WHAT IS DRIVING THE H I VELOCITY DISPERSION?

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ABSTRACT

We explore what dominant physical mechanism sets the kinetic energy contained in neutral, atomic (H i) gas. Both supernova (SN) explosions and magnetorotational instability (MRI) have been proposed to drive turbulence in gas disks and we compare the H i line widths predicted from turbulence driven by these mechanisms to direct observations in 11 disk galaxies. We use high-quality maps of the H i mass surface density and line width, obtained by The H i Nearby Galaxy Survey. We show that all sample galaxies exhibit a systematic radial decline in the H i line width, which appears to be a generic property of H i disks and also implies a radial decline in kinetic energy density of H i. At a galactocentric radius of r25—often comparable to the extent of significant star formation—there is a characteristic value of the H i velocity dispersion of 10 ± 2 km s−1. Inside this radius, galaxies show H i line widths well above the thermal value (corresponding to ∼8 km s−1) expected from a warm H i component, implying that turbulence drivers must be responsible for maintaining this line width. Therefore, we compare maps of H i kinetic energy to maps of the star formation rate (SFR)—a proxy for the SN rate—and to predictions for energy generated by MRI. We find a positive correlation between kinetic energy of H i and SFR; this correlation also holds at fixed Σ1, as expected if SNe were driving turbulence. For a given turbulence dissipation timescale, we can estimate the energy input required to maintain the observed kinetic energy. The SN rate implied by the observed recent SFR is sufficient to maintain the observed velocity dispersion, if the SN feedback efficiency is at least εSN ≳ 0.1 × (10^7 yr/τD), assuming τD ≃ 10^7 yr for the turbulence dissipation timescale. Beyond r25, this efficiency would have to increase to unrealistic values, ε ≳ 1, suggesting that mechanical energy input from young stellar populations does not supply most kinetic energy in outer disks. On the other hand, both thermal broadening and turbulence driven by MRI can plausibly produce the velocity dispersions and kinetic energies that we observe in this regime (r > r25).

Key words: galaxies: dwarf – galaxies: evolution – galaxies: ISM – galaxies: kinematics and dynamics – galaxies: spiral – stars: formation

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1. INTRODUCTION

The extended H i disks of spiral galaxies exhibit characteristic 21 cm line widths of 5–15 km s−1 on small scales. Line widths are observed to be ∼6–10 km s−1 even beyond r25, where the star formation rate (SFR) and the associated feedback are presumably inefficient (van der Kruit & Shostak 1982; Dickey et al. 1990; Kamphuis 1993; Rownd et al. 1994; van Zee & Bryant 1999). In some observed cases, the H i disks exhibit an overall outward decrease of the velocity dispersion to 6–8 km s−1 (Boulanger & Viallefond 1992; Petric & Rupen 2007).

The observed line widths are attributable in part to thermal broadening and in part to turbulence. At pressures typical of disk galaxies, interstellar atomic gas has two temperatures at which it can remain in stable thermal equilibrium (Wolfire et al. 1995). The gas is observed to be distributed with roughly 60% of the mass evenly distributed between the equilibrium temperatures (Kulkarni & Heiles 1987; Dickey & Lockman 1993; Dickey & Brinks 1993) and 40% transiting between them (Heiles 2001). The cold (∼100 K) neutral gas emits lines with a characteristic line width of ∼1 km s−1, while the warm (∼8000 K) neutral gas has a line width of ∼8 km s−1. Spectral lines observed to be broader than ∼8 km s−1 can be attributed to turbulence-stochastic fluctuations of velocity and pressure on scales much larger than the mean free path of the gas. Heating by a galactic interior or extragalactic background of ultraviolet (UV) radiation (Schaye 2004) may be significant in the outermost regions of H i disks, where velocity dispersions approach thermal values for the warm phase.

There are several energetic sources that can induce turbulent motions in the interstellar medium (ISM), among which feedback from recently formed stellar populations and magnetorotational instabilities (MRI; Balbus & Hawley 1991, 1998; Sellwood & Balbus 1999) are some of the most important. The stirred turbulence drives motions at smaller and smaller scales until viscosity dissipates the motion into thermal energy. This hierarchical description was formulated by Kolmogorov (1941) for an incompressible turbulent fluid, though it applies well to the small-scale dynamics of the gas in galaxy disks (Elmegreen et al. 2001, 2003). Ultimately, the ISM radiates away the thermal energy, e.g., by line cooling. Since the typical radiative cooling time (10^9 yr; Wolfire et al. 2003) is shorter than the time scale for turbulent energy to decay (∼10 Myr; Mac Low 1999), the turbulent energy must be continuously replenished on the decay timescale. The direct identification of the energy sources that sustain the turbulence at this rate has drawn considerable interest for well over three decades, but has not yet been
concluded (e.g., Mac Low & Klessen 2004; Elmegreen & Scalo 2004).

