The BLUEDISK Survey: Thickness of H I Layers in Gas-rich Spiral Galaxies

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Abstract

We use an empirical relation to measure the H I scale height of relatively H I-rich galaxies using 21 cm observations. The galaxies were selected from the BLUEDISK, THINGS, and VIVA surveys. We aim to compare the thickness of the H I layer of unusually H I-rich galaxies with that of normal spiral galaxies and find any correlation between the H I scale height and other galaxies’ properties. We found that on average the unusually H I-rich galaxies have H I disk thickness similar to that of the control sample and the galaxies selected from the THINGS and VIVA surveys within their uncertainties. Our results also show that the average thickness of the neutral hydrogen inside the optical disk is correlated with the atomic gas fraction inside the optical disk with a scatter of ∼0.22 dex. A correlation is also found between the H I scale height with the atomic-to-molecular hydrogen ratio, which indicates a link between star formation and the vertical distribution of HI, which is consistent with previous studies. This new scaling relation between the H I scale height and atomic gas fraction will allow us to predict the H I scale heights of a large number of galaxies, but a larger sample is needed to decrease the scatter.

Unified Astronomy Thesaurus concepts: Disk galaxies (391); Galaxy evolution (594); Disk flaring (390)

1. Introduction

Neutral hydrogen gas (H I hereafter) is the most abundant element in the universe and the primary fuel for star formation. For nearby galaxies, H I is observed at 21 cm in emission and its distribution is often used to study the distribution of dark matter in spiral and dwarf galaxies (e.g., Bosma 1981; de Blok et al. 2008) assuming that it traces the gravitational potential. Another application is the relationship between the gas surface density and star formation surface density, the so-called Kennicutt–Schmidt law (see Kennicutt 1998 for a review). These studies are based on the assumption that the thickness of the H I layer is negligible.

Knowing the three-dimensional distribution of H I allows us to study the shape of the dark matter halo (see Olling 1995, 1996) and the relationship between the gas volume density and star formation, recently known as volumetric star formation law (Bacchini et al. 2019a, 2019b, see Schmidt 1959 for theoretical background). Recent studies have also demonstrated the role of the gas disk thickness on gravitational instabilities of the galactic disk for high and low redshift galaxies (e.g., Romeo et al. 2010; Romeo & Agertz 2014; Hoffmann & Romeo 2012) previously assumed to be negligible.

In observations, the thickness of the H I layer is difficult to measure for less inclined galaxies and direct measurements are only possible for edge-on galaxies (e.g., NGC891, Sancisi & Allen 1979; van der Kruit 1981; Swaters et al. 1997). However, the measurements might still be affected by projection effects produced by a warp or flaring of the outer disk. Other methods include using the H I power spectrum (Dutta et al. 2009) and the spectral correlation function (Padoan et al. 2001), which require sub-kiloparsec spatial resolution observations. The size and distribution of H I shells have also been used as an indirect method to measure the H I thickness. The maximum diameter of the shell produced by supernovae explosion in the OB association region is believed to be comparable to the thickness of the H I layers (e.g Silich & Tenorio-Tagle 1998).

In theory, detailed modeling is usually assumed assuming that H I is in hydrostatic equilibrium (e.g., Olling 1995, 1996). The H I disk thickness is determined by the equilibrium between the confining pressure due to the gravitational potential and uplifting pressures produced by gas motions (Iorio 2018). In this framework, the vertical density distribution of the gas is described by the stationary Euler equation (Iorio 2018). The density profile is obtained by solving the Euler equation and assuming that the velocity dispersion is constant along the vertical direction and the gravitational potential of a rotating gas is symmetric. The gravitational potential is computed for each component (star, dark matter, and gas) and the scale height is varied until the model reproduces the observations using an iterative method. Bacchini et al. (2019b) applied this method on 12 galaxies selected from the THINGS survey (see also Abramova & Zasov 2008; Banerjee et al. 2011).

Recently, Wilson et al. (2019) estimated the vertical scale height of molecular hydrogen of five luminous and ultraluminous galaxies assuming vertical equilibrium. Wilson et al. (2019) used the original formulation by Spitzer (1942), which stated that the confining pressure due to gravity is equal to the uplifting forces produced by the interstellar medium (ISM) and formulated an empirical relation based on the measured velocity dispersion and surface densities, which are observable quantities to estimate the gas scale height. They also included the effects of other factors, such as magnetic field and cosmic rays, on the gas disk thickness (e.g., de Avillez & Breitschwerdt 2005; Girichidis et al. 2016; Hill et al. 2018).

