THE SHAPES OF THE H$_1$ VELOCITY PROFILES OF THE THINGS GALAXIES

R. IANJAMASIMANANA$^1$, W. J. G. DE BLOK$^{1,2}$, FABIAN WALTER$^3$, AND GEORGE H. HEALD$^2$

$^1$ Astrophysics, Cosmology and Gravity Centre, Department of Astronomy, University of Cape Town, Private Bag X3, Rondebosch 7701, South Africa; ianja@ast.uct.ac.za
$^2$ Netherlands Institute for Radio Astronomy (ASTRON), Postbus 2, 7990 AA Dwingeloo, The Netherlands
$^3$ Max-Planck Institut für Astronomie, Königstuhl 17, D-69117, Heidelberg, Germany

Received 2012 March 27; accepted 2012 July 19; published 2012 August 30

ABSTRACT

We analyze the shapes of the H$_1$ velocity profiles of The H$_1$ Nearby Galaxy Survey to study the phase structure of the neutral interstellar medium and its relation to global galaxy properties. We use a method analogous to the stacking method sometimes used in high-redshift H$_1$ observations to construct high-signal-to-noise (S/N) profiles. We call these high-S/N profiles super profiles. We analyze and discuss possible systematics that may change the observed shapes of the super profiles. After quantifying these effects and selecting a subsample of unaffected galaxies, we find that the super profiles are best described by a narrow and a broad Gaussian component, which are evidence of the presence of the cold neutral medium and the warm neutral medium. The velocity dispersion of the narrow component ranges from $\sim3.4$ to $\sim8.6$ km s$^{-1}$ with an average of 6.5 $\pm$ 1.5 km s$^{-1}$, whereas that of the broad component ranges from $\sim10.1$ to $\sim24.3$ km s$^{-1}$ with an average of 16.8 $\pm$ 4.3 km s$^{-1}$. We find that the super profile parameters correlate with star formation indicators such as metallicity, far-UV—near-UV colors, and H$_{\alpha}$ luminosities. The flux ratio between the narrow and broad components tends to be highest for high-metallicity, high-star-formation-rate galaxies. We show that the narrow component identified in the super profiles is associated with the presence of star formation, and possibly with molecular hydrogen.

Key words: galaxies: dwarf – galaxies: fundamental parameters – galaxies: ISM – galaxies: spiral – ISM: kinematics and dynamics – radio lines: ISM

Online-only material: figure set

1. INTRODUCTION

Gas in the interstellar medium (ISM) in disk galaxies can exist in molecular, atomic, or ionized phases. Most of it will be in the form of neutral atomic hydrogen (H$_1$) whose hyperfine transition can be detected at the 21 cm wavelength. Since the early work of Clark (1965), the neutral atomic ISM has been known to exist in two phases, known as the cold neutral medium (CNM) and the warm neutral medium (WNM). Clark (1965) first suggested that H$_1$ seen in emission and absorption had different line widths because it arose from two distinct components of the ISM. The narrow absorption spectra are caused by a cold component of the ISM (the CNM) with a temperature of $\sim100$ K whereas the broad emission spectra arose from a warm component with a temperature as high as $10^4$ K (the WNM). The existence of these two components was later confirmed by Radhakrishnan et al. (1972) using interferometric observations of H$_1$ emission and absorption spectra toward 35 extragalactic sources situated at intermediate and high Galactic latitudes. The CNM and the WNM are known to coexist in pressure equilibrium over a narrow range of pressure (Wolfire et al. 2003). The CNM dominates at high densities and pressures whereas the WNM prevails at low densities and pressures. These two components have been identified in the Milky Way, nearby dwarfs, and spiral galaxies by comparing H$_1$ seen in emission and absorption as well as from observations of H$_1$ emission alone.

Young & Lo (1996, 1997) and Young et al. (2003) analyzed H$_1$ emission velocity profiles of seven nearby dwarf galaxies. By fitting these profiles with Gaussian components, they found evidence for a broad component with a dispersion ranging from about 8 to 13 km s$^{-1}$ as well as a much narrower component with a dispersion ranging from 3 to 5 km s$^{-1}$. These velocity dispersions are larger than the predicted thermal line widths for the CNM and the WNM, showing that other energy sources are also playing a role in broadening the line profiles. Moreover, they found that the narrow component shows a clumpy distribution and tends to be located near star formation regions, whereas the broad component shows a more ubiquitous distribution. Because of the similarities of the observed properties of these two components with those of the CNM and WNM in M 31 and in our Galaxy, they associated the narrow component with the CNM and the broad component with the WNM phases of the ISM. A similar study was made by de Blok & Walter (2006) for the Local Group dwarf galaxy NGC 6822. They also found narrow and broad H$_1$ components with mean velocity dispersions of 4 km s$^{-1}$ and 8 km s$^{-1}$, respectively. Here also, the narrow component is usually located near star-forming regions, whereas the broad component tends to be found along every line of sight. Braun (1997) analyzed H$_1$ emission of 11 nearby spiral galaxies and found what he called a high brightness filamentary network (HBN) of H$_1$ emission, which he associated with the CNM, and a diffuse low brightness emission, which he identified with the WNM. The HBN dominates inside the optical radius $r_{25}$ where it accounts for 60%–90% of the H$_1$ emission, whereas the diffuse component dominates outside this radius. By averaging spectra with peak brightness temperature higher than 4$\sigma$ within annular ellipses in his sample, he found that the combined spectra were characterized by a narrow core superposed on broad Lorentzian wings. The width of the narrow line cores allowed Braun (1997) to give an upper limit of 300 K for the HBN. Braun (1997) also found that the kinetic temperature of the HBN increases with increasing radius. Braun (1997) interpreted this as a result of the decrease in the midplane thermal pressure toward the outer disks.
Understanding the properties of the gas in the ISM is crucial as it is the fuel for star formation. Most of this star formation occurs in giant molecular clouds (GMCs). These are self-gravitating clouds with masses $\sim 10^5 M_\odot$ and sizes $\sim 40$ pc (e.g., Tielens 2005). Hydrogen molecules ($\text{H}_2$) are the main constituents of GMCs, but unfortunately $\text{H}_2$ is not easily observable. Carbon monoxide (CO) is the second-most-abundant molecule in GMCs and can be detected at millimeter wavelengths. Typically, CO line emission is used to infer the amount and distribution of $\text{H}_2$ in galaxies using some CO-to-$\text{H}_2$ conversion factor (e.g., Leroy et al. 2011). Another approach, which needs to be shifted in velocity to the same reference velocity. We use the GIPSY task SHUFFLE to do this. This task uses a velocity field to define the amount by which a profile in the corresponding data cube needs to be shifted. We use Gauss–Hermite velocity fields as input for SHUFFLE. Gauss Hermite polynomial velocity fields give robust estimates for the radial velocity of the peak of the profile, even in the presence of profile asymmetries. For an extensive description, see de Blok et al. (2008).

To minimize the effects of noise, we only include individual profiles whose peak fluxes exceed the $3\sigma$ noise level in the data cubes. For each galaxy, we sum the shuffled profiles to produce what we call super profiles. These are high-quality profiles, which due to their increased $S/N$ allow us to reliably explore the presence of the cold and warm neutral components of the ISM. However, as information on the individual profiles is lost during the stacking, care needs to be taken that systematic effects and possible asymmetries in the input profiles are quantified, to prevent these from mimicking the presence of multiple components in the super profiles. This is discussed in detail in Section 6.

We show in Figure 1 examples of the super profiles of three galaxies (one quiescent galaxy—DDO154; one starburst galaxy—NGC 1569; and an interacting galaxy—NGC 5194; the rest are shown in Appendix A). These super profiles are summed over the entire $\text{H}_1$ disks of the galaxies using the $3\sigma$ cutoff mentioned previously. Typically, each super profile is the sum of a few hundred to a few thousand independent individual profiles (see Table 1). We also plot $3\sigma$ uncertainties (as defined in Section 3), though in many cases these are smaller than the symbols used to plot the profiles. The super profiles are characterized by broader wings and narrower peaks than purely Gaussian profiles. Most of the super profiles are symmetrical. These properties are all similar to what was found for the individual profiles of seven nearby dwarf galaxies studied by Young & Lo (1996, 1997) and Young et al. (2003), but observed at a much higher $S/N$.

In the following, we will analyze the shapes of the super profiles and see if they can be used to infer the presence of the CNM and WNM components of the ISM.