Numerical simulations have demonstrated that both hydrodynamical and magnetohydrodynamic turbulence decay over a relatively rapid timescale, comparable to the local dynamical time, i.e., ∼10 Myr (Mac Low et al. 1998; Stone et al. 1998; Mac Low 1999; Padoan & Nordlund 1999; Avila-Reese & Vázquez-Semadeni 2001; Ostriker et al. 2001), thus requiring a driving mechanism that continuously provides energy to the medium to maintain a steady state (Gammie & Ostriker 1996; Mac Low 1999).

Which mechanisms drive ISM turbulence remains a matter of debate. As first envisioned by Spitzer (1978), star formation itself injects energy back to the ISM and drives turbulence through stellar winds of O/B and Wolf–Rayet stars, UV ionizing radiation, and supernova (SN) explosions (e.g., Chiang & Prendergast 1985; Rosen et al. 1993; Kim et al. 2001; Dib et al. 2006; Joung & Mac Low 2006; Avillez & Breitschwerdt 2007). The energy input from SNe likely dominates stellar feedback (Kornreich & Scalo 2000; Mac Low & Klessen 2004). The overall galaxy kinematics can also generate some turbulence through spiral wave shocks (Roberts 1969), rotational shear (Schaye 2004), swing amplified shear instabilities (Huber & Pfenniger 2001; Wada et al. 2002), gravitational potential energy of the arms (Elmegreen et al. 2001, 2003), and nonlinear development of gravitational instability (Li et al. 2005, 2006). Magnetized disk instabilities include the MRI (Balbus & Hawley 1991, 1998; Sellwood & Balbus 1999; Dziourkevitch et al. 2004; Piontek & Ostriker 2005) and the magneto-Jeans instability (Wada & Koda 2004; Kim & Ostriker 2006; Kim et al. 2006). Finally, there could also be a contribution from thermal instability (Koyama & Inutsuka 2002; Kritsuk & Norman 2002; Dib & Burkert 2005; Hennebelle & Audit 2007).

In this paper, we attempt a direct observational identification of the energy sources that drive turbulence. Our results suggest that the energy input from young stars determines the H I line width within the star-forming region of galactic disks, while at large radii, where star formation is absent or feeble, the line width is either sustained by the MRI (Sellwood & Balbus 1999) or by thermal broadening from UV heating. We examine whether SN feedback, gas temperature, and MRI can effectively maintain the observed ISM line width, assuming that the energy loss occurs on the self-dissipation timescales predicted for the turbulence (Mac Low 1999). Mac Low & Klessen (2004) argue that SNe, among other mechanisms of energy injection, are the most effective in actively star-forming regions, while in the outermost regions of galaxy disks, where the SFR is low or zero, the MRI becomes important in sustaining both the magnetic field, even in low-density regions, and the gas velocity dispersion (Sellwood & Balbus 1999).

We use multiwavelength data in the radio, infrared (IR), and far-UV (FUV; Section 2), to compare detailed maps of the ISM kinetic energy density implied by 21 cm line widths to maps of the SFR density for a sample of nearby spiral and dwarf galaxies. In this comparison, we take the SFR density as a proxy for the energy input rate to the ISM. Relying on the measurement of the velocity dispersion as a tracer of turbulence in the neutral gas, we look at both the correlation between SFR and turbulent motions in the H I on a pixel-by-pixel basis and at their mean values as function of galactocentric distance (Section 3). We find that the azimuthal average of the H I velocity dispersion decreases radially much more slowly than the SFR (Section 4); specifically, the radial profile of H I velocity dispersion approaches the H I thermal value for the warm neutral medium where the radial profile of SFR truncates. Therefore, we investigate (1) pixel by pixel how the kinetic energy of the gas turbulence correlates with the SFR, especially in terms of SN rate and (2) what role thermal broadening and MRI play in regions of low SFR and considerable velocity dispersion (Section 5). In particular, we compare the current turbulent kinetic energy of the gas turbulence to the energy input from both SNe and MRI (and the efficiencies of this input), on the basis that the turbulence dissipation timescales, provided by extensive theoretical modeling, approximate the energy loss timescales.

2. DATA

The main observational data for our analysis are maps of the ISM kinetic energy surface density derived from high-resolution H I data. For a subsample, we include carbon monoxide (CO) emission maps to explore the contribution of the molecular gas to the kinetic energy budget. These maps are then compared, pixel by pixel, to analogous maps of the SFR surface density, derived from UV and thermal IR maps for the same objects.

