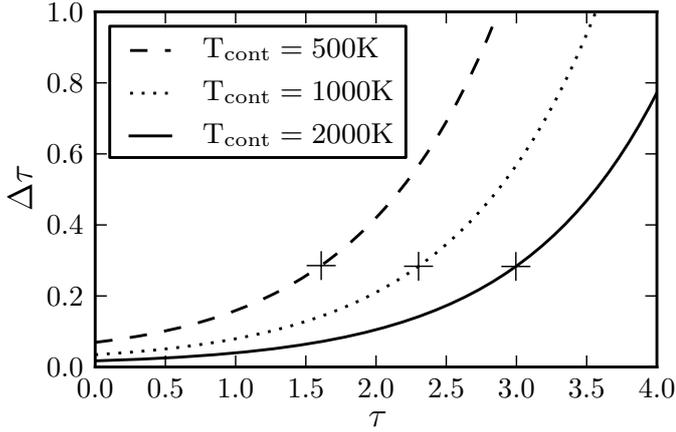
Even without the effect of filtering out the HI emission due to the interferometer, this simplification holds for strong continuum sources ( $T_{\text{cont}} > 500$  K). Figure 3 shows the relation between the simplified and actual optical depth as a function of the continuum brightness temperature, not taking the filtering of the interferometer into account. It clearly shows that even for high spin temperatures ( $T_S = 100$  K) and high optical depth ( $\tau = 2$ ), we miss less than 10% of the optical depth for a strong continuum source ( $T_{\text{cont}} \approx 2500$  K). Therefore, we are able to measure the optical depth for the HII region in the center of W43, even though we cannot determine a proper off position.

We also consider the effect of optically thick clouds. For these optically thick clouds, the absorption spectra approaches zero. Due to the rms of the spectra, it is also possible that the absorption spectra become negative, which is physically not meaningful. We set the optical depth to a lower limit for all absorption values that are close to zero. If the absorption spectrum  $T_{\text{on}}$  is smaller than 5 times the rms, we set the optical depth to

$$\tau_{\text{lower-limit}} = -\ln\left(\frac{5 \cdot \sigma(T_{\text{on}})}{T_{\text{cont}}}\right). \quad (7)$$

We find that the optical depth saturates for the main velocity range of W43-Main, which has consequences for our interpretation and conclusions.

The uncertainty of the optical depth (Eq. (4)) depends on  $T_{\text{on}}$ ,  $T_{\text{off}}$  and  $T_{\text{cont}}$ . To estimate the uncertainty, we assume an uncertainty of 20 K for all three quantities. The uncertainty of the optical depth is shown in Fig. 4 as a function of the optical depth itself for three different continuum brightness values. It shows



**Fig. 4.** Absolute uncertainty of the optical depth as a function of the optical depth itself for three different continuum background sources. The dashed, dotted, and solid line represent continuum sources with a brightness temperature of  $T_{\text{cont}} = 500$  K, 1000 K and 2000 K, respectively. The crosses on each line show the lower limit of the optical depth that we can observe for the given continuum brightness temperature. For larger optical depths, the absorption spectra saturates (see Sect. 4.1 for more detail).

that the uncertainty increases significantly for increasing optical depths. However, we are not able to measure these high optical depths, as the absorption spectra saturates for optically thick clouds, and we report lower limits (see Eq. (7)). These lower limits are marked with crosses in Fig. 4. Up to the lower limit of the optical depth the corresponding uncertainty is  $\sim 0.3$  for the three different continuum brightness values. For strong continuum sources, such as W43-Main, the uncertainty of the optical depth is  $\sim 10\%$  up to the lower limit of  $\sim 3$ .

### 3.4. Column density corrections

In addition to distinct, small continuum sources, such as HII regions or extragalactic jets, we also find weak diffuse continuum emission in the Galactic plane. This component has a strength between 10 and 50 K. Therefore, it is not strong enough to induce absorption features (HICA), but nevertheless it can influence the HI emission. To overcome this problem, the classical approach is to subtract this weak continuum emission during data reduction. Hence, we subtract  $T_{\text{cont}}$  in Eq. (3), and we find

$$\begin{aligned} T_{\text{B}} &= T_{\text{S}}(1 - \exp(-\tau)) + T_{\text{cont}} \exp(-\tau) - T_{\text{cont}} \\ &= (T_{\text{S}} - T_{\text{cont}})(1 - \exp(-\tau)). \end{aligned} \quad (8)$$

This shows that even if we subtract the continuum from our data, it can still influence the measured brightness temperature. If we neglect the weak continuum emission, our measured HI emission is suppressed and thus the calculated column density is underestimated. Therefore it is important to investigate the influence of the weak diffuse continuum emission.

In the following, we assess the assumption of optically thin emission and the influence of weak diffuse continuum emission on the determination of the measured column density for appropriate model clouds. We assume two model clouds, which have a spin temperature of 50 K and 100 K, respectively. We use Eq. (1) to calculate the expected column density  $N_{\text{HI}}$  for different optical depths in one velocity channel ( $dv = 1.24 \text{ km s}^{-1}$ ). Furthermore, we assume the cloud to be optically thin and use Eq. (2) to calculate the brightness temperature of the HI emission. Using this result, we can calculate the column density of the cloud, but this

time with the simplification of optically thin emission. Hence, we call it the observed column density  $N_{\text{HI}}(\text{observed})$ . The solid lines in Fig. 5 show the ratio of the expected and observed column density for a range of optical depths. Obviously, for small optical depths ( $\tau < 0.1$ ), our assumption of optically thin emission is sufficient and we observe more than 90% of the expected column density. For larger optical depths ( $\tau > 0.1$ ), however, we miss a significant fraction of the column density ( $>40\%$ ).

In addition, we add weak continuum emission in the background, which changes the brightness temperature according to Eq. (8) and therefore suppresses the HI emission. Nevertheless, if we still assume optically thin emission and do not consider the weak continuum emission, we can calculate the observed column density. The dashed and dotted lines in Fig. 5 show this case for continuum emission of 10 K and 30 K, respectively. Even for small optical depths ( $\tau < 0.1$ ) we miss a significant fraction of the column density, which depends on the ratio of the spin temperature and the continuum emission brightness temperature. In the worst case ( $T_{\text{S}} = 50$  K and  $T_{\text{cont}} = 30$  K), we observe only 40% of the expected column density, even for small optical depths.

To summarize, we measure the brightness temperature of the HI emission  $T_{\text{B}}$ , as well as the brightness temperature for the continuum  $T_{\text{cont}}$  and combine this information with the optical depth  $\tau$ , which we measure toward strong continuum sources. This allows us to calculate the corrected column density, by combining Eqs. (1) and (8), which yields

$$N_{\text{H}} = 1.8224 \times 10^{18} \left( \frac{T_{\text{B}}}{1 - e^{-\tau}} + T_{\text{cont}} \right) \int_{-\infty}^{\infty} \tau(v) dv, \quad (9)$$

where the column density  $N_{\text{H}}$  is given in units  $\text{cm}^{-2}$ , the brightness temperature  $T_{\text{B}}$  and the continuum brightness temperature  $T_{\text{cont}}$  are measured in K, and the velocity  $dv$  is given in  $\text{km s}^{-1}$ .

### 3.5. Continuum correction for strong point sources

For the HI continuum absorption (HICA) toward strong continuum sources, we also have to consider weak diffuse continuum emission, which contributes to the on and off positions. Therefore we have to modify the equation for the on and off positions (Eq. (3)) by adding another term for the weak diffuse continuum emission, which we call  $T_{\text{cont,dif}}$ . This does not change our result for the optical depth (Eq. (4)), as the optical depth depends solely on the difference between  $T_{\text{on}}$  and  $T_{\text{off}}$ . For the calculated spin temperature, however, we have to modify Eq. (5) to the following:

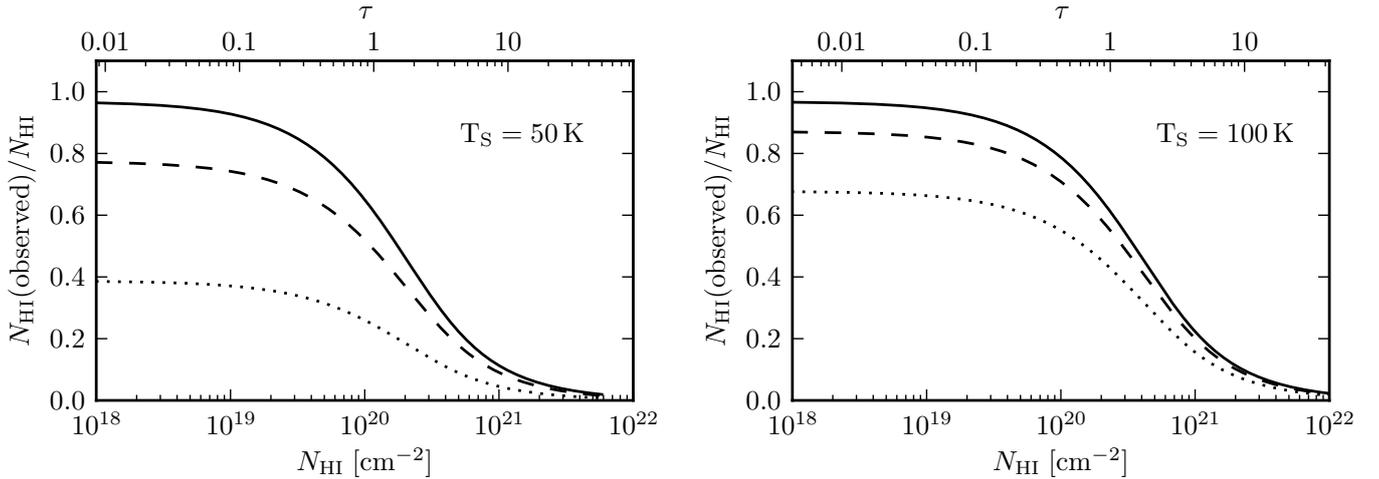
$$T_{\text{S}} = \frac{T_{\text{off}} - T_{\text{cont,dif}} e^{-\tau}}{1 - e^{-\tau}}. \quad (10)$$

The effect of the diffuse continuum correction is discussed in Sect. 5.2.

## 4. Results

### 4.1. Optical depths determined using compact continuum sources

As described in Sect. 3.3, we can use strong continuum sources in the background as light-houses that shine through foreground HI clouds and create absorption spectra. Below we characterize the continuum sources.