Here, we applied a modification of this method on a sample of 28 H I-rich and control galaxies from BLUEDISK (Wang et al. 2013), 14 spiral galaxies from the VIVA (Chung et al. 2009), and 12 from the THINGS (Walter et al. 2008) surveys. The BLUEDISK survey (Wang et al. 2013) was primarily designed to investigate the origin and existence of gas accretion in nearby galaxies. The survey consists of 23 galaxies with unusually large H I mass fraction according to the fundamental plane by Catinella et al. (2012) and control sample, which match in terms of their...
stellar mass, stellar surface density, and NUV-r color indexes. Several works have been done using BLUEDISK data such as the morphological studies of the H I gas using moment 0 maps (Wang et al. 2013, 2014). Therefore, we will make use of these measurements in this work. In this paper, we focus on the thickness of the H I gas layer and its relation to the gas fraction and other galaxies’ global properties. Our goal is to compare the thickness of the H I layer of unusually H I-rich galaxies with that of normal spiral galaxies and derive scaling relations that will be useful to study the thickness of H I layers for a large sample of galaxies that will be available in the near future.

The paper is structured as follows. Section 2 describes the sample selection and method. The result of the tilted ring analysis, the measurements of H I scale height, and the correlation between the scale height with other galaxy properties are presented and discussed in Section 3. A summary is given in Section 4.

2. Data and Analysis
2.1. Sample Selection

Our main sample is selected from the BLUEDISK H I survey (Wang et al. 2013). More details about the survey are given in Wang et al. (2013); here we give a brief summary. The BLUEDISK H I survey comprises galaxies that are unusually H I-rich based on the fundamental plane of Catinella et al. (2012) and the control sample, which matches in terms of stellar mass ($M_*$), stellar surface density ($\Sigma_*$), and color index (NUV-r). The galaxies were observed using the WRST interferometer. We excluded galaxies that are interacting or in close pairs following Wang et al. (2013, 2014). We further excluded galaxies that show complex H I distributions such as ID10 and ID39 (see Wang et al. 2013). The kinematic analysis tool $^{3}D$BAROLO (Di Teodoro & Fraternali 2015) also requires that the galaxy should be moderately inclined and have at least two resolution elements along the semimajor axis (e.g., Read et al. 2016; Iorio et al. 2017). We therefore select moderately inclined galaxies that have $R_{90,\text{HI}}$ (the radius that contains 90% of the H I flux) larger than 30". The $R_{90,\text{HI}}$ distribution of the galaxies modeled using $^{3}D$BAROLO and the selected sample are shown in Figure 1. Our selected sample consists of 28 H I-rich and control galaxies from BLUEDISK (Wang et al. 2013). The SFR are taken from Cormier et al. (2016) for the BLUEDISK sample. They were measured from a combination of archival WISE 22 $\mu$m (Wright et al. 2010) and GALEX FUV (Martin et al. 2005). The molecular gas masses are from CO follow-up observations of the BLUEDISK galaxies (Cormier et al. 2016). The CO(2-1) and CO(0-1) line observations were done with IRAM using the Heterodyne Receiver Array (HERA) instrument for 26 galaxies and the Eight Mixer Receiver (EMIR) instrument for 11 galaxies. The data were reduced using GILDAS standard...
packages. Reader are referred to Cormier et al. (2016) for more details about the observations and data reduction.

We further added moderately inclined galaxies from the VIVA (Chung et al. 2009; 14 galaxies) and THINGS (Walter et al. 2008; 12 galaxies) surveys for comparison with BLUEDISK. We select galaxies that are not strongly warped and have similar stellar mass with the BLUEDISK sample.

### 2.2. Tilted Ring Analysis

A tilted ring model is usually used to extract kinematics and orientation information from emission line observations. The galaxy is divided into concentric rings (e.g., Begeman 1989) and the rotation velocities and other orientation parameters are derived for each ring. The line-of-sight velocity is given as:

\[
V(x, y) = V_{sys} + V_c \sin(i) \cos(\theta) + V_r \sin(i) \cos(\Phi),
\]

where \(V_{sys}\), \(V_c\), and \(V_r\) are the systemic, circular, and radial velocities, respectively, \(i\) is the inclination angle, and \(\theta\) is the azimuthal angle in the plane of the galaxy, related to the major axis position angle \(\Phi\) by:

\[
\cos(\theta) = \frac{-(x - x_0) \sin(\Phi) + (y - y_0) \cos(\Phi)}{R}
\]

and

\[
\sin(\theta) = \frac{-(x - x_0) \cos(\Phi) + (y - y_0) \sin(\Phi)}{R \sin(i)}.
\]