3. PROFILE FITTING AND DECOMPOSITION

Following de Blok & Walter (2006), we fit the super profiles with single Gaussian and double Gaussian components using the GIPSY task XGAUPROF. All parameters (dispersion, central velocity, amplitude, constant background term) are left free in the fits. The uncertainties in the data points of each super profiles are defined as

$$\sigma = \sigma_{\text{ch,map}} \times \sqrt{N_{\text{prof}} / N_{\text{prof,beam}}},$$

(1)
Figure 1. Three examples of super profiles for the THINGS galaxies (the rest are shown in Appendix A). For each galaxy, we show the results from the single (top panel) and double (bottom panel) Gaussian fitting. The bottom panel of each plot show the residuals from the fits. Filled circles indicate the data. The solid lines represent the results from the single and double Gaussian fitting. The dotted and the dashed lines represent the narrow and broad components required in the double Gaussian fitting. We plot error bars as $3\sigma$ error bars, though in most cases they are smaller than the symbols plotted.

where $\sigma_{\text{rms, map}}$ is the rms noise level in one channel map, $N_{\text{prof}}$ is the number of stacked profiles at a certain velocity $V$, and $N_{\text{prof, beam}}$ is the number of profiles in one resolution element (i.e., the number of pixels or profiles per beam). The inverse square of these uncertainties is used as the weight during the fitting. Note that in Equation (1) we assume that the noise is uniform throughout each data cube. Though strictly speaking incorrect (due to the primary beam correction), this is a reasonable assumption as most of the galaxies only occupy the inner quarter or so of the area of the primary beam. The primary beam correction factors are therefore on average small. For 4 galaxies, we correct for the presence of a negative baseline level (caused by missing zero-spacings) prior to the Gaussian fitting procedure. We fit the baseline with a polynomial and subtract it from the super profiles. To illustrate this method, we show in Appendix A the super profiles before and after the correction as well as the polynomial fit to the baseline. In general the correction is of the order of 10% for the velocity dispersions and 20% for the fitted area of the super profiles. More details about this can be found in Appendix A.

In addition to the one- and two-component fits, we have also tried three-component Gaussian fits to check if this further improves the quality of the fits. Comparison of the quality of the different fits in Figure 2 and Table 1, as well as the amplitudes of the residuals in Figure 1, convincingly shows that the super profiles are non-Gaussian and best described by two Gaussian components. Following Braun (1997), we also fit the super profiles with a Lorentzian function. These results are presented in Appendix A. Figure 3 shows histograms of the derived velocity dispersions from both the single and the double Gaussian fitting. The distribution of the narrow component in Figure 3 has a mean of $7.6 \pm 2.5 \text{ km s}^{-1}$, whereas that of the broad component has a mean value of...
22.4 ± 10.0 km s⁻¹. Also, the broad component has a long tail of up to 60 km s⁻¹. The single Gaussian velocity dispersion has a mean of 12.5 ± 3.5 km s⁻¹. If we only consider galaxies with inclinations i < 60°, the single Gaussian velocity dispersion has a mean of 10.9 ± 2.1 km s⁻¹. This is in agreement with the mean second-moment value of 11 ± 3 km s⁻¹ which Leroy et al. (2008) derived for the same galaxies. Table 1 summarizes the various fit parameters.

4. VELOCITY DISPERSION OR BULK MOTIONS

Even though we have established that the super profiles are best described by two Gaussian components, interpretation of this is complicated by the possible presence of streaming or radial motions and asymmetrical input profiles, as well as the limited sensitivity and resolution of the observations. All of this could potentially affect the shapes of the super profiles. The brief analysis presented in the previous section did not take these effects into account. Here we investigate these effects, and attempt to identify a sample of galaxies where the super profiles trace the intrinsic velocity dispersions of the ISM. In Appendix B we also present a number of tests dealing with the accuracy of the shuffling method itself.

4.1. Modeling the Effects of Resolution and Inclination

The gradient in rotation velocity across the finite beam of a telescope can broaden velocity profiles. Although the THINGS galaxies have been observed at relatively high resolution, this could still affect the shapes of the profiles, especially for highly inclined galaxies.

To quantify these effects, we construct model data cubes of IC 2574 and NGC 2403 using the GIPSY task GALMOD. IC 2574 is a dwarf galaxy with a solid body rotation curve, a distance of ~4 Mpc and an inclination of 53°. NGC 2403 is a well-resolved, rotation-dominated galaxy typical of spirals found in the THINGS sample.

For the NGC 2403 models we use the observed position angle and inclination (63°) as given in de Blok et al. (2008). We adopt
a vertical Gaussian scale height of 100 pc, a single component velocity dispersion of 8 km s$^{-1}$, a constant H$\text{I}$ surface density, and a constant rotation curve of 130 km s$^{-1}$ (the maximum observed rotation velocity of NGC 2403). We adopt a channel spacing of 5.2 km s$^{-1}$ as in the THINGS observations. We also create an almost identical model, but with an inclination of 80$^\circ$ (note that the highest inclination in our sample is 76$^\circ$). We smooth these model data cubes to various resolutions and create the corresponding super profiles. We fit the artificial super profiles both with a single and a double Gaussian to see how the dispersion changes with resolution and to check whether resolution and inclination can create broad and narrow components from a single input component. We have also tested a case where the input rotation curve rises linearly up to 130 km s$^{-1}$ at 1 kpc and flattens. The results from the constant and the linearly rising plus flat rotation curve models are identical.

For the IC 2574 models, we use the average position angle derived by de Blok et al. (2008), but assume an inclination of 63$^\circ$ and 80$^\circ$ to facilitate a direct comparison with the NGC 2403 models. Here we also use a single component velocity dispersion of 8 km s$^{-1}$, and a constant H$\text{I}$ surface density but an input rotation curve that rises linearly to 80 km s$^{-1}$ at the edge of the H$\text{I}$ disk. We use a channel spacing of 2.6 km s$^{-1}$ as used by THINGS for IC 2574. We adopt a vertical Gaussian scale height of 0.1 kpc. We fit the model super profiles of the IC 2574 with both single and double Gaussians, but the results of the double Gaussian decomposition are not meaningful as the super profiles are almost perfectly Gaussian. So, for the IC 2574 models, we only present the single Gaussian fitting results. We have also tested the case where the scale height is 0.5 kpc but the results are similar to the 0.1 kpc models.

Figure 4 and Table 2 summarize the model super profile parameters as a function of the resolution. It is clear that profiles become broader with decreasing resolution, and more so for a higher inclination. For example, at 11$''$ (the average resolution of THINGS), the difference between the velocity dispersion measured from the 80$^\circ$ and the 63$^\circ$ inclination model data cubes of NGC 2403 is $\sim$9%. At a resolution of 60$''$, the difference is $\sim$29%. From Figure 4, it is apparent that we do not recover the input 8 km s$^{-1}$ dispersion even at very high resolution. This is a result of the finite channel spacing of the NGC 2403 data cubes used (5.2 km s$^{-1}$) in combination with the high inclination. However, for the IC 2574 models, the velocity dispersions approach the input 8 km s$^{-1}$ value, and this is due to the smaller channel spacing used (2.6 km s$^{-1}$).

Figure 5 shows a selection of the modeled super profiles of NGC 2403. It is clear that resolution effects can introduce a spurious broad component. We use the ratio between the areas of the narrow and broad components $A_n/A_b$ (i.e., the flux or mass ratio) to gauge whether any of the models resemble the data. Figure 6 shows the $A_n/A_b$ ratio as a function of resolution. This ratio decreases with resolution, showing the increasing importance of the spurious broad component. The extremely high ratios at high resolution should not be overinterpreted. These are simply due to the fitting routine being forced to fit an almost perfectly Gaussian profile with two components. At the lowest resolution in the models, the broad component created by the low resolution accounts for $\sim$13% of the total flux. In the THINGS data, the broad component accounts for up to $\sim$70% of the total flux. This discrepancy also indicates that resolution effects are not solely responsible for the observed broad components. Comparison of the models and data shows that at 11$''$ (the typical THINGS resolution), the resulting super profile is well fitted by a single Gaussian function. It also shows that the shape of the super profile only starts to

---

**Figure 3.** Histograms of velocity dispersions derived from both one- and two-component Gaussian fits. The dotted-line histogram represents the velocity dispersions derived from the single Gaussian fit. The solid-line and hatched histograms represent the velocity dispersions of the double Gaussian narrow and broad components, respectively.