**Fig. 5.** Ratio of observed and expected column density for a model cloud with spin temperatures of  $T_S = 50$  K and 100 K for the *left and right panel*, respectively. The solid lines show the ratio for the assumption of optically thin emission. The dashed and dotted lines show the ratio for the assumption of optically thin emission and a diffuse continuum source with brightness 10 K and 30 K, respectively.

**Table 1.** Continuum point sources that were used for HI absorption studies.

Name	RA(2000) (h:m:s)	Dec(J2000) (°:':")	Maj × Min ('' × '')	$T_{\text{cont}}$ K	$T_{\text{cont,dif}}$ K	Far Scutum arm	Spectral index	Location
G31.388−0.384	18:49:59.1	−1.32.55.9	21.3 × 20.3	2055 ± 24	20.2	yes	−0.82	ext. gal
G31.411+0.307	18:47:34.1	−1.12.45.5	24.0 × 23.0	914 ± 26	19.4	no	0.63	gal.
G30.234−0.138	18:47:00.4	−2.27.52.9	21.7 × 20.7	853 ± 23	42.1	no	0.00	gal.
G30.534+0.021	18:46:59.3	−2.07.27.9	28.0 × 21.5 <sup>a</sup>	653 ± 21	35.9	no	0.21	gal.
G31.242−0.110	18:48:44.7	−1.33.13.7	25.1 × 21.2	573 ± 22	30.1	no	0.58	gal.
G29.090+0.512	18:42:35.8	−3.11.04.7	20.0 × 10.0	571 ± 44	20.5	yes	−1.03	ext. gal
G30.744+1.008	18:43:51.4	−1.29.14.8	23.1 × 20.1	472 ± 36	16.9	yes	−0.90	ext. gal
G30.699−0.630	18:49:36.3	−2.16.27.2	22.3 × 19.6	403 ± 18	23.4	yes	−1.11	ext. gal

**Notes.** Continuum point sources in the observed field with brightness temperatures  $T_{\text{cont}} > 400$  K. The names and spectral indexes are based on work presented in Johnston et al. (in prep.) and are preliminary results. Coordinates, major, and minor axes of the 2D fit, maximum brightness temperature  $T_{\text{cont}}$  of the continuum point source and the diffuse weak continuum temperature around the point source are given. The column “far Scutum arm” indicates whether absorption features at  $v_{\text{LSR}} \approx -40$  km s<sup>−1</sup> are present in the HI spectra. The spectral index and the absorption of the far Scutum arm are used to determine the location of the point sources, which is given in the last column. <sup>(a)</sup> This source consists of two blended sources, which explains the large eccentricity.

To determine the optical depth of the HI accurately, we need continuum sources in the background which are brighter than the typical HI spin temperature (see Sect. 3.3). We extract all continuum sources in our field that have a brightness temperature  $T_{\text{cont}} > 400$  K and a point-like structure, which yields eight point sources. The analysis of extended sources follows in Sect. 4.4. We use a two-dimensional Gaussian to fit the position and size of the continuum source. To measure the continuum brightness temperature, we average over high- and low-velocity channels in our HI data cubes (−80 to −50 and 135 to 155 km s<sup>−1</sup>) that are not affected by the HI line. The results are shown in Table 1.

To determine the off spectrum ( $T_{\text{off}}$ ), we average the emission spectrum around the continuum source within an annulus with inner and outer radius of 60'' and 120'', respectively. The upper two panels of Fig. 6 show a typical emission and absorption spectrum. We use Eq. (4) to calculate the optical depth for each channel. To avoid unrealistic optical depths, we only calculate the optical depth for those channels in which the emission/absorption is five times larger than the corresponding noise. The gray shaded areas in the upper three panels in Figs. 6 and 7 show the 5 sigma level. The optical depth is set to zero for channels, where the emission/absorption is below five times the corresponding noise.

As explained in Sect. 3.3, we have to consider the effect of optically thick clouds for which we can determine only lower

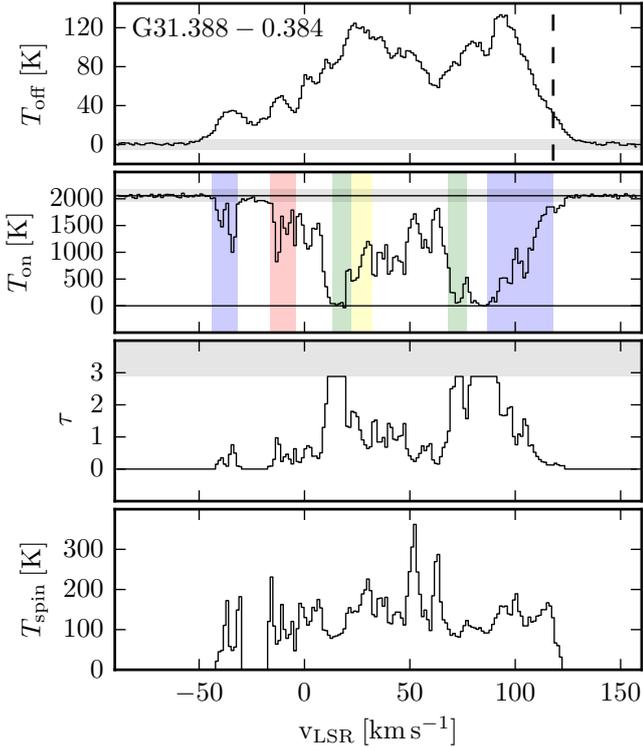
limits for the optical depth. The gray shaded areas in the third panels of Figs. 6 and 7 show these lower limits of the optical depth.

#### 4.2. HI spin temperature toward compact continuum sources

For each channel that allows for an optical depth measurement, we compute the spin temperature using Eq. (10). The spin temperature is shown in the fourth panel of Figs. 6 and 7. This method reveals absorption features in 655 channels for all eight continuum sources. The median of the spin temperature is 97.5 K and the distribution of all absorption features is shown in Fig. 8. For large optical depths, the spin temperature approaches the brightness temperature of the off position, however, for large optical depths ( $\tau \gtrsim 2$ ) we can only report lower limits for  $\tau$ . Hence, we overestimate the spin temperature in the optically thick regime. Nevertheless, this overestimation is small, as for optical depths of  $\tau = 2$  the measured spin temperature is  $T_{\text{spin}} \approx 1.16 \cdot T_{\text{off}}$  (see Eq. (5)). Therefore we overestimate  $T_{\text{spin}}$  by at most  $\sim 15\%$ . We discuss these results in detail in Sect. 5.2.

#### 4.3. Location of continuum sources

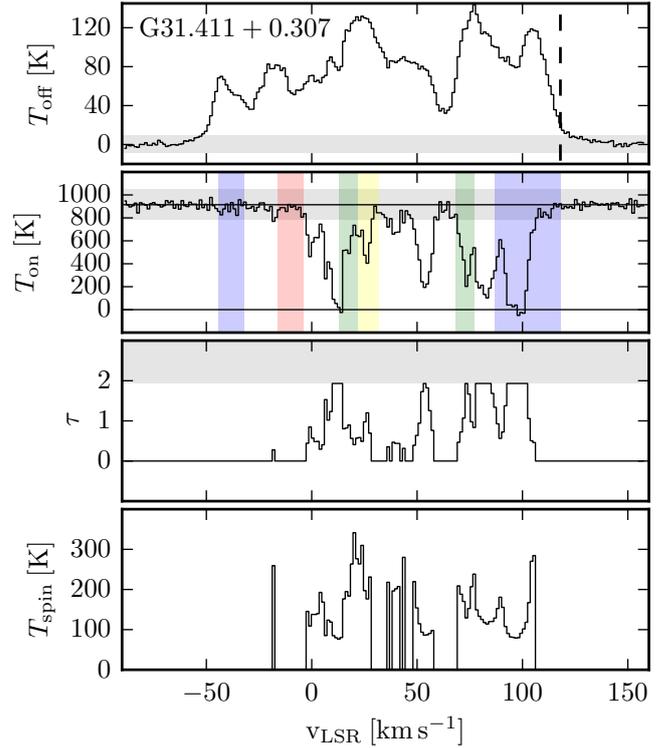
To characterize and understand the HI absorption spectrum toward the continuum point sources, it is important to know the



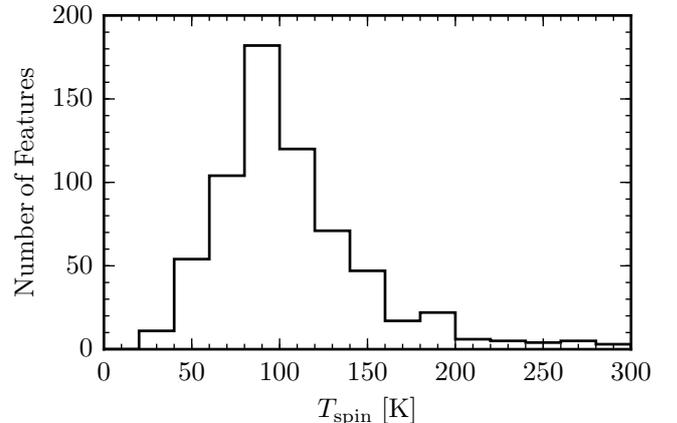
**Fig. 6.** HI emission and absorption spectrum of the extragalactic continuum point source G31.388–0.384. The emission spectrum is shown in the first panel and is measured in an annulus around the point source with inner and outer radii of 60'' and 120'', respectively (corresponds to 3 and 6 times the restoring beam). The second panel presents the absorption spectrum toward the point source. The color shaded areas represent the approximate velocities of the Milky Way spiral arms (Vallée 2008) in blue, red, green, and yellow, the Scutum-Centaurus, Cygnus, Sagittarius, and Perseus arm, respectively; the dashed black line in the first panel indicates the tangential velocity. In the *first two panels*, the gray shaded area indicates the  $5\sigma$  noise level. The *third panel* shows the optical depth computed using Eq. (4) and the gray shaded area indicates the saturated optical depth limit, computed using Eq. (7). In the *fourth panel*, the spin temperature is presented, which is computed using Eq. (10).

location of the continuum source. We can distinguish between extragalactic and Galactic point sources. The Galactic sources are mostly H II regions, whereas the extragalactic point sources are radio lobes from extragalactic jets or AGN. To distinguish between them, we have two criteria: the spectral index and HI absorption of the far Scutum-Centaurus arm. As we have to consider, e.g., primary beam effects or different spatial filtering of the interferometer for different frequencies, it is very difficult to determine accurate spectral indexes (e.g., Rau et al. 2014; Bhatnagar et al. 2011, 2013). For this analysis, we calculated the spectral indices, using flux measurements in the two most separated spectral windows at 1.05 and 1.95 GHz and are based on work presented in Johnston et al. (in prep.).