We use maps produced by The H I Nearby Galaxy Survey (THINGS; Walter et al. 2008), a survey of the 21 cm emission line carried out with the NRAO6 Very Large Array, to obtain the column density $\Sigma_{HI}$ and velocity dispersion $\sigma_{HI}$ of neutral hydrogen. The THINGS data have an angular resolution of ∼7′, and a velocity resolution of either 2.6 or 5.2 km s$^{-1}$ (see Table 1), and a 3σ sensitivity corresponding to a column density of N(HI) ⩾ 3.2 × 10$^{20}$ cm$^{-2}$. To avoid projection effects in the velocity dispersion maps, we consider only those galaxies that are more face-on than ∼50′ (see, e.g., Leroy et al. 2008), leaving 11 disk galaxies in total, including three dwarf galaxies (Holmberg II, IC 2574, and NGC 4214), listed in Table 1.

We complement the analysis of the H I gas with the mass surface density and velocity dispersion of molecular hydrogen (H$_2$) gas for about half of our galaxies: NGC 628, NGC 3351, NGC 3184, NGC 4214, NGC 6946. The H$_2$ maps are derived from CO $J = 2 \rightarrow 1$ emission maps, obtained at the HERA focal plane array. These maps have resolution of ∼11′ and 2.6 km s$^{-1}$, and sensitivity of $\Sigma_{HI} \geq 4 M_{\odot}$ pc$^{-2}$. To derive $\Sigma_{HI}$, we assume a conversion factor $\lambda_{CO} = 2 \times 10^{20}$ cm$^{-3}$ K km s$^{-1}$ and a line ratio $N(J = 2 \rightarrow 1)/N(J = 1 \rightarrow 0) = 0.8$.

The SFR density maps were derived by Leroy et al. (2008) from 24 μm and FUV maps, combining dust-enshrouded star formation activity and unobscured star formation, respectively. The MIPS 24 μm emission maps (Rieke et al. 2004) are taken from the Spitzer Infrared Nearby Galaxies Survey (SINGS; Kennicutt et al. 2003), and the FUV emission maps are taken from the Galaxy Evolution Explorer Nearby Galaxy Survey (GALEX-NGS; Gil de Paz et al. 2007), for a set of disk galaxies in common with the THINGS sample. The MIPS instrument has a resolution of ∼6′ at 24 μm, and a wide areal coverage, which typically covers ∼2$r_{25}$. The GALEX FUV images have a resolution (FWHM) of 5′′6 within the $\lambda = 1350–1750$ Å band and have a field of view of ∼1:25.

3. DATA ANALYSIS

As a first step in comparing the kinetic energy of the gas to possible drivers of turbulence, we convert the previously

6 The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.
described maps (Section 2) of \( H\) and \( H2 \) gas column density and kinematics, and the 24 \( \mu \)m FUV surface brightness into physical quantities. Specifically, we obtain mass surface density, \( \Sigma_{H1}, \Sigma_{H2}, \) velocity dispersion, \( \sigma_{H1}, \sigma_{H2}, \) and SFR surface density, \( \Sigma_{SFR}. \) Afterward, we proceed with a comparison between the turbulence kinetic energy, obtained from the gas mass surface density and velocity dispersion, and the SFR on a pixel-by-pixel basis.

### 3.1. Mass Surface Density and Velocity Dispersion

We determine the \( H\) mass surface density, \( \Sigma_{H1}, \) and the velocity dispersion, \( \sigma_{H1}, \) by taking the moments of fully reduced data cubes for our 11 sample galaxies (the prior reduction steps of which are described in Walter et al. 2008). We obtain the pixel-by-pixel maps of \( \Sigma_{H1}(x, y), \bar{v}(x, y), \) and \( \sigma(x, y), \) by calculating integrals over the data cubes for all the positions on the sky \( S_i(x, y, v_i). \) All the sums are calculated over those channels with signal identified by the THINGS masking (Walter et al. 2008); we only calculated moments for those \( (x, y) \) line-of-sight positions with signal in at least three channels.

The zeroth moment, \( \Sigma_{H1}, \) is calculated by integrating the \( H\) data cube along the velocity dimension for a total number, \( N, \) of velocity channels using

\[
\Sigma_{H1} = \sum_{i=1}^{N} S_i, \tag{1}
\]

where \( S_i \) denotes the signal within the \( i\)th velocity channel. Afterward, \( \Sigma_{H1} \) is corrected for inclination; the adopted inclinations are listed in Table 1. For each sample galaxy, the spectral dimension of the \( H\) data cubes is sufficiently broad to encompass all relevant velocity values.