**Figure 4.** Super profile parameters derived from the model data cubes of IC 2574 and NGC 2403 as a function of the resolution. Solid and open symbols represent the models of IC 2574 and NGC 2403, respectively. The circle symbols represent the 63$^\circ$ models, whereas the star symbols represent the 80$^\circ$ inclination models. We only present the single Gaussian fitting results of the IC 2574 models as these profiles do not show a double Gaussian function signature. Left panel: single Gaussian velocity dispersion. Middle panel: narrow component velocity dispersion. Right panel: broad component velocity dispersion.
significantly deviate from a single Gaussian at a resolution about six times worse than the THINGS resolution. In summary, models with single Gaussian input profiles are well recovered by the THINGS resolution.

The previous test investigated whether double components can be spuriously created using single component input models. We now investigate whether input double components can be recovered from limited resolution models. We use the 63° inclination model of NGC 2403 described before. Recall that this model assumes a filled HI disk with a Gaussian velocity dispersion of 8 km s\(^{-1}\). We will here refer to this as the broad component model. We also construct a second set of cubes, assuming a 4 km s\(^{-1}\) dispersion and disks that are only partially filled (we assume 20%, 40%, 60%, and 80% area filling factors). We refer to these as the narrow component models. We add each of the narrow component models to the broad component model, smooth the resulting cubes to different resolutions and then derive the corresponding super profiles. The narrow component models are scaled to give input \(A_n/A_b\) ratios equal to unity in the regions where both narrow and broad components are present. Figure 7 shows the measured narrow and the broad component velocity dispersions derived from the smoothed models, as a function of resolution. At high resolution, the super profile shapes are sensitive to the area filling factor of the narrow components.

### Table 2

| Resolution (\(^{\circ}\)) | NGC 2403 Models | IC 2574 Models |
|--------------------------|-----------------|----------------|
| Velocity Dispersion (\(\sigma\)) (km s\(^{-1}\)) | Velocity Dispersion (\(\sigma\)) (km s\(^{-1}\)) | Flux Ratio \(A_n/A_b\) | Velocity Dispersion (\(\sigma\)) (km s\(^{-1}\)) |
| (pc) | (pc) | |

**Inclination: 63°**

| Resolution (\(^{\circ}\)) | Velocity Dispersion \(\sigma_{1G}\) (km s\(^{-1}\)) | Velocity Dispersion \(\sigma_{n}\) (km s\(^{-1}\)) | Velocity Dispersion \(\sigma_{b}\) (km s\(^{-1}\)) | Flux Ratio \(A_n/A_b\) | Velocity Dispersion \(\sigma_{1G}\) (km s\(^{-1}\)) |
|--------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 4 | 62 | 8.8 | 8.5 | 15.5 | 83.3 | 78 | 8.1 |
| 8 | 124 | 8.8 | 8.6 | 15.4 | 60.6 | 155 | 8.1 |
| 11 | 171 | 8.6 | 8.6 | 15.4 | 56.6 | 213 | 8.1 |
| 20 | 310 | 8.9 | 8.8 | 15.6 | 23.4 | 388 | 8.2 |
| 30 | 465 | 9.3 | 9.0 | 16.1 | 12.4 | 582 | 8.3 |
| 40 | 621 | 9.8 | 9.3 | 16.8 | 7.9 | 776 | 8.4 |
| 50 | 776 | 10.1 | 9.6 | 17.5 | 5.6 | 970 | 8.6 |
| 60 | 931 | 10.6 | 9.8 | 18.1 | 4.2 | 1164 | 8.8 |

| Resolution (\(^{\circ}\)) | Velocity Dispersion \(\sigma_{1G}\) (km s\(^{-1}\)) | Velocity Dispersion \(\sigma_{n}\) (km s\(^{-1}\)) | Velocity Dispersion \(\sigma_{b}\) (km s\(^{-1}\)) | Flux Ratio \(A_n/A_b\) | Velocity Dispersion \(\sigma_{1G}\) (km s\(^{-1}\)) |
|--------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 4 | 62 | 9.4 | 9.0 | 16.1 | 9.0 | 78 | 8.1 |
| 8 | 124 | 9.5 | 9.1 | 16.4 | 7.7 | 155 | 8.1 |
| 11 | 171 | 9.7 | 9.2 | 16.6 | 6.6 | 213 | 8.1 |
| 20 | 310 | 10.4 | 9.6 | 17.7 | 4.0 | 388 | 8.2 |
| 30 | 465 | 11.4 | 10.0 | 19.0 | 2.6 | 582 | 8.3 |
| 40 | 621 | 12.5 | 10.6 | 20.5 | 1.8 | 776 | 8.5 |
| 50 | 776 | 13.6 | 11.2 | 21.9 | 1.4 | 970 | 8.7 |
| 60 | 931 | 14.9 | 11.8 | 23.3 | 1.2 | 1164 | 9.0 |

**Notes.** \(\sigma_{1G}\): velocity dispersion derived from one-component Gaussian fit. \(\sigma_{n}\): velocity dispersion of the narrow component. \(\sigma_{b}\): velocity dispersion of the broad component. \(A_n/A_b\): ratio of the fluxes or masses associated with the narrow and broad components. Here, only the single Gaussian results of the IC 2574 models are shown (see Section 4.1).
component. As we increase the number of narrow profiles in the disk, the super profiles’ narrow and broad component velocity dispersions approach the input dispersions of the narrow and broad component disks, respectively. At low resolutions, the super profile parameters become insensitive to the narrow component filling factor. The models thus show that at the THINGS resolution we are able to recover the presence of narrow and broad components from the models.

4.2. Effect of High-intensity Profiles

Another possible explanation for the non-Gaussianity could be that the shapes of the super profiles are dominated by a few lines of sight with high intensities and narrow dispersions. This implies some correlation between peak brightness of the input profiles and velocity dispersion. To test this, we create super profiles using the 50% brightest and 50% faintest (in terms of peak brightness) profiles in each galaxy.

We compare the parameters of the faint and the bright super profiles of each galaxy in Figure 8. Most velocity dispersion points scatter around the line of equality. However, four high-dispersion galaxies systematically deviate. These are NGC 2841, NGC 3521, NGC 3627, and NGC 925 (in order from highest to lowest difference). This may indicate some kind of the bulk motion of the gas caused by, e.g., interaction or tidal effects in these galaxies. In terms of area, the faint super profiles show $A_n/A_b$ ratios that tend to be smaller than those of the bright super profiles. The mean difference between the bright and faint $A_n/A_b$ ratios is $\sim 36\%$. As most of the faint profiles are found in the outer disks of the galaxies, this seems to indicate that the $A_n/A_b$ ratio in the outer H I disks is smaller than in the inner disks. This result will be discussed further in a future paper. On the whole though, it is clear that the dispersions of the super profiles of the bright and faint parts are not significantly different.

As an additional test, we also create super profiles by normalizing individual profiles by their peak intensity before summing them. This way, any possible effects of a small number of bright input profiles are removed. Figure 8 shows that, in terms of velocity dispersion, the normalized super profiles are very similar to the original ones. The correlation coefficient is $R^2 \approx 0.99$ for both the narrow and the broad components. In terms of area, the $A_n/A_b$ ratios derived from the normalized super profiles tend to be smaller than those from the original super profiles. The difference between the mean values is, however, only $\sim 1.3\%$. In summary, the shapes of the super profiles are not dominated by high-intensity, narrow-dispersion input profiles.

4.3. Effects of Radial Motions

Having ruled out resolution effects and high-intensity input profiles as the cause for the non-Gaussianity of the observed super profiles, we now investigate the effects of large-scale radial motions. A net radial motion in one direction will create an asymmetric tail in the velocity profiles. More specifically, for a given radial motion, the location of the tail with respect to the profile depends on the spatial position of the profile: a radial motion causing a tail on the high-velocity side of a profile that is located on one side of the major axis of the galaxy, will create a tail on the low-velocity side of the profile when it is located on the opposite side of the major axis. See Warner et al. (1973) and van der Kruit & Allen (1978) for a detailed discussion of these kind of patterns typically observed in velocity fields and profiles.