The tilted ring method is usually applied to velocity maps for high angular resolution observations (e.g., de Blok et al. 2008). However, it is severely affected by beam smearing for low resolution observations. Moreover, the derived rotation curves and velocity dispersion also depend on the method used to derive the velocity maps (de Blok et al. 2008). Three-dimensional tilted ring mitigates this problem since it uses all the information in the data, it also derives the rotation velocities and velocity dispersion simultaneously. Several 3D tilted ring software are available in the literature (e.g., TIRIFIC, Józsa et al. 2007; GBKFIT, Bekiaris et al. 2016; 3D-BAROLO, Di Teodoro & Fraternali 2015). Here we use the 3D-BAROLO software to derive the rotation curve, velocity dispersion and H\(\alpha\) surface density profiles of the BLUEDISK, VIVA, and THINGS galaxies.

### 2.3. H\(\alpha\) Disk Scale Height

The H\(\alpha\) disk scale height is usually measured assuming that the gas is in hydrostatic equilibrium (Olling 1995, 1996; Bacchini et al. 2019a, 2019b). This method requires prior knowledge of the dark matter distribution obtained through rotation curve decomposition in addition to the gas velocity dispersion and surface densities (Bacchini et al. 2019a, 2019b). However, mass modeling by decomposing the observed rotation curve is limited to few galaxies with high resolution emission line observations (see Bosma 1981; de Blok et al. 2008).
Figure 3. Channel maps for ID15. Top rows: data. Bottom rows: 3D-BARLO model. Only every three channel is shown, the beam and scale bar are plotted in the bottom left panel. The contours are $2\sigma$, $4\sigma$, $8\sigma$, and $10\sigma$, where $1\sigma \sim 0.0023 \text{ Jy beam}^{-1}$. 
Wilson et al. (2019) used a semiempirical formula to measure the molecular scale height of five luminous and ultraluminous infrared galaxies. By solving the equation of equilibrium for an isothermal gas (Spitzer 1942) and equating the confining pressure due to gravity $P_{\text{grav}}$ with the uplifting pressure produced by the gas motions, magnetic fields, and cosmic rays $P_{\text{ISM}}$, they showed that the scale height could be expressed entirely with observationally derived variables (Wilson et al. 2019).

The gas scale height is therefore expressed as (Equation (6) in Wilson et al. 2019).

$$h(R) = \frac{\sigma^2(R)}{\pi G \Sigma_{\text{gas}}} \times \left( \frac{1 + \alpha + \beta}{1 + g_{\text{galaxy}}/g} \right) \times \left( \frac{\Sigma_{\text{gas}}}{\Sigma_{\text{total}}} \right),$$

where $\sigma(R)$, $\Sigma_{\text{gas}}$, and $\Sigma_{\text{total}}$ are the velocity dispersion, gas surface density, and the total surface density within the gas layer; $g_{\text{galaxy}}/g$ is the ratio between the total gravitational acceleration of the galaxy and the gravitational acceleration due to the disk mass; $\alpha$ is the ratio between magnetic field and turbulence and thermal support; and $\beta$ is cosmic rays to turbulence and thermal support. Using magnetohydrodynamic simulation, Kim & Ostriker (2015) estimated the ratio between the vertical magnetic pressure to the turbulence plus thermal support.
support $\alpha \sim 0.3$. However, magnetic fields are more associated with dense molecular gas and not with H I. Using a sample of 20 nearby spiral galaxies, Van Eck et al. (2015) found that the magnetic field strength is correlated with molecular gas surface density and star formation rate but not with atomic gas. For dwarf irregular galaxies, Chyży et al. (2017) noted that the magnetic fields are very weak ($<4.2\mu G$). For individual galaxies, it has been found that the magnetic field is more associated with dense molecular gas than with atomic hydrogen gas (e.g., Tabatabaei et al. 2013a, 2013b). Our sample consists of H I-rich and normal spiral galaxies. Therefore, we will assume that the effect of magnetic field on atomic gas disk thickness is negligible as compared to turbulence and thermal support. The coefficient $\beta$ is also negligible ($\beta \sim 0.0$; see Parker 1966). We also assume that the average ratio between the gas and stellar surface densities ($\Sigma_{\text{gas}}/\Sigma_{\text{total}}$) could be approximated by the ratio between the H I mass within the optical disk to the stellar mass and that the molecular gas makes a small contribution to the total mass. The H I mass within the optical disk is measured from the H I intensity map by converting the total flux within the optical disk into mass using the following equation:

$$M_{\text{HI}}/M_\odot = 2.356 \times 10^5 S_{\text{HI}} D_{\text{Mpc}}^2,$$

where $S_{\text{HI}}$ is the total flux inside the optical disk in Jy K m s$^{-1}$ and $D$ is the distance in Mpc. The H I within the optical disk can also be predicted using the method developed by Wang et al. (2020) for low spatial resolution and single dish H I observations. Wang et al. (2014) investigated the shape of the H I surface density profiles using a large sample of nearby spiral and dwarf galaxies. They found that the profiles are well fitted using an exponential function and the outer part of the average profile of all the galaxies in their sample is almost universal. Wang et al. (2020) used the average profile from Wang et al. (2014) and estimated the fraction of H I mass outside the optical radius for galaxies selected from the xGASS sample. The H I mass within the optical disk is then given by the difference between the total H I mass and the H I outside the optical disk. The readers are referred to Wang et al. (2020) for more details about the method and the assumption used to estimate the H I mass within the optical disk.

Using the above assumptions and following Wilson et al. (2019), $g_{\text{galaxy}}/g$ could be written as:

$$\frac{g_{\text{galaxy}}}{g} = \frac{(1 + \alpha + \beta) \sigma_{\text{HI},0}}{2 \times \left( \frac{M_{\text{dyn}}}{M_{\text{HI,in}} + M_{\text{star}}} \right)^2},$$

and

$$\frac{\Sigma_{\text{HI, in}}}{\Sigma_{\text{total}}} \sim f_{\text{HI, in}} = \frac{M_{\text{HI, in}}}{M_{\text{HI, in}} + M_{\text{star}}},$$

where $M_{\text{dyn}}$ is the dynamical mass, $f_{\text{HI, in}}$ is the H I fraction within the optical disk, and $\sigma_{\text{HI},0}$ is the central H I velocity dispersion obtained by fitting the radial profile of the velocity dispersion with an exponential function ($\sigma(R) = \sigma_{\text{HI},0} \times \exp(-R/R_\odot)$).

Finally, the H I scale height is given by

$$h_{\text{HI}}(R) \sim K \times \frac{\sigma^2(R)}{\Sigma_{\text{HI}}},$$

where $K$ is given by

$$K = \frac{1.0}{\pi \sigma^2 \Sigma (1 + g_{\text{galaxy}}/g)} \times f_{\text{HI, in}}.$$

### 3. Results and Discussion

#### 3.1. Tilted Ring Analysis

The tilted ring results for the H I-rich galaxy ID15 is shown in Figure 2. The rotation curve is presented in the top panel. The errorbars are the quadratic sum of the statistical error and the difference between the approaching and receding sides of the galaxy. The inclination and position angle are in the middle and bottom panels; their average values are shown as dashed lines and summarized in Table 1. An arctan function (Courteau 1997) was fitted to the observed rotation curves in order to obtain the maximum circular velocity $V_{\text{max}}$ listed in Table 1. The channel maps are displayed in Figure 3 for ID15 where the data is shown in blue and the 3D-BAROLO model in red. The contour levels correspond to 2, 4, 8, and 10 times the detection threshold $1\sigma \sim 0.0023$ Jy BeG s$^{-1}$. The moment 0 and moment 1 maps are presented in Figure 4 and the position–velocity diagram is presented in Figure 5. These figures show a clear signature of noncircular motions along the minor axis of the galaxy.

#### 3.2. H I Disk Scale Height

Figure 6 compares the Wang et al. (2014) density profile with the 3D-BAROLO density profile. Wang et al. (2014) used one pixel radial bin ($\sim 4''$) using the moment 0 maps combined with photometric inclination and position angle; on the other hand, 3D-BAROLO uses larger radial bins based on the angular resolution of the data ($\sim 15''$) and uses the kinematic position and inclination angle listed in Table 1. The two density profiles are in good agreement except in the inner region. This might be because the 3D-BAROLO density profiles are averaged over larger radius compared to the Wang et al. (2014) profiles and 3D-BAROLO fitted inclination and position angle as functions of radius, while Wang et al. (2014) used a constant inclination and position angle determined from the optical photometry. Therefore, we will use the 3D-BAROLO density profiles throughout this paper.