The first-moment map, the intensity-weighted mean velocity along the line of sight, is given by

\[
\bar{v} = \frac{1}{\Sigma_{H1}} \sum_{i=1}^{N} v_i S_i, \tag{2}
\]

where \( v_i \) is the velocity value of the \( i\)th channel. We only use \( \bar{v} \) in this context to calculate the central second moment.

The variance, corresponding to the square of the line-of-sight velocity dispersion, is given by the intensity-weighted mean deviation:

\[
\sigma^2 = \frac{1}{\Sigma_{H1}} \sum_{i=1}^{N} (v_i - \bar{v})^2 S_i. \tag{3}
\]

Throughout our analysis, we restrict ourselves to the moment definition of Equation (3) to define the variance. We presume that \( \sigma \) (Equation (3)) is the most sensible tracer of turbulent or more precisely, disordered motions, since it is applicable to any line profile. We address the discussion of this assumption in Section 3.2.

We complement the \( H\) maps with \( H2 \) column density and kinematics data obtained from CO emission (Section 2). Following the same procedure previously adopted to calculate the relevant \( H\) maps, we obtain the mass surface density, \( \Sigma_{H2}, \) and the velocity dispersion, \( \sigma_{H2}, \) for the \( H2 \) gas. As described in the following sections, while \( H2 \) is an important contributor to the total mass surface density, its contribution to the total turbulent kinetic energy of gas turns out to be rather small in our sample.

#### 3.2. Realities of Measuring the Velocity Dispersion in THINGS

In the case of perfect signal, the second moment is exactly the kinetic energy of \( H\) gas. Even at limited signal-to-noise ratio (S/N) but with normally distributed noise, we expect the measured variance to scatter about the true value in a well-behaved way, so that by averaging measurements over enough area, we can approximate the true value.

As an alternative approach, assuming and then fitting a fixed line profile shape (e.g., a Gaussian) fails in two ways. First, toward the centers of galaxies, line profiles tend to be broad and often contain multiple emission components. Second, in the outskirts of galaxies, where individual lines of sight tend to have relatively low S/N, a simple Gaussian fit tends to underestimate the line width by latching onto only the peak of the emission. In the low S/N regime, the line profiles are approximately Gaussian. For a few sample galaxies (NGC 3184, NGC 5194, NGC 6946, and NGC 7793), we find that the Gaussian \( \sigma \)
value is systematically lower than the second moment. For these galaxies, however, the difference between Gaussian, \(\sigma\), and second moment is lower than \(\sim 2-3\) km s\(^{-1}\) in average. Since we do not know a priori the \(H\) gas line-of-sight velocity distribution, and the profiles are not necessarily Gaussian, the best tracer of kinetic energy, as a model independent estimate, is the variance.

Therefore, we avoid fitting and attempt to minimize systematics by measuring the second moment only on regions that have been identified to contain signal. The production of these “blanked cubes” is described in Walter et al. (2008) and is briefly summarized here. First, the cubes were smoothed to 30\(^\prime\) angular resolution. Then, all areas without \(S/N > 2\) in two consecutive velocity channels are blanked (set to 0). This does an excellent job of identifying all areas with significant emission but still left some false positives. These were removed by a by-eye inspection that focused on agreement with the overall velocity structure and morphology of the galaxy. We test the systematics induced by such blanking on a face-on galaxy by measuring \(\sigma\) on the blanked cube and then expanding the blanking mask and remeasuring \(\sigma\). We find that small expansions of the mask on both directions along the velocity dimension, e.g., by \(\pm 15\) km s\(^{-1}\), have almost no impact on the measured dispersion. Larger expansion begins to show systematic effects that we want to avoid (particularly at low \(S/N\)).

These blanked cubes minimize the effect of artifacts in the THINGS cubes and yield a more robust estimate of kinetic energy than fitting an assumed line profile. Therefore, the profiles of \(\sigma\) and \(E_k\) represent the best possible estimates using the available data. However, we emphasize that a rigorous attempt to match other observations or simulations to our measurements should bear in mind (and ideally duplicate or simulate) this blanking procedure.

### 3.3. Turbulent Kinetic Energy

With the moment definition of \(\Sigma_{H\text{i}}\) and \(\sigma_{H\text{i}}\), the \(H\) gas kinetic energy per unit area is given by \(E_k = 3/2 \times \Sigma_{H\text{i}} \sigma_{H\text{i}}^2\), where the factor 3/2 takes into account all three velocity components assuming that the velocity dispersion is isotropic. For the galaxies with molecular gas maps, we define the total kinetic energy as \(E_k = 3/2 \times (\Sigma_{H\text{i}} \sigma_{H\text{i}}^2 + \Sigma_{H_2} \sigma_{H_2}^2)\). In Section 4, we describe the relationship between the \(H\) gas kinetic energy, \(E_k\), and the \(\Sigma_{SFR}\) maps in a pixel-by-pixel scatter plot.