Figure 9 shows examples of super profiles extracted from the opposite sides of the major axes of each galaxy overlapped on top of the overall super profiles of these galaxies. We use a consistent definition of sides corresponding to their average position angle (PA). One side of the galaxy is chosen as the one with an average position angle of $90^\circ$ with respect to the receding semimajor axis (denoted as the PA$+90^\circ$ side); the other side has an average PA of $270^\circ$ with respect to the receding semimajor axis (the PA$+270^\circ$ side). We show in Figure 10 a histogram of the difference between the velocity dispersion derived from the opposite sides with respect to the major axes of each galaxy. For about 90% of the studied galaxies, the difference is less than $1.5 \text{ km s}^{-1}$. There are four galaxies with higher velocity dispersion differences. These are NGC 3031, NGC 3077 (both interacting), NGC 4826 (counter-rotating H I disk), and NGC 7331. The latter has the highest inclination ($76^\circ$) in the sample and the difference in velocity dispersion for this galaxy may be a projection effect. The velocity dispersion comparison presented above only works if the distortion due to radial motions is asymmetric. Therefore, we also measure the
skewness of each of the super profiles on the opposite sides of the major axis. We fit the super profiles with a Gauss–Hermite $h_3$ function. The skewness coefficient is defined as $4\sqrt{3}h_3$ and the results are shown in Figure 11. The apparent trend visible in the figure is mostly caused by highly inclined, interacting or disturbed, as well as starburst galaxies. It is possible that these galaxies suffer from radial motions, and thus they will not be part of our subsequent analysis, as described in detail in Section 5. The remaining outliers have very symmetrical profiles with only some faint extended wings showing up at levels well below 20% of the peak intensity. While these affect the skewness, they contain negligible flux, and have no impact on the dispersions or flux ratios. Most likely these apparent wings are caused by residual baseline effects.

In the following, we develop simple models to understand how radial motions affect the shapes of the super profiles. We do this by creating models which have different ratios of rotation and radial motions. We again use the 63° inclination NGC 2403 model discussed in Section 4.1. We create four new model data cubes by adding outward radial motions of 5, 10, 15, and 20 km s$^{-1}$, respectively, to the original model (thus shifting the input profiles in velocity). We again assume a single-component Gaussian velocity dispersion of 8 km s$^{-1}$, a constant rotation curve and a constant surface density $H_\text{I}$ disk for all models.

For each of the 5, 10, 15, and 20 km s$^{-1}$ model data cubes, we randomly choose 20%, 40%, 60%, 80% of the profiles and add these to the original NGC 2403 model (which contains no radial motions). We thus create 16 data cubes with different fractions of the disk area containing asymmetric profiles with different amounts of radial motion. We smooth these model data cubes to the THINGS 11″ resolution. The velocity fields derived from the combined, smoothed cubes are then used to shuffle profiles and derive the corresponding super profiles, which we then fit with single Gaussian functions.

Figure 12 shows the resulting velocity dispersions (as measured with a single Gaussian) as a function of the input expansion velocities. As expected, the velocity dispersions increase with increasing expansion velocities. The increase is steeper as we increase the fraction of gas with non-zero expansion velocities. We see that a radial motion of 5 km s$^{-1}$ causes only minimal broadening, independent of the area coverage. The most extreme model with 20 km s$^{-1}$ radial motions and 80% area coverage has a super profile that is broadened by $\sim$23%. Large-scale non-circular motions of this magnitude are rare in disk galaxies, and mostly only found in the central parts of barred galaxies. We can compare this with the work by Tacchernach et al. (2008) who used harmonic decompositions of the velocity fields of the THINGS galaxies to quantify the non-circular motions there. They found a median amplitude of all non-circular motions of $A_r = 6.7 \pm 5.9$ km s$^{-1}$. Of their 18 analyzed galaxies, 17 have $A_r \lesssim 10$ km s$^{-1}$ and only 1 has $A_r > 20$ km s$^{-1}$.
Ianjamasimanana et al.

Figure 9. Super profiles extracted from the opposite sides of the major axes of each galaxy. The super profiles from the two halves of each galaxy are represented as dashed and dotted lines. The overall super profiles are represented by the solid lines. At the bottom of each panel is the difference between the super profiles from the two sides and the total super profiles. Note that the super profiles are normalized to their peak values.

Figure 10. Histogram of the difference between the velocity dispersion derived from the opposite sides of the major axis, where PA+90° side refers to the position corresponding to a position angle (PA) of 90° with respect to the PA of the receding major axis and PA+270° side is the position corresponding to a PA offset of 270° from the receding major axis.

Finally, we repeat the procedure described above, but rather than assuming the same constant HI surface density disk for all models, we assume that the profiles with non-circular motion have an amplitude that is 30% of that of the profiles without non-circular motions. This choice will allow the non-circular motion profiles to mimic low-level broad wings in the super profiles. In this case we fit all resulting super profiles with double Gaussians.

We show in Figure 12 and Table 3 the fitted $A_n/A_b$ ratios as a function of input expansion velocities. The $A_n/A_b$ ratio decreases with increasing expansion velocities. If we assume that the non-circular motions in the THINGS galaxies are of the order of 10 km s$^{-1}$ or less (Trachternach et al. 2008), then these motions are only able to introduce spurious broad wings, containing at most 7% of the total flux, i.e., much smaller than observed. We therefore conclude that radial motions cannot be a major cause of the observed non-Gaussianity of the observed super profiles.

4.4. Thick Disks and Lagging Halos

Last, we investigate the possibility that our sample galaxies have a thin disk embedded in a "lagging" thick HI disk with a lower rotation velocity, as was found for NGC 891 (Swaters et al.)
Ianjamasimanana et al.

Figure 11. Skewness (defined as $4\sqrt{3}h$, where $h$ is the third coefficient of the Gauss–Hermite function) of the super profiles derived from the opposite sides of the major axis. PA+90° side: position corresponding to a position angle (PA) of 90° with respect to the PA of the receding major axis. PA+270° side: position corresponding to a PA offset of 270° from the receding major axis. The three outlying galaxies are, from left to right, NGC 1569, DDO 53, and NGC 3031. The plus and minus signs represent the signs of the skewness parameters. Symbols follow Figure 8.

Table 3

| $V_{rad}$ (km s$^{-1}$) | 20% | 40% | 60% | 80% |
|------------------------|-----|-----|-----|-----|
| 5                      | 109.8 | 102.1 | 99.3 | 98.2 |
| 10                     | 33.5  | 18.1  | 13.8 | 12.9 |
| 15                     | 7.9   | 3.3   | 2.0  | 1.4  |
| 20                     | 6.0   | 2.9   | 1.9  | 1.3  |

Notes. $V_{rad}$: input radial velocity used to construct the model data cubes. Percentage indicates the area coverage of gas with non-circular motions. $A_n/A_b$: flux ratio of the narrow and broad components.

5. DEFINING A CLEAN SAMPLE

In this section we define a subsample of galaxies that do not suffer from the effects of interaction or major bulk motions. Figure 16 shows the measured super profile velocity dispersions plotted against the inclinations of the THINGS galaxies. We see a narrow relation with galaxies with higher inclinations having broader profiles (as also shown for these galaxies in Leroy et al. 2008 and Tamburro et al. 2009). Many of the galaxies that do not follow the relation (NGC 1569, NGC 5194, NGC 2841, NGC 3627, NGC 3521, and NGC 7331) are known to be affected by strong sources of turbulence or bulk motion (such as interaction with other galaxies or starbursts). These galaxies are marked with different symbols in Figure 16. One thing to note
is the remarkable constancy of the $\sigma_n/\sigma_b$ ratio. The weighted average value of this ratio is $0.37 \pm 0.04$.

Based on inspection of Figures 10, 11, 14, 15, and 16, we exclude from the rest of our analysis galaxies, that do not follow the observed trend between inclination and velocity dispersion in Figure 16. We also exclude galaxies where the difference in velocity dispersion measured for the approaching and receding sides, or PA+90° and PA+270° sides is more than 1.5 km s$^{-1}$. Interacting galaxies will also not be considered. Based on these criteria, we are left with 22 galaxies which we identify as our clean sample. Their super profiles are expected to be less dominated by the various effects presented earlier. The clean sample is listed in Table 4.

6. EFFECTS OF ASYMMETRIC PROFILES

Having identified a sample likely not to be suffering from large-scale disturbances, we now take a detailed look at the shapes of the observed input profiles in this sample.

If the individual profiles used in the stacking are themselves asymmetric, this can also lead to the observed super profiles, as the sum of a negatively skewed and a positively skewed profile will be one with broader wings and a narrower peak than a Gaussian profile.

Here we check whether the broad components in the super profiles are intrinsic or artifacts due to asymmetric input profiles. We do this by selecting only symmetrical profiles, creating super profiles from those symmetrical input profiles and checking whether broad and narrow components are still present.