The velocity dispersion profiles are shown in the middle panels of Figure 7 for the H I-rich sample and Figure 8 for the control sample. They are fitted with an exponential function to obtain the central velocity dispersion. The fitting results are summarized in Table 1. The dashed line indicates a velocity dispersion of 10 km s$^{-1}$, which is a typical value for the velocity dispersion of neutral hydrogen gas. The radial variations of the H I scale height calculated using Equation (10) are in the right panels of Figures 7 and 8 for four H I-rich and control galaxies, respectively. The scale heights of the remaining galaxies are given in the Appendix.
Figure 7. H I surface density, velocity dispersion, and H I Scale height of four H I-rich galaxies. The density profiles obtained from 3dBAROLO are in the first column and the velocity dispersion profiles derived using 3dBAROLO are in the middle panels. The blue curves show the exponential fit to the observation and the dashed lines indicate $\sigma_{HI} = 10 \text{ km s}^{-1}$. The H I scale heights calculated using Equation (10) are in the third column. The red dashed line is the scale height assuming a constant velocity dispersion, the blue lines show the scale height when the exponential fit is used for the velocity dispersion, and the black circles with errorbars are the measured scale heights. The dashed horizontal lines are the average scale height inside the optical radius.
Figure 8. Same as Figure 4 but for control galaxies.
On average, the H\textsc{i}-rich galaxies have two times the H\textsc{i} gas fraction (\(\sim 0.43\)) compared to the control galaxies (\(\sim 0.17\)). The ratio between the H\textsc{i} and optical disk size (\(R_{\text{HI}}/r_{25}\)) and \(M_{\text{HI,\text{in}}}/M_{\text{HI}}\), where \(M_{\text{HI,\text{in}}}\) is the H\textsc{i} mass inside the optical disk also differ for the H\textsc{i}-rich and control samples. The H\textsc{i}-rich galaxies have an average \(R_{\text{HI}}/r_{25} \sim 1.78 \pm 0.54\) and \(M_{\text{HI,\text{in}}}/M_{\text{HI}} \sim 0.24 \pm 0.17\). On the other hand, the control galaxies have an average \(R_{\text{HI}}/r_{25} \sim 1.31 \pm 0.40\) and \(M_{\text{HI,\text{in}}}/M_{\text{HI}} \sim 0.38 \pm 0.18\). The H\textsc{i} disk scale height inside the optical disk for the H\textsc{i}-rich galaxies (\(\sim 0.41 \pm 0.29\) kpc) is, however, comparable with the control galaxies (\(\sim 0.29 \pm 0.14\) kpc) and galaxies from THINGS (\(\sim 0.68 \pm 0.58\) kpc) and VIVA (\(\sim 0.31 \pm 0.25\) kpc). The H\textsc{i}-rich and control galaxies also have similar star formation rates (SFR \(\sim 2.5 M_{\odot}\) yr\(^{-1}\)) and molecular gas mass (\(M_{\text{H}_2} = 2.5 \times 10^9 M_{\odot}\)) (Cormier et al. 2016). Previous studies have also shown that H\textsc{i}-rich galaxies are inefficient at forming stars (e.g., Cormier et al. 2016; Lemonias et al. 2014). One possible explanation is that the excess of H\textsc{i} is mostly located outside the optical disk (see, e.g., Wang et al. 2020).

One caveat of our method is the angular resolution of the BLUEDISK data, which lead to large uncertainties on the measured velocity dispersion. However, Read et al. (2016), Iorio et al. (2017), and Bacchini et al. (2019a) have shown that the velocity dispersion profiles derived using 3D\textsc{BAROLO} are reliable since it is corrected for beam smearing. 3D\textsc{BAROLO} also uses the full data cube instead of moment or Gaussian maps.

### 3.3. H\textsc{i} Disk Flaring

It is clear from Equation (10) that the scale height will systematically increase toward the outer part of the galaxy if the velocity dispersion is constant or have a small variation with radius. This is because the surface density exponentially decreases with radius (Wang et al. 2014). This phenomenon is commonly known as disk flaring and has been used to study the shape of the dark matter halo (Olling 1995, 1996). Previous studies have shown that the velocity dispersion profiles of nearby galaxies varies with radius (Tamburro et al. 2009; Mogotsi et al. 2016). The amplitude of the outer flaring thus depends on the velocity dispersion and H\textsc{i} surface density profiles. All galaxies in the BLUEDISK sample show disk flaring when the velocity dispersion is fixed to 10 km s\(^{-1}\) (e.g., Olling 1995, 1996).
The radial profiles of the HI scale height of the BLUEDISK galaxies can be divided into three categories:

1. Galaxies with scale height that increase with radius are in the first category; \( \sim 10 \) galaxies are in this category. Their velocity dispersion profiles are almost flat or have small variation with radius.