Four sources in our sample have negative spectral indices (Table 1), which is typical of synchrotron radiation from extragalactic jets or AGNs. The remaining four sources show flat or positive spectral indices, which indicates free-free emission from potentially optically thick H II regions. These four free-free emission sources also show no HI absorption feature for the far Scutum-Centaurus arm. Therefore, these sources reside in the Milky Way. Furthermore, we can study the HI absorption spectra and molecular emission spectra of the Galactic point sources



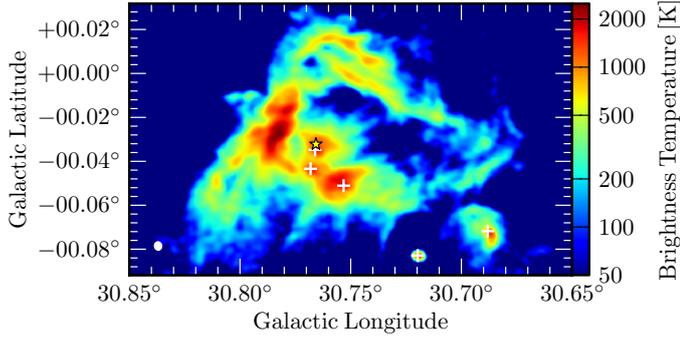
**Fig. 7.** Same layout as Fig. 6, except for the Galactic continuum source G31.411+0.307.



**Fig. 8.** Distribution of the spin temperature for all absorption features (655) toward point-like continuum sources. The median of the spin temperature is 97.5 K.

to estimate their distance and overcome the near-far distance ambiguity. This is done by Anderson et al. (2014) and they find that, e.g., the source G31.411+0.307 has a near distance of 6.6 kpc. For this source, we also see a sharp cutoff in the absorption spectra at  $v_{\text{lsr}} \approx 100 \text{ km s}^{-1}$  (see Fig. 7), which corresponds to the molecular line velocity reported in Anderson et al. (2014).

Figure 6 shows an example of an extragalactic continuum source. The characteristic absorption of the far Scutum-Centaurus arm at  $v_{\text{lsr}} \approx -40 \text{ km s}^{-1}$  is clearly observable. Furthermore, the absorption and emission spectra show a similar cutoff for high velocities, when approaching the tangential point of the near Scutum-Centaurus arm. On the other hand, the absorption spectrum of Fig. 7 neither shows the absorption of the far Scutum-Centaurus arm, nor approaches zero at the velocity



**Fig. 9.** Continuum emission at 1.4 GHz of W43-Main. The yellow star indicates the position of the OB cluster (Lester et al. 1985) and the white crosses marks the position of UCH II regions observed by the CORNISH survey (Hoare et al. 2012; Purcell et al. 2013).

of the tangential point. This is typical for Galactic continuum sources.

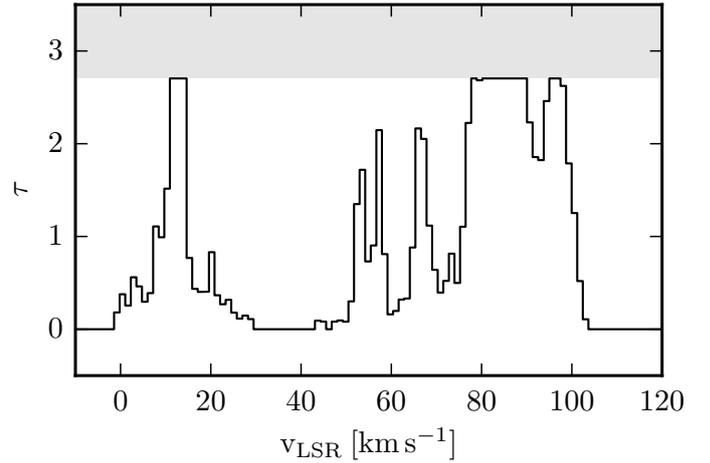
#### 4.4. Extended continuum sources – W43-Main

Besides point-like continuum sources, our observed field contains three strong ( $T > 800$  K) extended continuum sources. The most prominent source is the well-known H II region around W43-Main (Lester et al. 1985), which is shown in Fig. 9. This region has an angular extent of  $\sim 300''$ , which corresponds to  $\sim 8$  pc at a distance of 5.5 kpc. As our resolution is  $20''$ , we are able to resolve the internal structure well. It is known that the nebula is ionized by an OB cluster and the observed continuum signal is the result of free-free emission. Figure 9 shows the continuum emission of W43-Main and the yellow star marks the position of the OB cluster (J2000, 18h47m36s,  $-1^{\circ}56'33''$ , Lester et al. 1985). Furthermore, several UCH II regions can be found in the CORNISH survey, which are marked with white crosses (Hoare et al. 2012; Purcell et al. 2013). The maximum brightness temperature for this region is  $T_{\text{cont}} \sim 2200$  K and, therefore, we are able to calculate the optical depth, even though we cannot determine a proper off position (see Sect. 3.3 for details). The HI absorption spectra shows a cutoff at  $v_{\text{lsr}} \sim 100$  km s $^{-1}$  (see Fig. 10), which marks the velocity of the continuum source. We measure radio recombination line emission at the same velocity (Johnston et al., in prep.; Anderson et al. 2011). Therefore, the continuum source W43-Main is situated at  $v_{\text{lsr}} \approx 100$  km s $^{-1}$ , which is close to the tangent point velocity of the Scutum-Centaurus arm (Nguyen Luong et al. 2011).

Furthermore, the observed field contains two other extended continuum sources: W43-South and the supernova remnant SNR G029.7-00.2 with continuum brightness temperatures of at most  $T_{\text{cont}} \approx 1840$  K and  $T_{\text{cont}} \approx 850$  K, respectively.

#### 4.5. Optical depth of W43-Main

In Sect. 3.3, we described that we can determine the optical depth for strong continuum sources using the absorption spectrum. As the brightness of the continuum source W43-Main is  $T_{\text{cont}} \sim 2200$  K, the uncertainty for the optical depth measurement is  $\sim 10\%$  (see Fig. 3). Figure 10 shows the optical depth of W43-Main and the gray shaded area indicates the lower limit of our measurement with  $\tau_{\text{lower-limit}} = 2.7$ . The optical depth peak at  $v_{\text{lsr}} \approx 10$  km s $^{-1}$  can be allocated to the near Sagittarius arm and therefore is not connected to the actual star-forming region W43. In contrast, it is difficult to allocate the distinct absorption



**Fig. 10.** Optical depth of W43-Main, calculated using Eq. (6). The gray shaded area indicates the maximum measurable optical depth of  $\tau_{\text{lower-limit}} = 2.7$  calculated using Eq. (7).

features between 50 and 80 km s $^{-1}$  and it is not clear whether they are spatially connected to W43. The prominent absorption feature of W43 is situated between 80 and 100 km s $^{-1}$ . In this region, our measurement is saturated and, therefore, we can only report lower limits for the optical depth.

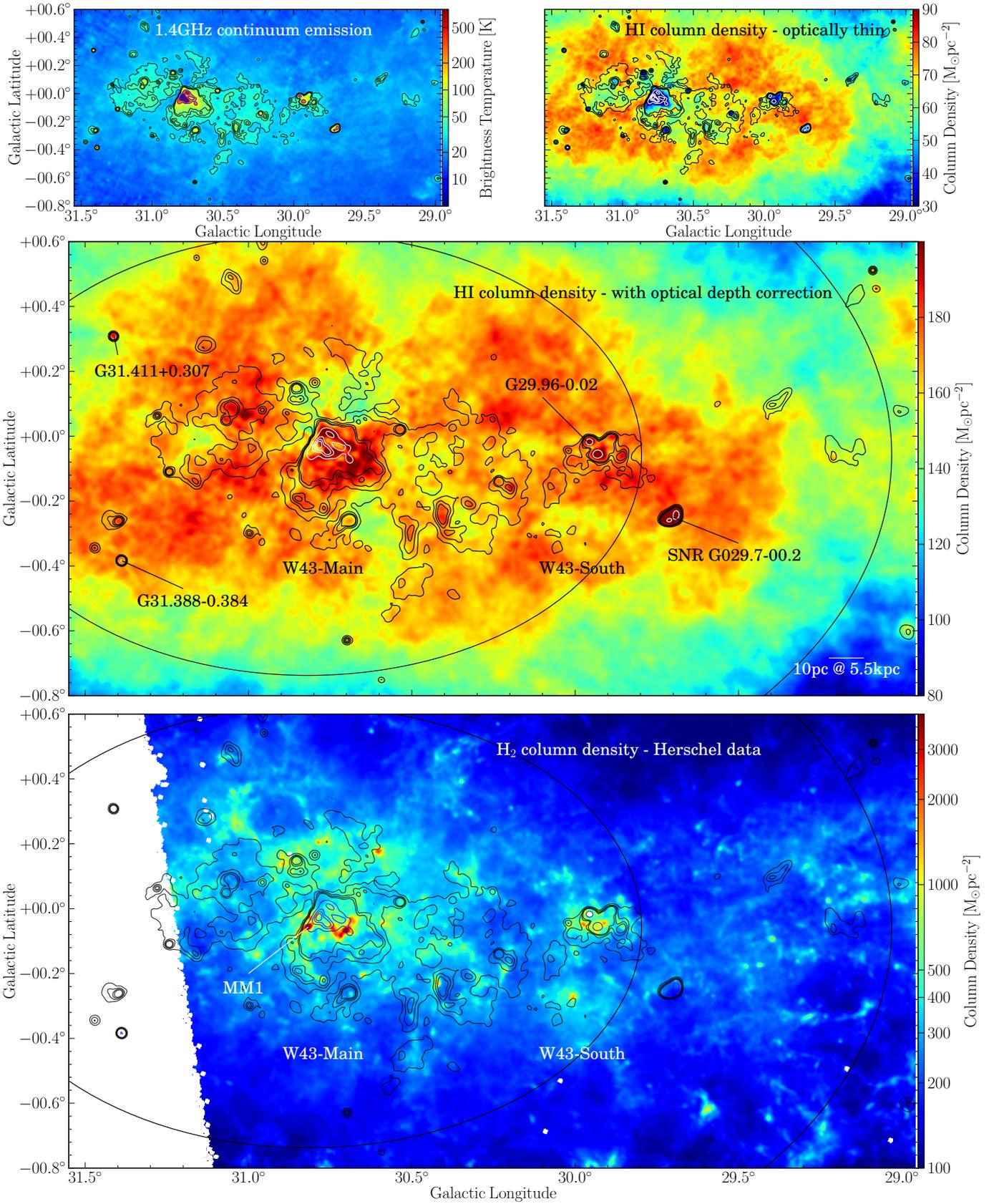
As we resolve the strong continuum source W43-Main spatially, we can determine the optical depth along different lines of sight and thus investigate the spatial distribution of absorption features as done in detail by Liszt et al. (1993). We refrain from this kind of study as we are mostly interested in the velocity range of W43 ( $v_{\text{lsr}} = 80\text{--}110$  km s $^{-1}$ ) at which the absorption features are mostly saturated preventing a detailed study of the spatial distribution. We instead measured the optical depth toward the strongest continuum peak to estimate the maximum optical depth possible (see Fig. 10), which is nevertheless a lower limit.