### 3.4. Star Formation Rate

We use maps of SFR surface density, \(\Sigma_{SFR}\), derived by Leroy et al. (2008), from combining the 24 \(\mu\)m and the FUV emission maps taken from the SINGS and the GALEX-NGS surveys (Section 2). Leroy et al. (2008) have calibrated the SFR represented by the UV and IR emission by comparing these maps to \(H\alpha\), 24 \(\mu\)m, and Pa\(\alpha\) emission from H \(\Pi\) regions and young compact stellar clusters (Calzetti et al. 2007). The 24 \(\mu\)m band emission is mostly radiation from hot dust heated by the UV light from young massive stars and therefore traces dust-shrouded, ongoing star formation over a timescale 3–10 Myr (Calzetti et al. 2005; Pérez-González et al. 2006; Tamburro et al. 2008), although part of the emission proceeds from outside the H \(\Pi\) regions, thus tracing older (greater than 10 Myr) stellar populations. FUV emission is mostly photospheric emission from O and B stars. It thus complements the 24 \(\mu\)m emission in regions poor in dust content, probing therefore low metallicity and older regions of star formation over timescales of \(\tau \sim 10-100\) Myr (Calzetti et al. 2005; Salim et al. 2007).

The calibration provides SFR estimates with an uncertainty of 40% at most at high SFR, depending on variations in geometry, dust temperature, and age of stellar populations (Leroy et al. 2008). At low SFR, a substantial part of the 24 \(\mu\)m emission proceeds from diffuse dust in the ISM, which may not be associated directly to recent star formation, with the dust being heated by nearby (young and old) star clusters. Leroy et al. (2008) argue that below a fiducial threshold of \(\Sigma_{SFR} = 10^{-10} M_\odot\) yr\(^{-1}\) pc\(^{-2}\), the SFR maps represent upper limits to the true SFR because of the contribution of this diffuse dust component.

### 4. RESULTS

In this section, we describe our two main results: (1) the observation that a radial decline of the \(H\) velocity dispersion is pervasive throughout the entire sample with little dependence on galaxy type and (2) that we find correlation between the kinetic energy of gas and SFR with a slope close to unity and a similar proportionality constant in all objects. Both results depend on the exceptional quality of the data in terms of spatial and velocity resolution and the wide field of view. We reserve the broader interpretation of our results for Section 5.

In the following, we use units of \(r_{25}\), which provides a convenient normalization. Leroy et al. (2008) and Tamburro et al. (2008) measured the exponential scale lengths of near-IR emission from our sample, a good proxy for stellar mass. \(r_{25}\) is typically 4.6 ± 0.8 times the near-IR scale length, and the SFR maps yield comparable scale lengths to the near-IR. When we normalize by \(r_{25}\) then, it is roughly equivalent to normalizing by the scale length of the disk.

#### 4.1. Radial Profiles of \(\sigma_{H\text{i}}\)

To start, we determine the azimuthally averaged radial profiles of \(H\) velocity dispersion, SFR, and gas kinetic energy, by calculating the average values of \(\sigma_{H\text{i}}\) and \(\Sigma_{SFR}\) within annuli of \(\sim 15\)\(^\prime\) width. The resulting \(\sigma_{H\text{i}}(r)\) and \(\Sigma_{SFR}(r)\) profiles are shown in Figure 1. They exhibit a radial decline of H gas velocity dispersion as a common characteristic for all sample galaxies independent of their dynamical mass. While previous studies have reported this individually for a few disk galaxies (i.e., Boulanger & Viallefond 1992; Petric & Rupen 2007), we show for the first time that this is true for a significant sample of dwarf and normal spiral galaxies.

To characterize the \(\sigma_{H\text{i}}\) radial gradients, we fit a linear relation to the radial profiles of \(\sigma_{H\text{i}}\) for all \(r \geq r_{25}\), a regime where \(\sigma(r)\) is approximately linear with \(r\) for all the galaxies of the sample. With \(\sigma(r)\) going from \(\gtrsim 20\) km s\(^{-1}\) down to \(\sim 5\) ± 2 km s\(^{-1}\) near the outermost observed radius (Figure 1), the velocity dispersion decreases with radius by \(\sim 3-5\) km s\(^{-1}\) per \(\Delta r_{25}\); for comparison, azimuthal variations at a fixed radius are \(\lesssim 5\) km s\(^{-1}\). In Figure 2, we display and summarize the intercept value of \(\sigma_{H\text{i}}(r)\) at \(r_{25}\) and the H gas mass-weighted median of \(\sigma_{H\text{i}}\) for all sample galaxies individually. Our observations resolve the outward radial \(\sigma_{H\text{i}}\) decline well, since a typical \(r_{25}\) for our sample galaxies corresponds to \(\sim 30-40\) times the 7\(^\text{th}\) H resolution limit and the typical radial extent of the H emission is \(2-4 \times r_{25}\).