2. Galaxies with constant scale height are in the second category; \( \sim 7 \) galaxies are in this category. Their velocity dispersion profiles decrease with radius and are well fitted with an exponential function (examples: ID11 and ID23).

3. Galaxies with complex scale height profiles are in the third category.

The spiral HI-rich galaxy ID17 is an example of when the disk scale height is constant with radius. For this galaxy, the velocity dispersion decreases by 5 km s\(^{-1}\) between 40\(''\) and 100\(''\). ID47 is another galaxy that exhibits similar behavior.

Figure 9 shows the effect of velocity dispersion on the thickness of the HI layer. This figure demonstrates that higher values for the velocity dispersion will lead to a thicker gas layer and more prominent outer flaring. Theoretically, the velocity dispersion is driven by stellar feedback and gas inflow (Krumholz et al. 2018). The flaring of HI disks, therefore, should carry information about the radial distribution of most recent star formation and radial motion of the gas. This topic will be investigated more thoroughly in a future study. Thus, care should be taken when assuming a constant velocity dispersion. For example, Figure 9 shows that a constant velocity dispersion of 8 km s\(^{-1}\), which is commonly adopted in the literature (see Olling 1995, 1996) is able to reproduce the
HI scale height for ID17 but will lead to a thinner HI layer for ID15.

HI surface density is another parameter that determines the thickness of the HI layer. Particularly in the outer disk where HI dominates the gravitational potential of the baryons (HI densities drop much slower than the stars or molecular gas, in relatively HI-rich galaxies). Figure 10 shows different density profiles for ID15. Each profile is modeled using an exponential function with the same scale length but different central surface density. We then compute the corresponding scale height using the same velocity dispersion profile but different surface density profiles. The results are shown in the bottom panel of Figure 10. It shows that the disk is thicker when the surface density is low and vice versa. Environmental effect is also an important factor since it could modify the HI surface density and velocity dispersion profiles. It also produces noncircular motions that could not be classified into thermal or turbulent motions. A detailed analysis of the effect of the environment on the HI thickness will be deferred to the upcoming paper.

The average HI scale height within the optical disk is summarized in Table 1. The central velocity dispersion and the circular velocity $V_{\text{max}}$ are plotted against the average HI scale height inside the optical disk in the left panels of Figure 11 and the flaring amplitude $h_{\text{fla}} - \langle h_{\text{HI,in}} \rangle$ in the right panels. The bottom panels of this figure show a clear trend with velocity dispersion. Galaxies with larger central HI velocity dispersion are thicker on average and do not exhibit disk flaring.

3.4. Correlations with Galaxy Global Properties

This section discusses relationships between the estimated HI scale height inside the optical disk with global optical
and H I properties. We found no correlation between the R-band concentration index \( R_{90}/R_{50} \) and the H I scale height as shown in the left panel of Figure 12 with a Pearson correlation coefficient of \( \rho \sim -0.04 \) and a \( p \)-value of 0.95. We also did not find any correlation between the HI scale height and the H I concentration index \( R_{90}/R_{50} \), which is the ratio between the radius that contains 90% and 50% of the HI fluxes (\( \rho \sim 0.04 \) and \( p \)-value 0.94) and the ratio between the radius of the H I and optical disk (\( \rho \sim 0.03 \) and \( p \)-value 0.97). These results imply that for the BLUE-DISK galaxies, there is no relation between the vertical extend of the HI and the central concentration of the stars and gas.

We also explore the relation between the H I disk thickness and the atomic gas fraction. Figure 13 plots the ratio between the H I and stellar mass as a function of the HI scale height.