#### 4.6. HI column density with optically thin assumption

In this section, we assess the HI column density and the HI mass of the GMC associated with W43. These two quantities depend strongly on the chosen velocity range. Nguyen Luong et al. (2011) defined for the “main” and “complete” velocity range of W43 values of  $v_{\text{lsr}}(\text{main}) = 80\text{--}110$  km s $^{-1}$  and  $v_{\text{lsr}}(\text{complete}) = 60\text{--}120$  km s $^{-1}$ . In the following, we use the “complete” velocity range, but we stress that a different velocity range can significantly change the column density and mass.

As described in Sect. 3.2, we can determine the column density by assuming optically thin HI emission. For this method, the column density is proportional to the observed HI brightness temperature. The column density map assuming optically thin emission is shown in the top right panel of Fig. 11. To estimate the mass, we integrate this column density over the main region of W43 ( $l = 29.0\text{--}31.5^{\circ}$ ,  $|b| \leq 1^{\circ}$ ). We mask all regions, where the emission spectrum has negative values, and exclude them. Given a distance of 5.5 kpc (Zhang et al. 2014), our analysis finds an HI mass of  $M = 2.7 \times 10^6 M_{\odot}$  ( $l = 29.0\text{--}31.5^{\circ}$ ,  $|b| \leq 1^{\circ}$ ,  $v_{\text{lsr}} = 60\text{--}120$  km s $^{-1}$ ).

Weak diffuse continuum emission can influence the HI emission spectrum and therefore the HI column density calculation needs to be modified according to Eq. (8) (Sect. 3.4). The top right panel of Fig. 11 shows this effect clearly. The color



**Fig. 11.** *Top left panel:* continuum emission at 21 cm in Kelvin. *Top right and middle panels:* HI column density for optically thin assumption and optical depth corrections, respectively. The continuum and HI emission data are based on VGPS, whereas the optical depth correction used in the *middle panel* is based on the THOR data. The *bottom panel* shows the H<sub>2</sub> column density from the HiGAL data (Nguyen-Lu’o’ng et al. 2013). In all panels, the black and white/blue contours present the continuum emission at 21 cm (black contours show levels of 10, 30, and 70 K; white/blue contours show levels of 200, 400, 600, and 800 K). The black ellipses in the *middle and lower panels* have an equivalent radius of  $r = 80$  and 140 pc. Several important objects are marked.

represents the column density determined by the optically thin assumption and the black contours indicate the weak diffuse continuum emission. These two components show a clear anti-correlation. However, this anti-correlation is the result of the expected observational effect in which HI emission is suppressed by weak continuum emission (see Sect. 3.4). To overcome this problem, we have to consider the optical depth, which we discuss in the next section.

#### 4.7. HI column density with optical depth correction

With the measurement of the optical depth and the weak continuum emission, we can correct the HI emission as explained in Sect. 3.4. This allows for a more accurate determination of the column density, which is shown in the middle panel of Fig. 11. We chose the “complete” velocity range of  $v_{\text{lsr}} = 60\text{--}120 \text{ km s}^{-1}$ . As we correct for the optical depth, we are able to observe a larger HI column density. We also correct for the weak continuum emission around W43-Main. This correction removes the anti-correlation between the continuum emission and the HI column density. Hence, we determine the HI mass to be  $M = 6.1 \times 10^6 M_{\odot}$  ( $l = 29.0\text{--}31.5^{\circ}$ ,  $|b| \leq 1^{\circ}$ ,  $v_{\text{lsr}} = 60\text{--}104 \text{ km s}^{-1}$ ).

The optical depth spectrum of W43-Main (Fig. 10) shows, that the absorption ends abruptly at  $100 \text{ km s}^{-1}$ , but the HI emission as well as CO emission (Nguyen Luong et al. 2011; Carlhoff et al. 2013) reveals features up to  $v_{\text{lsr}} = 110 \text{ km s}^{-1}$ . The reason for the abrupt drop in the absorption spectrum is not the absence of HI, but the location along the line of sight of the continuum source at this velocity (see Sect. 4.3 for further details). As we do not see HI in absorption for velocities larger than  $100 \text{ km s}^{-1}$ , we are also not able to determine the corresponding optical depth. Therefore we cannot apply our corrections to the HI column density for velocities larger than  $100 \text{ km s}^{-1}$ . Hence, the velocity range for the previously mentioned HI mass is only  $v_{\text{lsr}} = 60\text{--}104 \text{ km s}^{-1}$ . Nevertheless we can determine the HI mass for the velocity range from  $v_{\text{lsr}} = 104\text{--}120 \text{ km s}^{-1}$  using the optically thin assumption. This reveals a HI mass of  $M = 0.5 \times 10^6 M_{\odot}$ . Hence, the total HI mass for W43 in the velocity range  $v_{\text{lsr}} = 60\text{--}120 \text{ km s}^{-1}$  is  $M = 6.6 \times 10^6 M_{\odot}$  with the optical depth correction for the velocity range  $v_{\text{lsr}} = 60\text{--}104 \text{ km s}^{-1}$  and optically thin assumption for the velocity range  $v_{\text{lsr}} = 104\text{--}120 \text{ km s}^{-1}$ . This is 2.4 times larger than the HI mass determined with the optically thin assumption.

The limitations and uncertainties of our determined HI column density and HI mass with the optical depth corrections are discussed further in Sect. 5.3.

#### 4.8. HI self absorption

The HI self absorption (HISA) method uses the diffuse broad HI emission background of the Milky Way as illumination for colder foreground clouds (e.g., Gibson et al. 2000, 2005a,b; Li & Goldsmith 2003; McClure-Griffiths et al. 2006). Dark regions on maps and narrow absorption features in spectra reveal these HISA features. The terminology “self absorption” can be misleading: the HI emission and absorption can occur in the same cloud or at the same position, but does not have to. The advantage of this method is that it is possible to map entire absorption clouds and study their intrinsic structure. In contrast, the disadvantage is that a sufficient background emission with the same velocity as the absorbing cloud is necessary to detect HISA features. Therefore this method misses a large portion of the cold HI clouds. The differentiation between actual HISA features and

the lack of HI emission can also be challenging. Gibson et al. (2005b), however, present an efficient method to detect HISA features automatically. Another disadvantage is that the optical depth and spin temperature can only be measured together and further assumptions are needed to disentangle these two values.

As described in the previous section, we correct for the optical depth effects and weak continuum emission. This correction does not account for locally confined HISA features, as we assume a uniform optical depth for the entire W43 region. The HISA features could have a higher and spatially varying optical depth that we cannot measure. Furthermore, the weak and diffuse continuum emission around W43 makes the search for HISA features even more complicated. Hence, we refrain from searching and analyzing the possible HISA features around W43. Therefore, we are likely missing some cold neutral hydrogen in our analysis. We will conduct future HISA studies in other parts of the Milky Way THOR study with less diffuse continuum emission.

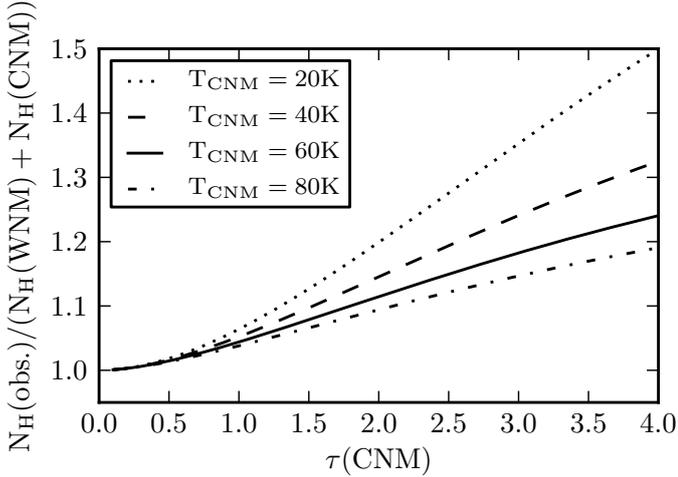
## 5. Discussion

### 5.1. Phases of the neutral atomic hydrogen

It is well known that the neutral atomic ISM has several phases that coexist side by side with very different properties (e.g., Clark 1965; Wolfire et al. 1995, 2003; Heiles & Troland 2003b). The main constituents are the cold neutral medium (CNM) and the warm neutral medium (WNM) with spin temperatures on the order of  $<100 \text{ K}$  (Strasser et al. 2007) and  $\sim 10^4 \text{ K}$  (Murray et al. 2014; Roy et al. 2013a), respectively. Furthermore, their density differs by two order of magnitude (CNM:  $n_{\text{H}} \sim 50 \text{ cm}^{-3}$ , WNM:  $n_{\text{H}} \sim 0.5 \text{ cm}^{-3}$ , e.g., Stahler et al. 2005). Because of the different spin temperature and density of the CNM and WNM, their corresponding optical depths are significantly different with typical values of  $\tau_{\text{WNM}} \sim 10^{-3}\text{--}10^{-4}$  (Murray et al. 2014) and  $\tau_{\text{CNM}} \gtrsim 0.1$  (Strasser & Taylor 2004). This is important for our interpretation.