To select symmetrical profiles, we create masks based on the difference between the third-order Hermite (HER3) velocity field values and intensity-weighted mean first moment values (IWM). The former trace the velocity of the peak of the profile, the latter the intensity-weighted mean value. For asymmetric profiles there will therefore be a difference between the HER3 and the IWM values. For symmetrical profiles the difference between HER3 and IWM is small, and this can be used to efficiently select symmetrical input profiles. If super profiles created from only the symmetric profiles still show broad components, then these are likely to be intrinsic. We thus define three masks based on the difference in velocity between HER3 and IWM, $\Delta_{H-I}$, as follows:

1. Symmetrical profiles (SP): positions where $|\Delta_{H-I}| \leq 5$ km s$^{-1}$.
Figure 14. Top left panel: comparison of the widths of the super profiles from the approaching and receding sides of the galaxies. The largest of each of these velocity dispersions is represented by \( \sigma_{\text{large}} \) and the smallest one by \( \sigma_{\text{small}} \). The dashed line represents the line of equality. Top right panel: histogram of the difference between the velocity dispersion derived from the approaching and receding halves of the galaxies. Bottom left panel: narrow component velocity dispersion as a function of the amplitudes of non-circular motions, \( A \), derived by Trachternach et al. (2008). Bottom right panel: broad component velocity dispersion as a function of \( A \). Note that only the 18 galaxies that are part of Trachternach et al. (2008) sample are shown here. Symbols are as in Figure 8.

Figure 15. Skewness (defined as \( 4\sqrt{3}h_3 \), where \( h_3 \) is the third Gauss–Hermite polynomial coefficient) of the super profiles derived from the receding and approaching side of each galaxy. The two outlying galaxies in the lower left quadrant are DDO 53 (top) and NGC 1569 (bottom). The plus and minus signs represent the signs of the skewness parameters. Symbols are as in Figure 8.

2. Left-handed asymmetrical profiles (LHAP): positions where \( \Delta_{H-I} < -5 \text{ km s}^{-1} \).

3. Right-handed asymmetrical profiles (RHAP): positions where \( \Delta_{H-I} > 5 \text{ km s}^{-1} \). SP therefore selects symmetrical profiles; the other two masks LHAP and RHAP select only asymmetrical profiles. We show for all galaxies the location of the symmetrical and asymmetrical profiles in Figure 17. We create super profiles using the three masks and fit them with both single and double Gaussian components. Examples of the super profiles of NGC 3521 created using the three kinds of masks, overplotted on top of its total super profiles are shown in Figure 18. It is clear that the masks produce the expected results.

We compare the dispersions from the original super profiles (i.e., those derived from using the entire H\(_2\) disk; see Section 2) with those derived using the SP mask in Figure 19 (top panel). The dispersions of the narrow component from the original super profiles are similar to those from the SP super profiles. However, the dispersions of the broad component from the original super profiles tend to be larger than those from the SP super profiles. This is what we would expect if the original profiles were broadened by asymmetry in the input profiles. We can remove this effect by only selecting symmetric profiles.

To test whether the \( |\Delta_{H-I}| \leq 5 \text{ km s}^{-1} \) criterion produces symmetrical profiles, we create new masks with \( |\Delta_{H-I}| \leq 2 \text{ km s}^{-1} \). This selects only very symmetrical profiles but at the cost of a reduced number of input profiles. Using the more strict condition results in a loss of about 60% of the profiles. Figure 19 (bottom panel) compares the \( |\Delta_{H-I}| \leq 5 \text{ km s}^{-1} \) SP mask velocity dispersions with the \( |\Delta_{H-I}| \leq 2 \text{ km s}^{-1} \) equivalent. It is clear that the dispersions of the broad components of the latter
The broad component velocity dispersions derived from the wingless side of the LHAP and RHAP super profiles tend to be smaller than those derived from the SP super profiles. However, there is no major difference between the narrow component velocity dispersions derived from the wingless side of LHAP and RHAP super profiles and those from SP super profiles (see Figure 20). The measurements of the narrow component velocity dispersion are thus more robust than those of the broad component.

7. SUPER PROFILES AND GLOBAL PROPERTIES OF GALAXIES

Figure 21 shows the distribution of the narrow and broad component velocity dispersions derived using the SP profiles in the clean sample galaxies. The narrow component has a much tighter distribution than the broad component, with mean values of 6.5 ± 1.5 km s⁻¹ and 16.8 ± 4.3 km s⁻¹, respectively. We adopt the definition of spirals and dwarfs given in Leroy et al. (2008). They define dwarfs as galaxies with rotation velocities \( V_{\text{rot}} \lesssim 125 \text{ km s}^{-1} \), stellar masses \( M_\ast \lesssim 10^{10} M_\odot \), and absolute \( B \) magnitude \( M_B \gtrsim -20 \text{ mag} \). Galaxies more massive than this are defined to be spirals. Dividing our clean sample into dwarfs and spirals, we find their velocity dispersions are identical within the uncertainties. For the dwarfs, we find values of 6.7 ± 1.4 km s⁻¹ and 18.7 ± 4.3 km s⁻¹, respectively.

The \( A_n/A_b \) ratios differ though. For the spirals we find a mean of 0.63 ± 0.24; for the dwarfs a value of 0.49 ± 0.20, indicating a larger importance of the narrow component in spirals. We summarize the fitted parameters of the clean sample super profiles in Table 4.

In the following, we explore possible correlation between global galaxy properties and super profile shapes. If the narrow and broad components identified here are related to the CNM and the WNM phases of the ISM, we expect some correlation between these two components and tracers of star formation. For example, Schaye (2004) suggests that the transition from the warm to the cold phase of the ISM triggers disk instabilities which eventually leads to star formation. We use
The metal abundance is taken from Moustakas et al. (2010). Thus, \( H_\alpha \) emission is a tracer of recent star formation over a timescale of \( \lesssim R_0 \), and the correlation coefficient is \( \sim -0.56 \). In principle this could reflect more efficient cooling, but as turbulence must also play a large role in determining the value of the velocity dispersion, it is more likely that this trend is a reflection of a metallicity–SFRH relation. High-metallicity galaxies tend to have higher SFRs, and for these high-SFR (high-metallicity) galaxies, the broad component velocity dispersion is likely to be larger which will give a lower \( \sigma_n/\sigma_b \) ratio.

The \( \sigma_n/\sigma_b \) ratio is higher for bluer (FUV–NUV) colors; the correlation coefficient is \( R \sim -0.61 \). As low-metallicity galaxies are on average also bluer in FUV–NUV, this relation probably reveals similar information as the metallicity versus \( \sigma_n/\sigma_b \) relation. There is only a weak correlation between dispersion ratio and \( H_\alpha \) luminosities \( (R \sim -0.20) \). This weak correlation may be due to the fact that the super profile parameters and the \( H_\alpha \) luminosities have not been derived from the same regions within the galaxies. This will be an interesting topic for follow-up studies.

In terms of the \( A_\alpha/A_b \) ratio, which should measure the amount of cold gas (CNM) relative to warm gas (WNM), we find that the fraction of the narrow components relative to the broad components tends to be high for high-metallicity galaxies \((R \sim 0.53)\). We find similar relations in terms of FUV–NUV colors and \( H_\alpha \) luminosities with correlation coefficients \( R \sim 0.53 \) and \( R \sim 0.47 \), respectively. These correlations are all preliminary indications that the presence of cold gas is associated with star formation.