Remarkably, we find that all galaxies have the same H velocity dispersion at their respective \(r_{25}\): a general value of \(\sigma(r_{25}) \sim 10\) ± 2 km s\(^{-1}\), which displays no apparent trend with the dynamical mass and morphological type, and is consistent
with the H\textsc{I} mass-weighted median value \(\langle \sigma \rangle\) (see Figure 2 and Table 1). The radial \(\sigma_{HI}\) gradient has in all cases the same sign as the much steeper decline of the mean SFR as function of radius as shown for comparison in logarithmic scale in Figure 1.

Since the sample galaxies are more face-on than 50\(^\circ\), the systematic increase of \(\sigma_{HI}\) toward the center cannot be due to increasing beam smearing effects. We analyze the combined effect of beam smearing, inclination and rotation curve on the velocity dispersion by constructing a sample data cube containing signal in only one velocity channel per each \((x, y)\) spatial position (i.e., intrinsic \(\sigma_{HI} = 0\)) and characterized by the same inclination, and rotation curve of NGC 5055—the most inclined disk of the sample with a fast rotation speed. After convolving this sample data cube with a kernel of 7\(''\) FWHM (the resolution of our H\textsc{I} maps), we calculate the velocity dispersion using second moments (Equation (3)) as done throughout our analysis (Section 3.1). The resulting line broadening from beam smearing for a disk with the rotation curve and orientation of NGC 5055 is only \(<\sim 5\text{ km s}^{-1}\), lower than the observed velocity dispersion in NGC 5055 by \(<\sim 10\text{–}20\text{ km s}^{-1}\). The fractional contribution of the velocity dispersion from beam smearing to the total observed velocity dispersion is only 20\% in the central region \((r < 1/4 r_{25})\) and at most 10\% at larger galactocentric radii.

4.2. The H\textsc{I} Kinetic Energy Density as a Function of Radius

The H\textsc{I} kinetic energy density, \(E_k\), in each pixel exhibits a clear radial decline, as shown in the full pixel-by-pixel distribution (Figure 3), where the black contours and color scale indicate the density of pixels at each H\textsc{I} kinetic energy and radius, while the red contours show the sum of atomic and molecular kinetic energy. The latter diverges from the H\textsc{I} kinetic energy in the inner parts of some galaxies, indicating that the cold molecular gas contributes to the kinetic energy budget. Since every galaxy of the sample includes \(\sim 2 \times 10^5\) pixels with significant signal, we display in Figure 3 the density contours of the data points.

We include the analysis of the H\textsc{II} mass surface density and velocity dispersion derived from the CO emission for a few sample galaxies (Section 3), to quantify the contribution of the molecular gas to the total kinetic energy at high H\textsc{II}-to-H\textsc{I} mass ratio. The total kinetic energy \(E_k = E_{HI} + E_{H_2}\) is plotted in Figure 3 (with red contours) for the galaxies with CO data. For the galaxies NGC 4736, NGC 5055, and NGC 6946, \(E_{H_2}\) is comparable to \(E_{HI}\) or even dominant in the central regions of galaxy disks; for these galaxies the H\textsc{II} mass and spatial extent is considerable. For those galaxies where the H\textsc{I} gas dominates the total gas mass, i.e., NGC 628, NGC 3184, NGC...
3351, and the dwarf galaxies Holmberg II, IC 2474, and NGC 4214, characterized by little or no detected molecular gas, the molecular gas does not contribute much to the total kinetic energy.

4.3. Correlation between $E_k$ and $\Sigma_{SFR}$

In Figure 4, we compare pixel by pixel the relation between the kinetic energy density of the H i gas, $E_k = E_{H_1} + E_{H_2}$, and the SFR surface density—a proxy for the energy input rate by SN. We find that in all galaxies these quantities are well correlated with a slope close to unity and with no evident dependence on dynamical mass (Figure 4). Note that a considerable fraction of all data points in Figure 4 lies below the noise estimated for the $\Sigma_{SFR}$ maps (Section 3.4). These data points lie in the outermost parts of galaxy disks ($r > 2 \times r_{25}$), where there is little or no ongoing star formation (see Figure 3).