Because of the low optical depth of the WNM, we see in absorption merely the CNM. Hence, the optical depth shown in Fig. 10 is the optical depth of the CNM. As the absorption spectra are strongly dominated by the CNM, we are not able to measure the optical depth of the WNM and we assume the WNM is optically thin. In contrast, we see a combination of the CNM and WNM for the HI emission. For the correction of the column density (see Sect. 4.7), we use the optical depth information from the absorption study to correct the HI emission data. As we do not distinguish between the two phases, we might combine two different quantities, namely the optical depth of the CNM with the emission of the CNM and the WNM. This could lead to an overestimation of the column density. In the following, we assess this effect.

If we assume a CNM cloud with varying  $T_{\text{spin}}(\text{CNM}) \sim 20\text{--}80 \text{ K}$  and varying optical depth surrounded by a WNM with  $T_{\text{spin}}(\text{WNM}) \sim 7000 \text{ K}$  (Murray et al. 2014) and optical depth  $\tau(\text{WNM}) \sim 5 \times 10^{-3}$ , we can calculate the column density of each component separately (CNM and WNM). Furthermore, we can calculate the brightness temperature that we would observe and apply our correction method described in Sect. 3.4. Finally, we can compare the actual column density of the CNM and WNM with the column density we would observe with our correction method and investigate the overestimation of the actual column density. The result is shown in Fig. 12, which shows the ratio of the observed and actual column density as a function of the optical depth of the CNM  $\tau(\text{CNM})$  for different



**Fig. 12.** Ratio of the observed and actual column density as a function of the CNM optical depth  $\tau(\text{CNM})$  for different CNM spin temperatures  $T_{\text{spin}}(\text{CNM})$ .

CNM spin temperatures  $T_{\text{spin}}(\text{CNM})$ . Figure 12 shows that we measure the column density accurately for the optically thin case and we overestimate the column density for larger optical depths. However, even for the extreme case ( $T_{\text{spin}}(\text{CNM}) \sim 20$  K,  $\tau(\text{CNM}) \sim 3$ ), we overestimate the column density by at most 1.35. This effect is smaller than the underestimation of the column density due to saturated optical depths and therefore we only consider a single cold component in the following. Similar results in simple simulations for different combination of CNM and WNM fraction and a wide range of  $N_{\text{H}}$  and  $\tau$  were found by Chengalur et al. (2013) and Roy et al. (2013a,b).

## 5.2. HI spin temperature measurements toward point sources

The spin temperature is the best measure of the kinetic temperature of the HI gas along the line of sight. Hence, it is a principal determinant of the physical processes that occur in the HI gas.

As described in Sect. 3.5, we corrected the HI spin temperature for diffuse weak continuum emission. If we neglect this correction we would systematically overestimate the HI spin temperature and our sample would have a median HI spin temperature of 110 K. That means the median value would be  $\sim 12$  K higher compared to our corrected value of 97.5 K (see Fig. 8).

Similar studies of the spin temperature with similar methods can be found in the literature. For example, Strasser & Taylor (2004) report a median spin temperature of 120 K. This is  $\sim 20$  K higher than our value of 97.5 K, but they do not consider the diffuse weak continuum emission and therefore probably overestimate the spin temperature.

Heiles & Troland (2003a,b) developed an extensive method to fit Gaussian components to the absorption and emission spectra. Spectral features shown in absorption and emission are assigned to the cold neutral medium (CNM), whereas emission-only features are assigned to the warm neutral medium (WNM). Using this method, they are able to distinguish these two phases and measure their properties, such as the spin temperature, individually. However, they report that it is difficult to use their method for sources close to the Galactic plane ( $|b| < 10$  deg), as multiple components can overlap and the Galactic rotation can broaden their profiles. Figures 6 and 7 illustrate this problem for our region and for these spectra it is impossible to find unique

Gaussian components. As Heiles & Troland (2003a,b) are able to fit individual components, they find on average lower spin temperatures for the CNM in the range of  $\sim 40$ – $70$  K. Given that we can not distinguish between the CNM and the WNM, the measured spin temperature is a column density weighted mean between these two components (Strasser & Taylor 2004). This could explain the increased spin temperature reported in Sect. 4.2. Another explanation for the increased spin temperature could be the strong radiation field of W43.

Further complications in our sample are the Galactic continuum sources. As these only trace the optical depth up to their location within the Milky Way, we miss the optical depth of the hydrogen behind the continuum source. On the other hand, the off-position measurement traces all the hydrogen along the line of sight. As the kinematic distance is uncertain due to near and far ambiguities, we cannot use the velocity to distinguish the distance of the emitting and absorbing hydrogen. Hence we underestimate the optical depth for the Galactic continuum sources and therefore overestimate the spin temperature. However, we do not see a significant difference in the mean spin temperature for Galactic and extragalactic continuum sources and we can neglect this effect.

## 5.3. Column density and mass estimate

In Sect. 4.7 we explained that we correct the HI column density for optical depth effects as well as for the diffuse continuum emission. This leads to a more accurate estimate of the column density and a more accurate mass estimate. Nevertheless these corrections have limitations which we discuss in the following section.

As we need a strong continuum source in the background to determine the optical depth, we can measure the optical depth only toward certain locations. For our HI column density correction, we used the strong continuum source W43-Main. Furthermore we assumed that the optical depth is the same for the entire cloud. This assumption might not hold, especially for the outer parts of the cloud. To investigate this effect, we compared the optical depth measurements for other sources at other positions. However, in the range of  $v_{\text{lsr}} = 80$ – $110$  km s $^{-1}$ , we find that the optical depth is mostly saturated and determined by the corresponding lower limit. Two examples are given in the third panel of Figs. 6 and 7, which reveal a lower limit of  $\tau_{\text{lower-limit}} = 2.9$  and  $\tau_{\text{lower-limit}} = 1.9$ , respectively. Other continuum sources that have a larger separation from the Galactic mid-plane show similar results. For example, the continuum source G30.699–0.630 has a Galactic latitude of  $b \approx 0.6^\circ$  and still shows a saturated optical depth for the velocity range of W43 with a lower limit of  $\tau_{\text{lower-limit}} = 1.5$ . If we use this continuum source to correct for optical depth effects and the weak diffuse continuum emission, we determine a mass of  $M = 4.8 \times 10^6 M_{\odot}$  for the whole cloud ( $l = 29.0$ – $31.5^\circ$ ,  $|b| \leq 1^\circ$ ,  $v_{\text{lsr}} = 60$ – $120$  km s $^{-1}$ ). Hence, by using W43-Main to correct the optical depth for the entire cloud, we do not overestimate the mass in the outer parts significantly, but at most by a factor of 1.4. We also use this mass estimate as a lower limit for the mass of W43.

The saturation of the optical depth is the second limitation we have to consider, especially for the inner part of the cloud. In this region, we underestimate the opacity and, therefore, the column density which would lead to a further underestimation of the mass. Estimating this effect is difficult and, therefore, we report only lower limits for the column density and the mass in the inner part of W43.

The third limitation is the distance of the continuum source that we use to determine the optical depth. As explained in Sect. 4.3, the continuum source W43-Main is located close to the tangential point of the Scutum-Centaurus arm at a distance of 5.5 kpc. Hence, we only see HI absorption as far as this distance, and miss all the HI that is located behind the continuum source but still within the cloud. If we assume that the continuum source is at the center of the cloud, we underestimate the column density by a factor of two. Another approach to overcome this limitation is to look at other more distant continuum sources. The continuum source G31.388–0.384 is extragalactic and has a comparable brightness temperature to W43-Main. Hence, it is an ideal candidate for this test. We used the optical depth shown in the third panel of Fig. 6 to correct the HI column density and measured the corrected mass for the same area and velocity range, as in Sect. 4.7. The absorption spectrum of W43-Main and G31.388–0.384 are similar, except for the velocity range  $v_{\text{lsr}} = 100\text{--}120\text{ km s}^{-1}$ , which is missing in the W43-Main spectrum. We can also use the optical depth measurements of G31.388–0.384 to correct the HI emission. However, as these absorption spectra are similar, the corrected masses are the same within the uncertainties ( $M = 6.9 \times 10^6 M_{\odot}$  for the correction with the optical depth of G31.388–0.384).

Summing up, we might overestimate the mass in the outer part of W43, but underestimate the mass in the inner part of W43. Because of the position of the continuum source, we might underestimate the mass by a factor of two. As explained in Sect. 4.8, we also miss some HI due to self-absorption. Hence we report the HI mass of W43 to be a lower limit of  $M = 6.6_{-1.8} \times 10^6 M_{\odot}$ .

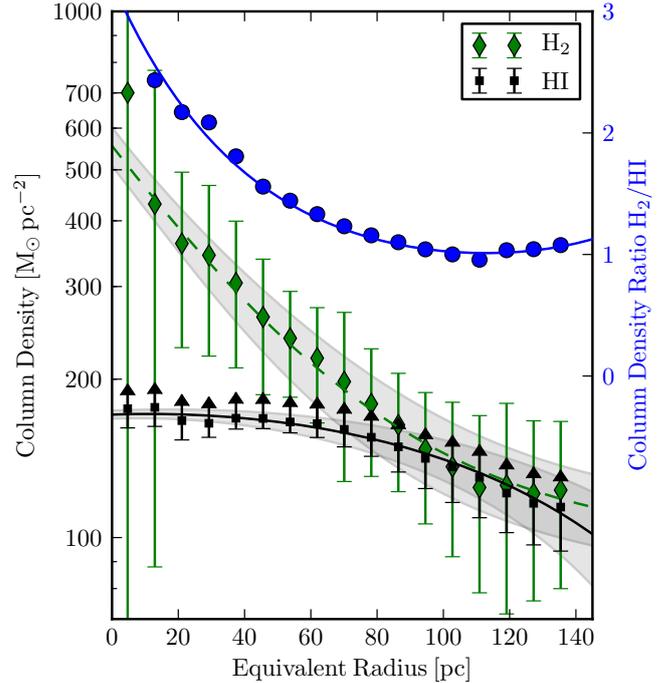
Several HI mass estimates are given in the literature (Nguyen Luong et al. 2011; Motte et al. 2014). All of them are calculated with the assumption of optically thin emission.

Motte et al. (2014) measured the HI mass in the inner part of W43 ( $l = 29^{\circ}6 \sim 31^{\circ}4$  and  $b = -0^{\circ}5 \sim 0^{\circ}3$ ) and for the velocity range ( $v_{\text{lsr}} = 60\text{--}120\text{ km s}^{-1}$ ). The assumption of optically thin emission reveals an HI mass of  $M = 0.9 \times 10^6 M_{\odot}$ . If we use our corrected HI column density to measure the mass in this area, we determine a HI mass of  $M = 2.2 \times 10^6 M_{\odot}$  (this value is smaller than the value given in Sect. 4.7 as we only consider the inner part of W43). As outlined above, we claim that this mass estimate is a lower limit and, therefore, the mass determined with the optically thin emission is at least a factor of 2.4 too small. This has implications for theoretical models, which we discuss in Sect. 5.6.