### Table 4

**Fitted Parameters of the Clean Sample**

| Galaxy   | \( \sigma_n \) (km s\(^{-1}\)) | \( \sigma_b \) (km s\(^{-1}\)) | \( \sigma_\alpha \) (km s\(^{-1}\)) | \( A_\alpha/\sigma_b \) | \( \chi^2_{G}/\chi^2_{BG} \) |
|----------|-------------------------------|-------------------------------|-------------------------------|----------------------|---------------------|
| DDO 53   | 9.7 ± 0.1                     | 6.0 ± 0.1                     | 13.3 ± 0.2                    | 0.41 ± 0.03          | <0.01               |
| DDO 154  | 9.6 ± 0.1                     | 6.3 ± 0.1                     | 12.9 ± 0.2                    | 0.50 ± 0.04          | <0.01               |
| Ho I     | 8.9 ± 0.1                     | 5.4 ± 0.1                     | 12.2 ± 0.2                    | 0.39 ± 0.02          | 0.02                |
| Ho II    | 8.9 ± 0.1                     | 5.0 ± 0.1                     | 11.7 ± 0.2                    | 0.33 ± 0.02          | <0.01               |
| IC 2574  | 9.8 ± 0.2                     | 5.7 ± 0.2                     | 13.7 ± 0.3                    | 0.42 ± 0.03          | 0.10                |
| M81 dwA  | 8.2 ± 0.1                     | 3.4 ± 0.1                     | 10.1 ± 0.2                    | 0.14 ± 0.01          | 0.01                |
| NGC 628  | 8.8 ± 0.2                     | 4.5 ± 0.1                     | 11.6 ± 0.1                    | 0.27 ± 0.02          | 0.03                |
| NGC 925  | 12.6 ± 0.2                    | 8.6 ± 0.2                     | 20.4 ± 0.8                    | 0.74 ± 0.06          | 0.02                |
| NGC 2366 | 12.2 ± 0.2                    | 8.2 ± 0.1                     | 17.7 ± 0.3                    | 0.58 ± 0.03          | <0.01               |
| NGC 2403 | 10.7 ± 0.2                    | 6.6 ± 0.1                     | 16.8 ± 0.2                    | 0.60 ± 0.06          | 0.02                |
| NGC 2903 | 12.6 ± 0.3                    | 8.2 ± 0.2                     | 24.3 ± 0.7                    | 0.78 ± 0.04          | <0.01               |
| NGC 2976 | 11.9 ± 0.2                    | 8.5 ± 0.1                     | 19.9 ± 0.4                    | 0.86 ± 0.05          | <0.01               |
| NGC 3184 | 10.4 ± 0.3                    | 5.9 ± 0.1                     | 17.9 ± 0.2                    | 0.44 ± 0.01          | <0.01               |
| NGC 3198 | 13.1 ± 0.2                    | 8.5 ± 0.1                     | 20.0 ± 0.3                    | 0.64 ± 0.03          | 0.07                |
| NGC 3351 | 9.9 ± 0.2                     | 7.0 ± 0.1                     | 21.5 ± 0.7                    | 0.95 ± 0.06          | 0.02                |
| NGC 3621 | 11.3 ± 0.2                    | 7.5 ± 0.2                     | 18.7 ± 0.7                    | 0.71 ± 0.06          | 0.16                |
| NGC 4214 | 8.3 ± 0.1                     | 4.2 ± 0.0                     | 10.9 ± 0.1                    | 0.29 ± 0.01          | 0.25                |
| NGC 4736 | 10.0 ± 0.2                    | 7.1 ± 0.1                     | 20.3 ± 0.7                    | 0.99 ± 0.07          | 0.03                |
| NGC 5055 | 13.3 ± 0.3                    | 7.9 ± 0.3                     | 20.8 ± 0.7                    | 0.55 ± 0.05          | 0.17                |
| NGC 5236 | 10.6 ± 0.2                    | 5.5 ± 0.1                     | 15.1 ± 0.1                    | 0.36 ± 0.03          | 0.03                |
| NGC 6946 | 10.1 ± 0.2                    | 6.4 ± 0.3                     | 17.5 ± 0.1                    | 0.65 ± 0.09          | 0.02                |
| NGC 7793 | 10.4 ± 0.2                    | 6.7 ± 0.1                     | 17.0 ± 0.2                    | 0.63 ± 0.02          | 0.21                |

**Notes.** Column 1: name of galaxy; Column 2: velocity dispersions derived from the single Gaussian fit; Column 3: velocity dispersions of the narrow component; Column 4: velocity dispersions of the broad component; Column 5: \( A_\alpha/\sigma_b \) ratio. Column 6: ratio of the \( \chi^2 \) values from the single and double Gaussian fitting. Spiral galaxies (adopting the definition of Leroy et al. 2008) are marked in bold face; the rest are dwarf galaxies (using the same definition).
Figure 17. Location of symmetric and asymmetric profiles for the THINGS galaxies. Blue pixels represent symmetric profiles (SP). Green and red pixels represent left-handed asymmetric profiles (LHAP) and right-handed asymmetric profiles (RHAP), respectively. Ellipses represent the optical radius $r_{25}$. The small gray circles indicate the approaching sides.

8. DOES THE NARROW COMPONENT TRACE MOLECULAR GAS?

Star formation and molecular hydrogen are intimately connected. Unfortunately, molecular hydrogen is not directly observable and CO emission is usually used as a tracer. Usually a constant CO-to-H$_2$ conversion factor is assumed to derive the amount of H$_2$ present in a galaxy. However, the strength of the CO emission line depends on the metal abundance of galaxies and CO is difficult to detect in low-metallicity environments. CO may also not trace all the H$_2$ content of galaxies because unlike H$_2$, CO cannot self-shield (e.g., Krumholz et al. 2011)
and therefore, in regions with low metal and dust abundances where both CO and H$_2$ are present, UV photons from young stars will easily dissociate CO while leaving H$_2$ intact.

As H$_2$ forms as the cold phase of the neutral medium cools, we test here whether the narrow component identified in the super profiles can be used to infer the amount of H$_2$ in galaxies. This is motivated by early observations made by Young & Lo (1996, 1997) and de Blok & Walter (2006). They found that the narrow component tends to be located near regions of star formation. The narrow component could thus be associated with the star formation in a manner similar to that of H$_2$. Also, from a theoretical point of view, H i must pass through a cold phase before turning molecular.

We consider the 11 galaxies in the clean sample that have also been detected in CO in the HERA CO-Line Extragalactic Survey (HERACLES; Leroy et al. 2009). HERACLES provides maps of CO $J = 2 \rightarrow 1$ emission in 18 THINGS galaxies (though the full HERACLES sample is larger) at $13^{\prime\prime}$
angular resolution and 2.6 km s$^{-1}$ velocity resolution using observations with the IRAM 30 m telescope. The CO-detected galaxies have metallicities ranging from 8.25 to 9.12 in units of [12 + log(O/H)].

If the narrow component is indeed associated with molecular gas then we expect correlations between the $A_n/A_b$ ratio and the $H_2$ to $H\text{\textsc{i}}$ mass ratio. When masses are measured in identical regions, this translates in correlations between the respective surface densities as well. We also test for correlations with the narrow and broad components velocity dispersion ratios.

We derive super profiles and average $H\text{\textsc{i}}$ and $H_2$ mass surface densities in the overlap regions in the sample galaxies where both CO and $H\text{\textsc{i}}$ are detected. Restricting ourselves to the overlap regions means we are testing only the regime where both gas phases are present. We do not investigate the regime where all gas has turned molecular and no $H\text{\textsc{i}}$ is present anymore.

Figure 17. (Continued)
Figure 18. Examples of super profiles of NGC 3521 using LHAP (left panel), SP (middle panel), and RHAP (right panel) represented by the dashed lines, overplotted on top of the total super profile (shown as solid lines).

Figure 19. Top panels: comparison of the velocity dispersions of the original super profiles to those derived from SP profiles using $|\Delta_H - I| \leq 5 \text{ km s}^{-1}$. Bottom panel: comparison of the velocity dispersions derived from SP profiles using $|\Delta_H - I| \leq 5 \text{ km s}^{-1}$ with those derived from SP profiles using $|\Delta_H - I| \leq 2 \text{ km s}^{-1}$. Dashed lines are lines of equality. Symbols are as in Figure 8.
Comparison of the velocity dispersions derived from the SP super profiles to those derived from the wingless sides of the LHAP (top panel) and RHAP (bottom panel) super profiles using $|\Delta\xi| \leq 2$ km s^{-1}. The dashed lines are lines of equality. Symbols are as in Figure 8.

Figure 20. Comparison of the velocity dispersions derived from the SP super profiles to those derived from the wingless sides of the LHAP (top panel) and RHAP (bottom panel) super profiles using $|\Delta\xi| \leq 2$ km s^{-1}. The dashed lines are lines of equality. Symbols are as in Figure 8.

Figure 21. Histograms of the velocity dispersion of the clean sample. The solid line histogram represents the narrow component. The dotted line histogram represents the broad component.
Figure 22. Top panel: velocity dispersion ratio as a function of metallicity, FUV−NUV colors, and Hα luminosities. Bottom panel: flux ratio of the narrow and broad components as a function of metallicity, FUV−NUV colors, and Hα luminosities. The triangle symbols represent interacting galaxies (those that are tidally interacting with a nearby companion or are being affected by their environment; these are NGC 3031, NGC 4449, NGC 5194, NGC 5457, and NGC 3077). The open circle symbols represent galaxies that are disturbed kinematically due to the effect of e.g., star formation (NGC 1569, NGC 3521, and NGC 3627). The star symbols indicate non-interacting galaxies that have an anomalously high velocity dispersion (NGC 7331 and NGC 2841). The diamond shaped symbols represent non-interacting and non-disturbed galaxies where the dispersions measured on the opposite sides of the galaxies differ by more than 1.5 km s−1. (NGC 4826 and M81 DwB; see Section 5 for the choice of this value). Filled circle symbols represent our clean sample galaxies.