The bottom panel of this figure shows that the HI scale height is strongly correlated with the H I fraction estimated within the optical disk with a Pearson correlation of \( \rho \sim 0.77 \) and a \( p \)-value of \( \sim 10^{-6} \). We further added galaxies from the THINGS and VIVA HI surveys to the relation and used the atomic gas fraction instead of HI fraction. The bottom panel of Figure 14 shows a strong correlation between the atomic gas fraction inside the optical disk with the HI disk thickness. We derive the following scaling relation between the HI disk scale height and the atomic gas fraction measured inside the optical disk:

\[
\log(h_{\text{HI, in}}) = 0.8196 \times \log f_{\text{atm, in}} + 0.178 \pm 0.22,
\]

**Table 2**

| Sample                        | Slope (\( \alpha \)) | Intercept (\( \beta \)) | rms Scatter | Correlation Coef. | \( p \)-value: |
|-------------------------------|-----------------------|--------------------------|-------------|-------------------|---------------|
| BLUEDISK (HI-rich)            | 0.83 ± 0.35           | -0.08 ± 0.18             | 0.23        | 0.47              | 0.031         |
| BLUEDISK (HI-rich+control)    | 1.11 ± 0.33           | 0.025 ± 0.18             | 0.32        | 0.55              | 0.002         |
| BLUEDISK + THINGS             | 1.05 ± 0.20           | 0.034 ± 0.12             | 0.32        | 0.62              | 1.15e-5       |
| BLUEDISK +THINGS + VIVA       | 0.63 ± 0.10           | -0.12 ± 0.085            | 0.38        | 0.65              | 2.36e-7       |

Figure 15. Relation between H I scale height and the atomic gas fraction derived using different combinations of the sample. Lines and symbols are the same as in Figure 14.
where the atomic gas fraction inside the optical disk is given by

$$\log f_{\text{atm, in}} = \log \left( \frac{1.36M_{\text{HI, in}}}{1.36M_{\text{HI, in}} + M_\ast} \right)$$

The 1σ scatter is smaller $\sim 0.22$ dex if $f_{\text{atm, in}}$ is used compared to 0.38 dex if $\log f_{\text{atm}}$ is used instead. The relation between the H I scale height and atomic gas fraction can be expressed as

$$\langle h_{\text{HI}} \rangle = C_1 \times f_{\text{atm}}^{C_2},$$

where $C_1$ and $C_2$ are constants.

### 3.5. The H I Scale Height–Atomic Gas Fraction Relation

We checked if the relation between the H I scale height and the atomic gas fraction relation measured inside the optical disk is produced in a specific sample. We derive the relation using a different combination of the sample using the total atomic gas fraction in Figure 15. The fitting results are summarized in Table 2. We found no correlation between scale height and the total atomic gas fraction if only the BLUEDISK H I-rich galaxies are used in the fit with a $p$-value of 0.031. The fit improves when control galaxies are also added to the fit but the $p$-value of 0.002 still suggests no correlation. The scatter also increases by 0.1 dex. A correlation is found when both the THINGS and VIVA are also added to the fit. However, the scatter

### Table 3

The H I Scale Height–H I Fraction Relation Coefficients Using the H I Mass inside the Optical Disk

| Sample                          | Slope ($\alpha$) | Intercept ($\beta$) | rms Scatter | Correlation Coef. | $p$-value |
|---------------------------------|------------------|---------------------|-------------|------------------|-----------|
| BLUEDISK (H I-rich)             | 0.85 ± 0.14      | 0.26 ± 0.13         | 0.15        | 0.80             | 1.12e-5   |
| BLUEDISK (H I-rich+control)     | 1.05 ± 0.11      | 0.42 ± 0.11         | 0.14        | 0.88             | 6.28e-10  |
| BLUEDISK + THINGS               | 0.79 ± 0.09      | 0.11 ± 0.08         | 0.20        | 0.78             | 5.47e-10  |
| BLUEDISK + THINGS + VIVA        | 0.78 ± 0.08      | 0.14 ± 0.08         | 0.22        | 0.84             | 1.37e-13  |

Note. $\log h_{\text{HI}} = \alpha \log f_{\text{atm, in}} + \beta$. 

Figure 16. Relations between H I scale height and the atomic gas fraction inside the optical disk derived using a different combination of the sample. Lines and symbols are the same as in Figure 14.
relation becomes more flat with a slope of \(\sim 0.6\) compared to \(\sim 1.1\) when BLUEDISK galaxies alone are used. This change of slope is mainly driven by the VIVA galaxies that have lower H\(_I\) fractions but similar scale heights to the THINGS and BLUEDISK galaxies. On the other hand, a clear correlation is found when the atomic gas fraction inside the optical disk is used. The fitting results are shown in Figure 16 and summarized in Table 3 for the fit using the atomic gas fraction inside the optical disk. The slope of the relation also does not change significantly when adding more galaxies and the scatter is smaller compared to the slope obtained when the total atomic gas fraction is used. Upcoming surveys such as WALLABY will provide us with a large enough sample that spans a wide range of H\(_I\) fractions and will give us a clear picture of the H\(_I\) scale height–atomic gas fraction relation.