#### 5.4. Spatial distribution of hydrogen

Beside the total HI mass, knowing the spatial distribution of the HI is crucial to understand the formation of W43. As we have corrected the column density map for optical depth effects and the weak diffuse continuum emission, we can use this corrected column density map (see Fig. 11) to investigate the HI spatial distribution in more detail, especially in the center.

Similar work was done by Motte et al. (2014). They measured the HI column density in rectangular annuli around the center of W43 ( $l = 30.5^{\circ}$ ,  $b = 0^{\circ}$ ) with an aspect ratio of 3:2 and find an increasing HI column density inward from  $N_{\text{HI}} \sim 40 M_{\odot} \text{ pc}^{-2}$  at a distance of 170 pc to  $N_{\text{HI}} \sim 80 M_{\odot} \text{ pc}^{-2}$  at a distance of 50 pc from the center (velocity range  $v_{\text{lsr}} = 60\text{--}120\text{ km s}^{-1}$ ). Since they assume optically thin HI emission, they underestimate the HI column density, especially in the central region (as discussed in Sect. 5.3).



**Fig. 13.** Column density of HI and H<sub>2</sub> measured in elliptical annuli around W43 MM1. The x-axis presents the equivalent radius of these elliptical annuli. The black and green lines represent the fitted curves with the corresponding  $1\sigma$  uncertainties shown as a gray shaded area. The larger symbols (diamonds for H<sub>2</sub>, squares for HI) present the averaged value of the elliptical annuli and their corresponding variations within the annuli. As the optical depth spectra saturates, we can only determine lower limits for the HI column density. The blue dots and line show the H<sub>2</sub> and HI column density ratio of the data and the fitted curves, respectively.

To compensate for the approximate elliptical structure of W43, we choose elliptical annuli with an aspect ratio of 3:2 for major and minor axis, which fits the large scale structure of W43 well (see Fig. 11). As we focus on W43-Main, we choose the most massive submillimeter peak W43-MM1 ( $l = 30.8175^{\circ}$  and  $b = -0.0571^{\circ}$ , Motte et al. 2003) as the center for the ellipses. The width of each annulus is 10 pc for the major axis and 6.6 pc for the minor axis. For each elliptical annulus, we calculated the equivalent radius  $r = \sqrt{\text{major} \cdot \text{minor}}$  and assigned these values as the distance to the center shown in Fig. 13.

The black squares in Fig. 13 represent the HI column density mean value and the corresponding standard deviation of each elliptical annulus. We confirm the result of Motte et al. (2014), which indicates that the HI column density rises inward. Our corrections allow us for the first time to study the central region of W43 ( $r < 50\text{ pc}$ ) and, within the uncertainties, we report a flat column density distribution in this inner region. However, we mention that this flatness could also be due to the underestimation of the column density in the central part, as the optical depth saturates and therefore the column density is a lower limit.

Furthermore, the diamond symbols in Fig. 13 present the column density of the molecular hydrogen. The H<sub>2</sub> distribution is centrally concentrated and the column density rises steeply toward the center, which is different from the HI profile. The large uncertainties in the center are due to the clumpiness of the molecular hydrogen as the most prominent clumps, such as W43-MM1, are located in the first two elliptical annuli. Beside W43-Main, the second most prominent molecular clump

is W43-South (see Fig. 11). However, in this analysis we focus on W43-Main and, therefore, we choose W43-MM1 as the center for the ellipses. Furthermore, we masked W43-South for this analysis, as it would introduce a large uncertainty at an equivalent radius of  $r \sim 50$  pc.

We use a nonlinear least square method (“curvefit” in the scipy package) to fit the mean values of the thin elliptical annuli with their corresponding uncertainties. For the HI column density we assume a quadratic radial distribution, i.e.,

$$N_{\text{HI}}(r) = a \cdot r^2 + b \cdot r + c, \quad (11)$$

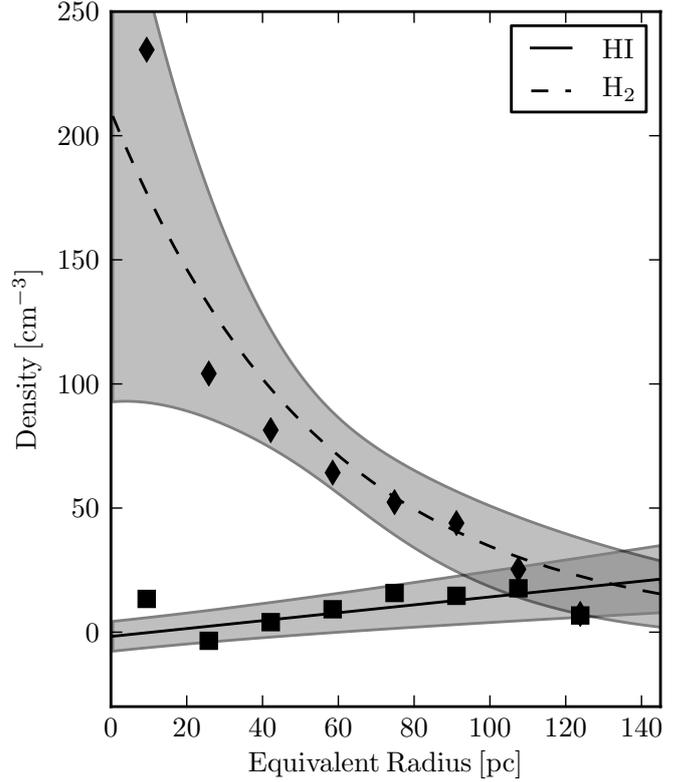
where  $N_{\text{HI}}(r)$  describes the HI column density and  $r$  describes the equivalent radius. The free parameters  $a$ ,  $b$  and  $c$  have the fitted values of  $a = -3.9 \pm 0.7 \times 10^{-3} M_{\odot} \text{pc}^{-4}$ ,  $b = 0.089 \pm 0.099 M_{\odot} \text{pc}^{-3}$  and  $c = 171 \pm 3 M_{\odot} \text{pc}^{-2}$ . For the H<sub>2</sub> distribution we assume an exponential function to fit the data as follows:

$$N_{\text{H}_2}(r) = d \cdot \exp(-e \cdot r) + f, \quad (12)$$

where  $N_{\text{H}_2}(r)$  describes the H<sub>2</sub> column density and  $r$  describes the equivalent radius. The free parameters  $d$ ,  $e$ , and  $f$  have the fitted values of  $d = 458 \pm 44 M_{\odot} \text{pc}^{-2}$ ,  $e = 0.022 \pm 0.004 \text{pc}^{-1}$  and  $f = 97 \pm 15 M_{\odot} \text{pc}^{-2}$ .

The black and green lines in Fig. 13 present the column density fits and the gray shaded areas represent their corresponding uncertainties. Both, the HI and H<sub>2</sub> distributions are well fit by the assumed functions. As the uncertainties for the innermost part of the H<sub>2</sub> distribution ( $r < 20$  pc) are large, the fitted curve deviates from the data points and this area has to be treated cautiously. We also tested different functions to fit the data, such as functions with only two free parameters, or a Gaussian distribution for the HI distribution, but the results were similar within the uncertainties. Finally, we chose the aforementioned functions as they could reproduce well the ratio of the H<sub>2</sub> and HI column density. This ratio is shown in blue in Fig. 13. The circles represent the ratio of the data points, whereas the solid line represents the ratio of the fitted curves. The ratio stays fairly constant at  $N_{\text{H}_2}/N_{\text{HI}} \approx 1$  for  $140 \text{ pc} > r > 60$  pc. For this region, the HI column density also rises to its maximum value of  $N_{\text{HI}} \approx 170 M_{\odot} \text{pc}^{-2}$ . Further inward ( $r < 60$  pc), the HI column density stays constant at this maximum value, whereas the H<sub>2</sub> column density rises sharply. Hence, the H<sub>2</sub>/HI ratio also rises sharply to values above three. Summing up, the column density measurements imply that we have a mixture of HI and H<sub>2</sub> in the outskirts of the cloud and a molecular dominated region in the center. In the following, we investigate this structure for the particle density.

As mentioned before, we find a flat column density for the HI distribution toward the center of W43-Main, but what does this imply for the actual density in the center? If we assume that W43 has an elliptical shape, we can decompose the cloud into different layers, similar to an onion. Furthermore, we assign the appropriate column density to each layer with the information given in Fig. 13. As the column density is additive, the appropriate column density of each layer is the measured column density at the position of the considered layer minus the column density of all layers further outside. Hence, a flat HI column density distribution toward the center (see Fig. 13) means that the layers in the center have no or a very small column density and therefore also a very small particle density. In the following section, we use the concept of an elliptical layered structure to determine the actual particle density and show that indeed the HI particle density drops toward the center of W43 within this model.



**Fig. 14.** Density of HI and H<sub>2</sub> as a function of the distance toward the center of W43 (equivalent radius). The diamonds and the dashed line represent the molecular hydrogen, whereas squares and the solid line represent the atomic hydrogen. The corresponding  $3\sigma$  uncertainties from the fit introduced in Eq. (14) are shown as gray shaded areas.