Figure 23. Velocity dispersion (left panel) and $A_n/A_b$ ratio (right panel) as a function of $H_2$ and $H_1$ mass surface density ratio. Each galaxy. The observed upper limit on $\sigma_n/\sigma_b$ and $A_n/A_b$ seems to vary systematically with $\Sigma_{H_2}/\Sigma_{H_1}$. The respective correlation coefficients are $R = 0.47$, and $R = -0.70$. A possible interpretation of the observed trend between log($\sigma_n/\sigma_b$) and log($\Sigma_{H_2}/\Sigma_{H_1}$) is that galaxies having larger fractions of molecular gas are expected to have more abundant star formation, which drives turbulence to the ISM and results in higher $\sigma_b$ values and thus lowers the log($\sigma_n/\sigma_b$) ratio. The trend in $A_n/A_b$ ratios might reflect the fact that atomic gas passes through the CNM phase before turning into molecular. Thus, galaxies having larger $A_n/A_b$ (more cold atomic gas) ratio are expected to have larger molecular gas fractions. This result serves as early indication that the narrow component may be associated with molecular gas. It will be interesting to study the spatial
distribution of these two gas components in more detail and investigate whether the locations of the narrow components correlate with those of the molecular gas.

9. SUMMARY

We have conducted in-depth analyses of the shapes of the H$\text{I}$ velocity profiles of galaxies from the THINGS sample. To minimize the effect of noise on the velocity profiles, we have constructed high-S/N profiles by aligning individual profiles in velocity and stacking them. We call these super profiles. We have quantified the relevant systematic effects that may change the intrinsic shapes of the super profiles and defined a clean sample where the observed shapes of the super profiles are less affected by these effects.

We have fitted the super profiles with single, double and triple Gaussian models, as well as Lorentzian models. Based on a $\chi^2$ analysis, we found that the shapes of the super profiles are optimally described by the sum of a narrow and a broad Gaussian component. The narrow component velocity dispersions of the clean sample range from 3.4 to 8.6 km s$^{-1}$ with a mean of 6.5 ± 1.5 km s$^{-1}$. The broad component velocity dispersions range from 10.1 to 24.3 km s$^{-1}$ with a mean of 16.8 ± 4.3 km s$^{-1}$. Note that due to the limitation of the data, the derived velocity dispersions are overestimated by at most 20%. The combined effects of the finite channel spacing, the inclination (see Figure 4) and the inclination (see Figure 16) contribute about 15% while the effects of radial motions (whose magnitude is expected to be less than ~10 km s$^{-1}$; see Section 4.3) contribute about 5%.

We have investigated possible correlations between the shapes of the super profiles and global properties of galaxies. We found that the flux ratio of the narrow and broad components tends to be high for high-metallicity, high-SFR galaxies. The flux ratio also increases with increasing bluer FUV−NUV colors. We interpret these correlations as evidence that cold H$\text{I}$ gas is associated with star formation. In addition, the velocity dispersion ratio of the narrow and broad components decreases with increasing metallicity, FUV−NUV colors, and Hz luminosities.

We present tentative evidence that the narrow component is associated with molecular gas. We find that upper limits on $\sigma_n/\sigma_b$ and $A_n/A_b$ change with $\Sigma_{\text{HI}}/\Sigma_{\text{HI}}$, suggesting that the cold neutral phase and the molecular phase are related. The observed trend between the $A_n/A_b$ ratio and the $\Sigma_{\text{HI}}/\Sigma_{\text{HI}}$, reflects the fact that atomic gas passes through the CNM phase before turning into molecular. Based on this preliminary analysis, it is expected that the location of the narrow component (CNM) correlates with the location of molecular gas. Higher resolution pixel-by-pixel studies of the H$\text{I}$ line profiles should be able to confirm this.

We thank the anonymous referee for helpful and constructive comments that have contributed to this paper. R.I. acknowledges financial support from the South African Research Chairs Initiative of the Department of Science and Technology and National Research Foundation.

APPENDIX A

SUPER PROFILES: GAUSSIAN AND LORENTZIAN

In this appendix, we present the super profiles of the entire THINGS sample (see Section 2 for an explanation on how these profiles were generated). Note that we correct for the presence of a negative bowl in the super profiles of NGC 628, NGC 2403, NGC 5236, and NGC 5457 by fitting a polynomial to the baseline and subtract the polynomial from the super profiles (see Figure 24 for illustration). We summarize in Tables 5 and 6.

### Table 5

| GALAXY   | $\sigma_{b,c}$ (km s$^{-1}$) | $\sigma_n$ (km s$^{-1}$) | $\sigma_b$ (km s$^{-1}$) |
|----------|----------------|----------------|----------------|
| Before negative bowl correction |
| NGC 628  | 8.4           | 4.0            | 10.0           |
| NGC 2403 | 10.4          | 6.0            | 15.0           |
| NGC 5236 | 10.7          | 5.1            | 15.0           |
| After negative bowl correction |
| NGC 628  | 9.0           | 4.4            | 11.6           |
| NGC 2403 | 11.1          | 6.6            | 18.4           |
| NGC 5236 | 11.2          | 5.6            | 16.8           |

**Notes.** $\sigma_{1G}$: velocity dispersion derived from the single component Gaussian fit. $\sigma_n$: velocity dispersion of the narrow component. $\sigma_b$: velocity dispersion of the broad component.

### Table 6

| GALAXY   | $A_{b,c}/A_{1G,a,c}$ | $A_n/A_{b,c}$ | $A_{b,c}/A_{b,a,c}$ |
|----------|----------------------|---------------|---------------------|
| Before negative bowl correction |
| NGC 628  | 0.89                 | 0.67          | 0.93                |
| NGC 2403 | 0.91                 | 0.76          | 0.94                |
| NGC 5236 | 0.95                 | 0.81          | 0.97                |
| After negative bowl correction |

**Notes.** b.c. = Before correction (i.e., before negative bowl correction). a.c. = After correction (i.e., after correcting for the negative bowl).
Figure 25. Super profiles of the THINGS galaxies. For each galaxy, we show the results from the single (left panel) and double (middle panel) Gaussian fitting. The right panels show a fit with a Lorentzian function. The bottom panels of each set of plots show the residuals from the fits. The filled circles indicate the data. The solid black lines represent the results from the single, the sum of the double Gaussian, and the Lorentzian fitting. The dotted and the dashed lines in the middle panel represent the narrow and broad components required in the double Gaussian fitting. We plot error bars as $3\sigma$ error bars, though in most cases they are smaller than the symbols plotted.

(The complete figure set (93 images) is available in the online journal.)

the super profiles’ parameters before and after the negative bowl correction.

Following Braun (1997), we have also fitted the super profiles with a Lorentzian function. We compare the reduced $\chi^2$ values from the double and Lorentzian fitting in Table 7. Of the 34 fitted super profiles, 4 can be well fitted by either a double Gaussian or a Lorentzian function (i.e., their reduced $\chi^2$ values agree within 10%). For 25 super profiles, a double Gaussian function is clearly preferred. Finally, for five super profiles, a Lorentzian function best describe the shapes of the profiles.

Overall, a double Gaussian function seems to be an optimal description of the profiles. We do not attempt to make any physical interpretation of the Lorentzian fitting results; however, we summarize the fitted parameters in Table 7.

The super profiles of the THINGS galaxies are shown in Figure 25. For each galaxy, the left panel represents a plot of the super profile fitted with a single Gaussian component whereas the middle and right panels represent super profiles fitted with a double Gaussian and a Lorentzian functions, respectively. The filled circles indicate the data points. The solid black lines
represent the results from fitting with a single and double Gaussian, as well as Lorentzians. The dashed and the dotted lines represent the narrow and broad components required in the double Gaussian fitting. We show the residual from the three kinds of fits at the bottom panel of each figure. For the four galaxies with negative bowls mentioned earlier, the open and the filled circle symbols represent the data points before and after the correction, respectively. The dashed lines represent the polynomial fits to the negative bowls.

**APPENDIX B**

**SYSTEMATIC SHUFFLE UNCERTAINTIES**

Choosing the wrong offset velocity in the profile shuffling procedure could artificially broaden super profiles. As the SHUFFLE method as implemented in GIPSY uses velocity field values as input, the type and accuracy of the velocity field used is important as well. To get an idea of the uncertainties in velocity field values in real data, we show in Figure 26 the uncertainties in the central velocity value of the fitted third-order Hermite $h_3$ profiles of NGC 2403 plotted against the fitted amplitudes (see de Blok et al. 2008). As expected, low amplitude profiles have larger uncertainties. These uncertainties could in principle create an “artificial” broad component in the super profiles. We therefore carry out an experiment to quantify the effect of these uncertainties on the super profiles. We test a case where all profiles have random offsets with respect to their proper “shuffle” values as well as a case where the offsets depend on the amplitude of the spectra. To do this, we create artificial data cubes. The data cubes contain purely Gaussian profiles, which all have a 6 km s$^{-1}$ velocity dispersion but with different amplitudes. We use the observed peak flux distribution of NGC 2403 as input probability distribution for our models. We then randomly pick one thousand amplitudes using this distribution and generate Gaussians using these amplitudes and the 6 km s$^{-1}$ constant velocity dispersion. The position along the velocity axis of the model profiles is taken from the observed velocities of the profiles of NGC 2403. We create a data cube using the input spectra described above and derive a velocity field from it, which we refer to as the true velocity field. We then add uniform random offsets to the true velocity field and use the modified velocity field to shuffle profiles.