### 3.6. Relation with Star Formation Rates and Molecular Hydrogen Content

In this section we explore the correlation between H\(_I\) scale height with the molecular gas content and SFR. In Figure 17, the star formation rates, star formation rates per unit gas (atomic and molecular), and specific star formation rates are plotted as a function of the H\(_I\) scale height inside the optical disk. This figure shows that the scale height is correlated with the specific star formation rate and the star formation rate per molecular gas mass with a \(p\)-value smaller than 0.001. No correlation was found between the H\(_I\) thickness and the star formation rate nor the star formation rate per H\(_I\) mass. In Figure 18, the molecular to H\(_I\) ratio inside the optical disk (top) and the total molecular to H\(_I\) ratio (bottom) are plotted as a function of the H\(_I\) scale height. This figure shows that the H\(_I\) scale height is more correlated with H\(_I\) to molecular gas inside the optical disk with a correlation coefficient of 0.58 and a \(p\)-value of \(<0.001\) and not with the total H\(_2\) to H\(_I\) ratio. Note that, theoretically, midplane pressure is a key factor in both setting the H\(_I\) thickness, and the conversion of H\(_I\) to the molecular gas (Blitz & Rosolowsky 2006; Ostriker et al. 2010). The role of midplane pressure in setting the H\(_2\) to H\(_I\) conversion has been confirmed by Leroy et al. (2008).

### 4. Summary

We used an empirical relation from Wilson et al. (2019) to estimated the average H\(_I\) scale height of spiral galaxies selected from BLUEDISK (Wang et al. 2013), THINGS (Walter et al. 2008), and VIVA (Chung et al. 2009) H\(_I\) surveys. We investigated correlations between the H\(_I\) scale height with other optical and H\(_I\) global properties.

Our main results are as follows:
1. The H I-rich galaxies from BLUEDISK have similar H I disk thickness inside the optical disk on average (\(\sim 0.41 \pm 0.29\) kpc) to the control (\(\sim 0.29 \pm 0.14\) kpc), THINGS (\(\sim 0.68 \pm 0.58\) kpc), and VIVA (\(\sim 0.31 \pm 0.25\) kpc) galaxies.

2. The H I scale height radial profiles can be divided into three categories. The first category consists of galaxies where the H I disk thickness increases with radius, the second category has a H I scale height that is constant with radius, and the third category has complex scale height radial profiles. The complexity may reflect a mixture of effects from gas inflow, the resulting radial distribution of gas surface density, stellar feedback, and environmental effects.

3. The average H I scale height within the optical disk is correlated with the atomic gas fraction. Such correlations would be useful when estimating the H I disk thickness of a large sample of galaxies.

4. The average scale height within the optical disk is also correlated with the central H I velocity dispersion. However, a larger sample is needed before further interpretation.

5. The relation between \(M_{H_2}/M_{HI}\) and the H I scale height confirm the role of gas disk thickness on star formation efficiency, which has been previously reported (e.g., Leroy et al. 2008).

Measuring the gas disk thickness is a challenging task and direct measurements are only available for a handful of edge-on galaxies. A scaling relation is therefore crucial and will allow us to estimate the vertical extent of H I in a large sample of galaxies. The WALLABY survey will observe \(\sim 500,000\) galaxies but most of these will be unresolved. Single dish radio telescopes, such as FAST, will detect a large number of galaxies in H I. These upcoming surveys will provide H I masses for a significant number of galaxies. We can therefore explore statistically the effect of the vertical extent of H I on star formation efficiency in nearby disk galaxies.

A dedicated survey of edge-on galaxies will increase the number of galaxies with measured scale height and will help us to better understand the vertical distribution of H I. This will also allow us to test different theories of vertical equilibrium.

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**Appendix**

**H I Scale Heights of the Remaining BLUEDISK Galaxies**

Figures A1 to A4 show the surface density, velocity dispersion, and vertical scale height profiles of the remaining H I-rich galaxies selected from BLUEDISK. The remaining control galaxies are in Figure A5.
Figure A1. H I scale height of the remaining H I-rich galaxies. See Figure 7 for details.
Figure A2. H I scale height of the remaining H I-rich galaxies (continued).
Figure A3. H I scale height of the remaining H I-rich galaxies (continued).
Figure A4. H I scale height of the remaining H I-rich galaxies (continued).
Figure A5. H I scale height of the remaining control galaxies. See Figure 8 for details.

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