### 5.5. Linking column density to particle density

While the column density neglects the third dimension, it does not necessarily reflect the actual particle density. Hence, we have to estimate the third dimension. Using the elliptical, layered structure for W43 previously described and the results presented in Fig. 13, we estimate the particle density in each layer, i.e.,

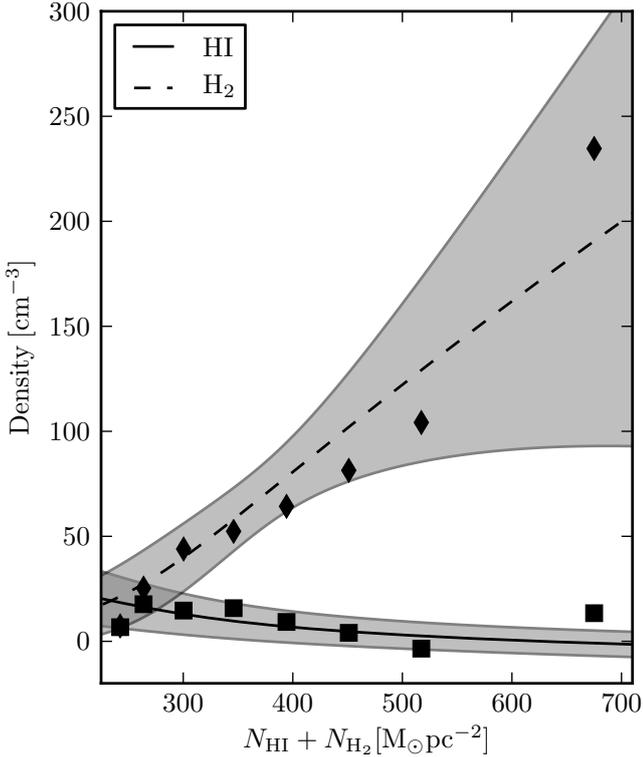
$$n_i = \frac{(N_i - N_{i+1})}{2 (r_{i+1} - r_i)}, \quad (13)$$

where  $n_i$  describes the particle density of layer  $i$ ;  $N_i$  and  $N_{i+1}$  describes the column density of layer  $i$  and layer  $i+1$ , respectively; and  $r_i$  and  $r_{i+1}$  describes the equivalent radius of layer  $i$  and  $i+1$ . The factor of two accounts for the two layers of the elliptical annuli in the front and back of the cloud. The result for this calculation is shown in Fig. 14 as squares and diamond data points for the HI and H<sub>2</sub> density, respectively. To increase the signal to noise ratio, we used larger elliptical annuli with a major axis of 20 pc and a minor axis of 13.3 pc.

In addition, we can use the fitted curves of the column density to estimate the density as well, by inserting Eqs. (11) and (12) into Eq. (13). Hence, the radial distribution of the HI and H<sub>2</sub> densities are

$$\begin{aligned} n_{\text{HI}} &= -0.5 (a (r_i + r_{i+1}) - b), \\ n_{\text{H}_2} &= \frac{d}{2 (r_{i+1} - r_i)} (\exp(-e \cdot r_i) - \exp(-e \cdot r_{i+1})), \end{aligned} \quad (14)$$

where  $n_{\text{HI}}$  and  $n_{\text{H}_2}$  describes the particle density of HI and H<sub>2</sub>, respectively;  $r_i$  describes the equivalent radius of layer  $i$ ; and  $a$ ,

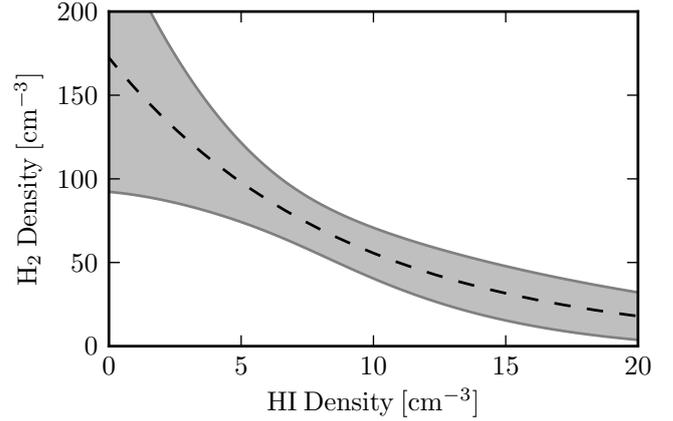


**Fig. 15.** Particle density of HI and H<sub>2</sub> as a function of the total column density ( $N_{\text{HI}} + N_{\text{H}_2}$ ). The diamonds and the dashed line represents the molecular hydrogen, whereas squares and the solid line represents the atomic hydrogen. The corresponding  $3\sigma$  uncertainties from the fit introduced in Eqs. (11) and (12) are shown as gray shaded areas.

$b$ ,  $c$ , and  $d$  are the free fit parameters introduced in Eqs. (11) and (12). In Fig. 14, the calculated density distributions are shown as black lines with the corresponding uncertainties as a gray shaded areas. We note that the density distributions of HI and H<sub>2</sub> are very distinct. While the HI distribution follows a simple linear relation, the H<sub>2</sub> distribution shows an exponential increase toward the center. The particle density shows a mixture of the atomic and molecular hydrogen in the outskirts of W43 ( $r > 100$  pc) and a molecular dominated interior similar to the measurements of the column density. However, the particle density of the atomic hydrogen drops to almost zero toward the center, which results in the observed constant column density.

Another way to present our results is shown in Fig. 15. This figure shows the particle density of HI and H<sub>2</sub> introduced in Eq. (14) as a function of the total column density ( $N_{\text{HI}} + N_{\text{H}_2}$ ). High column density regions, i.e., the central region of W43, are dominated by molecular hydrogen. On the other hand, we find an equivalent mixture of atomic and molecular hydrogen for low column density regions, which represent the envelope of W43.

In addition, we study the correlation between the HI and H<sub>2</sub> density. To do so, we replace the equivalent radius in Fig. 14 and plot the H<sub>2</sub> density as a function of the HI density. Figure 16 shows the corresponding plot with the uncertainties for the H<sub>2</sub> density. The statistical and systematical uncertainties for this plot are relatively large, but nevertheless we see an anti-correlation between the HI and H<sub>2</sub> density. This can be explained with a simple model that H<sub>2</sub> forms out of HI in the innermost part of W43. However, we do not detect a sharp transition between H<sub>2</sub> and HI predicted by Krumholz et al. (2008, 2009). In the following section, we discuss possible implications.



**Fig. 16.** Particle density of molecular hydrogen as a function of the atomic hydrogen. The black curve represents the best-fit curves from Fig. 14 and the gray shaded area shows the  $3\sigma$  uncertainty for the H<sub>2</sub> fit.

### 5.6. Column density threshold for atomic hydrogen

A fundamental question of molecular cloud formation is how does molecular hydrogen form out of neutral atomic hydrogen and what are the corresponding conditions (Dobbs et al. 2014). It is well known that the density must be high enough to shield the molecular hydrogen from the interstellar radiation field, to avoid dissociation back to its atomic form (Hollenbach & Tielens 1997; McKee & Ostriker 2007; Krumholz et al. 2008, 2009; Mac Low & Glover 2012).

To describe this transition, Krumholz et al. (2008, 2009) suggest an analytic model, which is based on the assumption of a spherical cloud that is embedded in an isotropic external radiation field. They approximate that the transition between HI in the envelope and H<sub>2</sub> in the center occurs in an infinitely thin shell. An important result is that an HI column density of  $\sim 10 M_{\odot} \text{pc}^{-2}$  is necessary to shield the molecular hydrogen from the interstellar radiation field. If the cloud reaches this critical HI column density the formation of molecular hydrogen is efficient enough that most of the hydrogen goes into molecular form and the column density of HI remains relatively constant at this level. Therefore we should not expect to observe HI column densities larger than  $\sim 10 M_{\odot} \text{pc}^{-2}$ , contradicting our results presented in Fig. 13. Furthermore, they show that this HI column density threshold is independent of the external radiation field, but has a weak dependence on the metallicity of the gas.

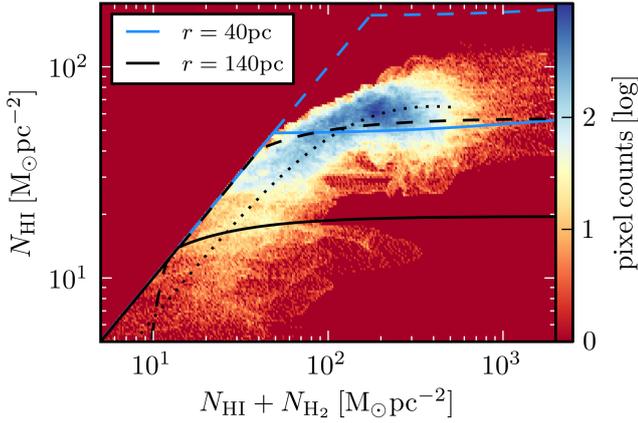
This model has three free parameters. First, the ratio of the measured CNM density  $n_{\text{CNM}}$  to the minimal CNM density  $n_{\text{min}}$ , i.e.,

$$n_{\text{CNM}} = \phi_{\text{CNM}} \cdot n_{\text{min}}. \quad (15)$$

The minimal CNM density is determined by the pressure balance with the warm neutral medium (WNM) and has a typical value of  $n_{\text{min}} \approx 7-8 \text{ cm}^{-3}$ . As the range of pressure balance between the CNM and the WNM is limited, the maximum CNM density can be at most  $\sim 10 \cdot n_{\text{min}}$ . Hence,  $\phi_{\text{CNM}}$  can vary between 1 and 10. Krumholz et al. (2009) assume  $\phi_{\text{CNM}} \approx 3$  for their fiducial value. The second free parameter is the ratio of the CNM density  $n_{\text{CNM}}$  to the molecular density  $n_{\text{mol}}$ , i.e.,

$$n_{\text{mol}} = \phi_{\text{mol}} \cdot n_{\text{CNM}}. \quad (16)$$

Krumholz et al. (2009) suggests that this ratio is  $\phi_{\text{mol}} \approx 10$  and should not vary significantly. The last free parameter is the



**Fig. 17.** Column density of the atomic hydrogen ( $v_{\text{lsr}} = 60\text{--}120 \text{ km s}^{-1}$ ) as a function of the total hydrogen column density ( $N_{\text{HI}} + N_{\text{H}_2}$ ). The column density for the envelope ( $r > 140 \text{ pc}$ ,  $N_{\text{HI}} = 107 \pm 20 M_{\odot} \text{ pc}^{-2}$ ,  $N_{\text{H}_2} = 116 \pm 18 M_{\odot} \text{ pc}^{-2}$ ) is subtracted. The solid and dashed lines describe the theoretical model of Krumholz et al. (2008, 2009) for solar values ( $G_0 = 1$ ,  $Z = 1$ ) and for more realistic values of W43 ( $G_0 = 5$ ,  $Z = 1.4$ ), respectively. The blue and black colors represent the model parameters at different equivalent radii of  $r = 40$  and  $140 \text{ pc}$ , respectively. The black dotted line shows the fitted curve of the elliptical annulus analysis introduced in Sect. 5.3.

metallicity  $Z$ . This model is supported by extragalactic observations (Krumholz et al. 2009) as well as observations in the Perseus molecular cloud by Lee et al. (2012). They find a uniform HI column density of  $N_{\text{HI}} \sim 6\text{--}8 M_{\odot} \text{ pc}^{-2}$  for  $\text{H}_2$  column densities up to  $N_{\text{H}_2} \sim 80 M_{\odot} \text{ pc}^{-2}$ . To fit their data to the model of Krumholz et al. (2009), they fixed  $\phi_{\text{mol}} = 10$  and  $Z = 1.0 Z_{\odot}$  and fitted  $\phi_{\text{CNM}}$ , which reveals values of  $\phi_{\text{CNM}} \approx 6\text{--}10$ .