For the first test, we give all the input spectra uniform random offsets (between $-5$ and 5 km s$^{-1}$, $-10$ and 10 km s$^{-1}$, etc.). For the second model test, only profiles with amplitudes less than 25% of the overall peak amplitude are given uniform random offsets (for the case of NGC 2403, where the maximum profile peak value is 9.2 mJy, this value corresponds to 2.3 mJy). Larger amplitude profiles are assumed to have zero offset.

Figure 27 (left panel) shows examples of super profiles derived from the first set of model cubes. The super profiles get broader as we increase the offsets but the two components retrieved by the double Gaussian fitting are all similar in amplitude and dispersion. In other words, there are no broad and narrow components. The results of a single Gaussian fit to the simulated super profiles show that at $(-5, 5)$ km s$^{-1}$ offsets, the resulting broadening due to incorrect shuffling is about 1 km s$^{-1}$. At $(-10, 10)$ km s$^{-1}$, this increases to $\sim$3 km s$^{-1}$. At $(-15, 15)$ km s$^{-1}$ offsets, the width of the resulting super profiles is twice as large as the width of the input profiles. At $(-20, 20)$ km s$^{-1}$ offsets, the super profiles start to have double-peaked features.
Figure 27. Examples of simulated super profiles derived by giving all input spectra (left panel) and low-amplitude spectra (right panel) uniform random offsets. The dotted and the dashed lines represent the narrow and broad components required in the double Gaussian fitting. The solid black lines represent the results from the double Gaussian fitting.

Table 8

| Offsets (km s$^{-1}$) | Uniform | Amplitude Dependent |
|----------------------|---------|---------------------|
|                      | $\sigma_{1G}$ (km s$^{-1}$) | $\sigma_n$ (km s$^{-1}$) | $\sigma_b$ (km s$^{-1}$) | $\sigma_{1G}$ (km s$^{-1}$) | $\sigma_n$ (km s$^{-1}$) | $\sigma_b$ (km s$^{-1}$) |
| −5, 5                | 7.1     | 6.5                 | 6.7                      | 6.6                     | 6.1                 | 6.7                      |
| −10, 10              | 9.2     | 7.1                 | 7.2                      | 6.9                     | 6.2                 | 7.6                      |
| −15, 15              | 11.9    | 8.0                 | 7.8                      | 7.3                     | 6.1                 | 9.4                      |
| −20, 20              | 15.0    | 8.8                 | 9.3                      | 7.3                     | 6.1                 | 11.4                     |
| −25, 25              | ...     | ...                 | ...                      | 7.3                     | 6.2                 | 14.6                     |
| −30, 30              | ...     | ...                 | ...                      | 7.2                     | 6.2                 | 18.5                     |

Notes. Column 1: range of offsets. Columns 2–4: derived dispersions using the offset range given in Col. 1 as applied to all profiles. Columns 5–7: derived dispersions using the offset range given in Col. 1 as applied only to profiles with an amplitude less than 2.3 mJy. $\sigma_{1G}$ denotes the velocity dispersion derived from a single Gaussian fitting; $\sigma_n$ the velocity dispersion of the narrow component and $\sigma_b$ the velocity dispersion of the broad component.

Figure 27 (right panel) shows examples of super profiles derived from the second model cube. We start to clearly see a broad component resulting from incorrect shuffling at (−15, 15) km s$^{-1}$ offsets. The wings of the simulated super profiles get more and more pronounced with increasing offsets.

We summarize in Table 8 the velocity dispersion of the super profiles derived from the two tests.

The above results show that we need an offset of at least 15 km s$^{-1}$ to explain the non-Gaussianity of super profiles by incorrect shuffling. As Figure 26 shows, the maximum uncertainties in the fitted amplitudes are around 5 km s$^{-1}$. This is three times smaller than the offset required to create a broad component. At (−5, 5) km s$^{-1}$ offsets, i.e., equal to the maximum uncertainty in the real data, the broadest of the two components required in the double Gaussian fitting has a velocity dispersion of $\sim 6.7$ km s$^{-1}$ at these offsets. Thus, we introduce a broadening of only $\sim 10\%$ to the broad component by going from 0 to (−5, 5) km s$^{-1}$ offsets. Obviously, as this is the maximum uncertainty in the data, the real broadening is likely to be much smaller.

Uncertainties in the SHUFFLE procedure are not sufficient to create a broad component that we see in our super profiles. The offsets required to create a broad component are much larger than inferred for real data.

REFERENCES

Bolatto, A. D., Leroy, A. K., Jameson, K., et al. 2011, ApJ, 741, 12
Braun, R. 1997, ApJ, 484, 637
Clark, B. G. 1965, ApJ, 142, 1398
de Blok, W. J. G., & Walter, F. 2006, AI, 131, 363
de Blok, W. J. G., Walter, F., Brinks, E., et al. 2008, AI, 136, 2648
Fabello, S., Catinella, B., Giovanelli, R., et al. 2011, MNRAS, 411, 993
Fraternali, F., van Moorsel, G., Sancisi, R., & Oosterloo, T. 2007, AJ, 132, 3124
Kennicutt, R. C., Lee, J. C., Funes, J. G., Sakai, S., & Akiyama, S. 2008, ApJS, 178, 247
Kobulnicky, H. A., & Kewley, L. J. 2004, ApJ, 617, 240
Krumholz, M. R., Leroy, A. K., & McKee, C. F. 2011, ApJ, 731, 25
Krumholz, M. R., McKee, C. F., & Tumlinson, J. 2009, ApJ, 693, 216
Lee, J. C., Gil de Paz, A., Kennicutt, R. C., et al. 2011, ApJS, 192, 6
Leroy, A. K., Bolatto, A., Gordon, K., et al. 2011, ApJ, 737, 12
Leroy, A. K., Walter, F., Bigiel, F., et al. 2009, ApJ, 137, 4670
Leroy, A. K., Walter, F., Brinks, E., et al. 2008, AI, 136, 2782
Moustakas, J., Kennicutt, R. C., Tremonti, C. A., et al. 2010, ApJS, 190, 233
Muñoz-Mateos, J. C., Gil de Paz, A., Zamorano, J., et al. 2009, ApJ, 703, 1569
Oosterloo, T., Fraternali, F., & Sancisi, R. 2007, AI, 134, 1019
Pilyugin, L. S., & Thuan, T. X. 2005, ApJ, 631, 231
Radhakrishnan, V., Murray, J. D., Lockhart, Peggy, & Whittle, R. P. J. 1972, ApJS, 24, 15
Schaye, J. 2004, ApJ, 609, 667
Schruba, A., Leroy, A. K., Walter, F., et al. 2012, AI, 143, 138
Swaters, R. A., Sancisi, R., & van der Hulst, J. M. 1997, ApJ, 491, 140
Tamburro, D., Rix, H.-W., Leroy, A. K., et al. 2009, AJ, 137, 4424
Tielens, A. G. M. 2005, The Physics and Chemistry of the Interstellar Medium (Cambridge: Cambridge Univ. Press)
Trachternach, C., de Blok, W. J. G., Walter, F., Brinks, E., & Kennicut, R. C. 2008, AJ, 136, 2720
van der Kruit, P. C., & Allen, R. J. 1978, ARA&A, 16, 103
Walch, S., Wuensch, R., Burkert, A., Glover, S., & Whitworth, A. 2011, ApJ, 733, 47
Walter, F., Brinks, E., de Blok, W. J. G., et al. 2008, AJ, 136, 2563
Warner, P. J., Wright, M. C. H., & Baldwin, J. E. 1973, MNRAS, 163, 163
Wolfire, M. G., McKee, C. F., Hollenbach, D., & Tielens, A. G. M. 2003, ApJ, 587, 278
Young, L. M., & Lo, K. Y. 1996, ApJ, 462, 203
Young, L. M., & Lo, K. Y. 1997, ApJ, 490, 710
Young, L. M., van Zee, L., Lo, K. Y., Dohm-Palmer, R. C., & Beierle, M. E. 2003, ApJ, 592, 111