The complex W43 is a more extreme test case for this theory as we have a much larger mass reservoir as well as an OB cluster that acts as a strong radiation source in the center. For this analysis, we extracted the column density of HI and  $\text{H}_2$  for each pixel. As a basis for the HI column density, we chose the optical depth corrected version with a velocity range of  $v_{\text{lsr}} = 60\text{--}120 \text{ km s}^{-1}$ . For the  $\text{H}_2$  column density, we again use the HiGal data (see Sect. 2.4). Even though the data base is the same as that used in Sect. 5.5, we stress that the method is different. Here we conduct a pixel by pixel comparison, whereas in Sect. 5.5 we averaged the column density over elliptical annuli. In addition, we focus merely on the inner part of W43 with  $r < 140 \text{ pc}$  and, therefore, we have to subtract the column density of the envelope. We assess the column density at  $r = 140 \text{ pc}$  as the envelope column density and subtract this value. The column density for the HI and  $\text{H}_2$  envelopes are  $N_{\text{HI}} = 107 \pm 20 M_{\odot} \text{ pc}^{-2} = 1.3 \pm 0.3 \times 10^{22} \text{ cm}^{-2}$  and  $N_{\text{H}_2} = 116 \pm 18 M_{\odot} \text{ pc}^{-2} = 7.3 \pm 1.1 \times 10^{21} \text{ cm}^{-2}$ , respectively.

Figure 17 shows the result of the pixel by pixel comparison of the HI and  $\text{H}_2$  column density. Since we subtracted the column density of the envelope for this analysis, the values are smaller than in Fig. 13. For better readability, we do not show each single pixel comparison, but we performed a pixel binning. We do not observe the predicted threshold for the HI column density of  $\sim 10 M_{\odot} \text{ pc}^{-2}$ , instead our data show high HI column density values, peaking between  $N_{\text{HI}} = 50\text{--}80 M_{\odot} \text{ pc}^{-2}$ . Nevertheless we will try to fit the analytical model of Krumholz et al. (2009) to our data.

As described in Sect. 5.5, we use elliptical annuli to estimate the particle density. We can use this information (Fig. 14) to

**Table 2.** Densities and model parameter.

$r$ [pc]	$n_{\text{HI}}$ [ $\text{cm}^{-3}$ ]	$n_{\text{H}_2}$ [ $\text{cm}^{-3}$ ]	$\phi_{\text{mol}}$	$\phi_{\text{CNM}}$ ( $G_0 = 1$ )	$\phi_{\text{CNM}}$ ( $G_0 = 5$ )
140	$20 \pm 4$	$17 \pm 5$	0.85	2.7	0.58
80	$11 \pm 3$	$49 \pm 5$	4.4	1.5	0.32
40	$5 \pm 2$	$101 \pm 8$	20.2	0.7	0.14

**Notes.** HI and  $\text{H}_2$  particle density for different equivalent radii with corresponding  $1\sigma$  uncertainty, extracted using the information given in Fig. 14 and using Eq. (14). The given uncertainties are the statistical uncertainties, but do not take the systematic uncertainties due to the saturation of the optical depth spectra into account. The model parameters  $\phi_{\text{mol}}$  and  $\phi_{\text{CNM}}$  are calculated using Eqs. (17) and (15), respectively. The parameter  $\phi_{\text{CNM}}$  is calculated for solar values ( $G_0 = 1$ ,  $Z = 1$ ) and for more realistic values of W43 ( $G_0 = 5$ ,  $Z = 1.4$ ).

determine the model parameters  $\phi_{\text{CNM}}$  and  $\phi_{\text{mol}}$  using Eqs. (15) and (17), respectively. Given that the HI and  $\text{H}_2$  densities vary as a function of equivalent radius, the model parameters  $\phi_{\text{CNM}}$  and  $\phi_{\text{mol}}$  also vary. We calculate the model parameters for three different distances  $r = 40$ ,  $80$ , and  $140 \text{ pc}$ , which characterize the molecular dominated interior, the transition region, and the well-mixed outer area. To calculate  $\phi_{\text{CNM}}$ , we have to know  $n_{\text{min}}$ , which is given by Krumholz et al. (2009) as

$$n_{\text{min}} \approx 31 \frac{G_0}{1 + 3.1 Z^{0.365}} \text{ cm}^{-3}, \quad (17)$$

where  $G_0$  and  $Z$  are the far-ultraviolet radiation intensity (in units of the Habing field) and the total metallicity, both normalized to their values in the solar neighborhood. For W43, we have a slightly higher metallicity of  $Z = 1.4 Z_{\odot}$  (Motte et al. 2014) and a large radiation field, which could be up to  $>100 G_0$  (Beuther et al. 2014) in the central region. We assume a more moderate radiation field for the outer regions of W43 with values around  $5\text{--}10 G_0$ . In Table 2, we present the HI and  $\text{H}_2$  density as well as the model parameters for different distances. The parameter  $\phi_{\text{CNM}}$  is calculated for solar values ( $G_0 = 1$ ,  $Z = 1$ ) and for more realistic values of W43 ( $G_0 = 5$ ,  $Z = 1.4$ ) that results in  $n_{\text{min}} = 7.5 \text{ cm}^{-3}$  and  $n_{\text{min}} = 34.4 \text{ cm}^{-3}$ , respectively. The solid blue and black lines in Fig. 17 show the theoretical column density for solar values and for the equivalent radius of  $r = 40$  and  $140 \text{ pc}$ , respectively, whereas the dashed lines represent the more realistic values of W43 ( $G_0 = 5$ ,  $Z = 1.4$ ). The dashed black line, which represents the outer area of W43 ( $r = 140 \text{ pc}$ ) with a moderate radiation field ( $G_0 = 5$ ,  $Z = 1.4$ ) might fit the data. However, the model parameters might have unrealistically low values of  $\phi_{\text{CNM}} = 0.58$  and  $\phi_{\text{mol}} = 0.85$ . Using a stronger radiation field increases  $n_{\text{min}}$  and therefore decreases  $\phi_{\text{CNM}}$  to even lower values. Hence, values with smaller distances and/or higher radiation fields predict column densities that are too high.

We do not have a conclusive answer as to why the model suggested by Krumholz et al. (2008, 2009) does not describe W43, but we suggest that the strong UV radiation produced by the central OB cluster (Blum et al. 1999) and several further clusters in the environment are responsible for the dissociation of the molecular hydrogen. Another explanation was given by Motte et al. (2014). They performed a similar analysis and their conclusion was that the analytical model by Krumholz et al. (2008, 2009) cannot describe a complicated molecular cloud complex, as we see several transition layers between HI and  $\text{H}_2$  along a single line of sight and the assumption of a simple spherical cloud, without internal radiation sources breaks down.

## 6. Conclusions

The HI, OH, Recombination line survey of the Milky Way (THOR) is a Galactic plane survey covering a large portion of the Galactic disk ( $l = 15\text{--}67^\circ$ ,  $|b| \leq 1^\circ$ ). We use the VLA to observe the 21 cm HI line, 4 OH lines, 19 H $\alpha$  recombination lines and the continuum from 1–2 GHz. We present the HI data of the pilot field centered on the GMC associated with W43 ( $l = 29.2\text{--}31.5^\circ$ ,  $|b| \leq 1^\circ$ ). The main results can be summarized as:

1. We measured the average spin temperature of the neutral hydrogen gas along the line of sight toward eight strong continuum sources. Half of them are Galactic and half of them are extragalactic. We find a median value of  $T_S = 95.7$  K, which is in agreement with other studies.
2. We can estimate the optical depth for the HI line toward strong continuum sources at various locations in W43. The measured optical depth saturates at the main velocity component of W43 ( $v_{\text{lsr}} = 80\text{--}100$  km s $^{-1}$ ) with lower limits of  $\tau \sim 2.7$  in the center. Hence, the derived HI masses based on optically thin emission strongly underestimates the hydrogen content. Employing further corrections for the weak and diffuse continuum emission, we obtain a lower limit for the HI mass of  $M = 6.6_{-1.8} \times 10^6 M_\odot$  for a velocity range of  $v_{\text{lsr}} = 60\text{--}120$  km s $^{-1}$  and an area of  $l = 29.0\text{--}31.5^\circ$  and  $|b| \leq 1^\circ$ . This is a factor of  $\sim 2.4$  larger than the HI mass estimates with the assumption of optically thin emission.
3. The measured HI column density exceeds values of  $N_{\text{HI}} \sim 150 M_\odot \text{pc}^{-2}$  over much of the inner region with  $r < 80$  pc. This is an order of magnitude larger than for low-mass star-forming regions such as Perseus.
4. As we corrected the HI column density for optical depth effects and the weak continuum emission, we are able to study the HI distribution spatially even in the innermost part of W43. We assumed an elliptical layered structure for the GMC associated with W43. This allows us to reconstruct the particle density of HI and we find a linearly decreasing HI density toward the center of W43 with values from  $n_{\text{HI}} = 20$  to almost  $0$  cm $^{-3}$ . Furthermore, we compared our results to the density of molecular hydrogen based on *Herschel* continuum data. The density of molecular hydrogen shows an exponential increase toward the center of W43 with values rising from  $n_{\text{H}_2} = 15$  to  $200$  cm $^{-3}$ . For smaller clumps, the density of H $_2$  can rise to even higher values.
5. We compared our measurements to the analytic model suggested by Krumholz et al. (2008, 2009). Our data does not show a sharp transition between HI and H $_2$ , and nor do we find the predicted threshold for the HI column density of  $\sim 10 M_\odot \text{pc}^{-2}$ . Based on these models, larger HI column densities should not exist, as molecular hydrogen should form for such high HI column densities. To fit the model, we have to assume low model parameters, which may indicate that the model is not applicable in a region with such a high radiation field. We suggest that the addition of an internal radiation field from a central cluster may be required to describe the observations. Thus, this work has shown that the HI content of W43 and its relation to H $_2$  challenges current models of H $_2$  formation.

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