We note that the slope of all correlations in Figure 4 flattens at high $E_k$ and $\Sigma_{SFR}$, although we argue in Section 4.2 that this is not caused by a higher abundance of molecular gas at higher $\Sigma_{SFR}$. The total kinetic energy $E_k = E_{H_1} + E_{H_2}$ is plotted in Figure 4 (with red contours) for the six sample galaxies with H2 data. Only for NGC 5055 and NGC 6946 is the kinetic energy of the molecular gas, $E_{H_2}$, important; in those cases the $E_{H_1} + E_{H_2}$ versus $\Sigma_{SFR}$ relation is linear and the slope is close to unity.

5. DISCUSSION

What scenario does our data support for producing the observed line widths? SN-driven turbulence seems likely to be the dominant factor broadening line widths within the radius of active star formation, since we find that the level of predicted SN energy is sufficient to account for the turbulent kinetic energy implied by the line width as a function of radius.

The radial slopes of SN energy and kinetic energy of the neutral (H i and H2) gas agree qualitatively so that the kinetic energy of the gas is proportional to the local SFR. Yet, the fact that the H i velocity dispersion approaches its thermal value of roughly $6 \text{ km s}^{-1}$ well beyond the radius of detectable star formation indicates that either (1) the line broadening is due to UV heating, with a warm neutral medium temperature of $\sim 5000 \text{ K}$ resulting in $\sigma_{H_1} \sim 6 \text{ km s}^{-1}$, or (2) the gas is actually turbulent and another mechanism such as the MRI is driving the turbulence. We now explore whether our new data support this scenario.

In the following, we compare the observed line widths with the most plausible mechanisms for generating them: SNe (Section 5.1), UV heating (Section 5.2), and MRI (Section 5.3). SNe and MRI both produce broad line widths by driving turbulence, while UV heating can produce thermal broadening. The required energy injection rate depends both on the kinetic or thermal energy of the gas, which can be derived from the observed line widths and the turbulence decay or cooling timescales, which must be derived from models. More precisely, the gas kinetic energy implied by the line width consists of a combination of turbulence and the thermal energy associated with the (warm) gas temperature, i.e., $E_k = E_{\text{turb}} + E_{\text{therm}}$. If the thermal broadening is much less effective than the turbulence, then $E_k \simeq E_{\text{turb}}$.

If the gas turbulence is mainly driven by SNe and MRI, then we expect the dissipation rate of turbulence to equal the sum of the energy input rates of SNe and MRI,

$$\dot{E}_k \simeq \epsilon_{SN} E_{SN}/\tau_{SN} + \epsilon_{MRI} E_{MRI}/\tau_{MRI}, \quad (4)$$

where $\epsilon_{SN}$ and $\epsilon_{MRI}$ are the efficiencies, and $\tau_{SN}$ and $\tau_{MRI}$ are the decay times of turbulence driven by the two mechanisms. Different mechanisms can result in different decay rates because they have different driving scales and magnitudes (Stone et al. 1998; Mac Low 1999).

5.1. Supernova Energy

Assuming steady state equilibrium between the energy input rate from SNe to turbulent gas motions and the energy loss rate from dissipation of this turbulence, then the resulting kinetic energy, $E_k = \epsilon_{SN} E_{SN}\tau_{SN}$, where $E_{SN}$ is the rate of released SN energy, which we estimate from the SFR, and the SN feedback efficiency, $\epsilon_{SN}$, is the fraction of SN energy converted to turbulent motions in the cold gas. Mac Low (1999) finds that the dissipation rate of turbulence depends on the driving scale, $\lambda$, and the velocity dispersion, $\sigma$, as

$$\tau_D \simeq 9.8 \left(\frac{\lambda_{100}}{\sigma_{10}}\right) \text{ Myr}, \quad (5)$$

where $\lambda_{100} = \lambda / 100 \text{ pc}$ and $\sigma_{10} = \sigma / 10 \text{ km s}^{-1}$. Numerical simulations of SN-driven turbulence yield $\lambda = 100 \pm 30 \text{ pc}$ (Joung & Mac Low 2006; Avillez & Breitschwerdt 2007), and our own analysis gives an average velocity dispersion, $\sigma = 10 \text{ km s}^{-1}$ (Section 4.1). The SN energy input rate, $\dot{E}_{SN}$, can be estimated from the SN rate implied by our SFR maps. The SN rate per unit area, $\eta$, depends on the fraction, $f_{\text{e} \rightarrow \text{SN}}$, of all recently formed stars that terminate in core-collapse SNe:

$$\eta = \frac{\text{SFR}}{\langle m \rangle} \times f_{\text{e} \rightarrow \text{SN}}, \quad (6)$$
where \( \langle m \rangle \) is the average mass of stars of the population. We assume that only those stars in the mass range \((8–120) M_\odot\) can form core-collapse SNe. The SFR maps used in our analysis assume an initial mass function (IMF), \( \phi(m) = m^{-\alpha} \), where \( \alpha = 1.3 \) for the mass range \((0.1–0.5) M_\odot\) and \( \alpha = 2.3 \) for the mass range \((0.5–120) M_\odot\) (see Leitherer et al. 1999; Calzetti et al. 2007). Then, the SN fraction

\[
f_{\text{SN}} \langle m \rangle = \frac{\int_{120 M_\odot}^{10 M_\odot} \phi(m) dm}{\int_{120 M_\odot}^{10 M_\odot} \phi(m) dm},
\]

yielding \( f_{\text{SN}} \langle m \rangle \simeq 1.3 \times 10^{-2} M_\odot^{-1} \). If we were to reduce the upper mass limit to 50 \( M_\odot \) yields \( f_{\text{SN}} \langle m \rangle \simeq 1.2 \times 10^{-2} M_\odot^{-1} \), and an upper mass limit of 20 \( M_\odot \) yields \( 0.9 \times 10^{-2} M_\odot^{-1} \). The effect of these variations on \( \eta \) is unclear, because the upper mass limit of the IMF also affects our translation of UV and IR light into SFR. The UV and IR maps are primarily sensitive to high-mass stars. Therefore, for a lower upper mass limit, less UV and IR light is emitted per unit star formed and if the upper mass limit is actually lower than we have assumed, then we have underestimated the true SFR. In calculating \( \eta \), these higher SFR and lower \( f_{\text{SN}} \langle m \rangle \) have opposite effects, leaving the impact of changing the upper mass limit on \( \eta \) unclear. As the upper mass limit decreases, we estimate less intrinsic UV and IR emission per high-mass star, which we have used to construct the maps. We neglect the contribution of type Ia SNe whose rate is \( \approx 1/3 \) of the core-collapse rate for the morphological types of our sample galaxies (Mannucci et al. 2005). In these circumstances, the SN rate can be straightforwardly calculated as a function of SFR, \( \eta = \eta(S_{\text{SN}}) \), and, depending on the adopted assumptions, the SN rate is characterized by an uncertainty of a factor \( \approx 1/3 \). We assume that for each SN explosion, only a fraction \( \xi_{\text{SN}} \lesssim 1 \) of \( 10^{51} \text{ erg} \)—roughly the energy released by a single SN event (Heiles 1987)—is converted into turbulence. Then, in steady state the kinetic energy of the gas turbulence, \( E_k = \eta \times (\xi_{\text{SN}} 10^{51} \text{ erg}) \tau_D \), is

\[
\text{Figure 3. Radial distributions of H}^\text{I} \text{ kinetic energy per unit area, } E_k = 3/2 \Sigma_{\text{HI}} \sigma_T^2, \text{ for the galaxies of our sample (Section 4.2). The number of pixels falling at each}
\]

\[
\text{position in the plot is represented in color scale and contoured in black. The red contours}
\]

\[
\text{represent the sum of kinetic energies for H}^\text{I} \text{ and H}_2 \text{ gas, which diverge from}
\]

\[
\text{the H}^\text{I} \text{ contours only near galactic centers. The solid green lines represent the total SN energy released over the self-dissipation timescale}
\]

\[
\text{for values of the SN efficiency, } \xi_{\text{SN}} = 1 \text{ (above) and } 0.1 \text{ (below), as discussed in Section 5.1. The SN energy estimates plotted here retain only those values above the } \Sigma_{\text{SN}} \text{ noise}
\]

\[
\text{threshold, } \Sigma_{\text{SN}} \geq 10 M_\odot \text{ yr}^{-1} \text{ pc}^{-2} \text{ (Section 3.4). The blue solid lines indicate MRI energy produced over the corresponding timescale for turbulence dissipation}
\]

\[
\text{for values of the MRI efficiency, } \xi_{\text{MRI}} = 1 \text{ (above) and } 0.1 \text{ (below), as discussed in Section 5.3. The gray horizontal shadow indicates the noise level of } E_k.
\]
fall to within the noise (see Section 3.4), while the measured $\epsilon_4$ is typically well constrained. Nevertheless, $\epsilon_{SN} = 1$ remains problematic, since it would imply that all the kinetic energy of SN remnants would be deposited as kinetic energy of the gas. In fact, Tenorio-Tagle et al. (1991) argue that the expected SN efficiency, $\epsilon_{SN}$, should be at most $\sim 0.5$. Values greater than 0.5, therefore, either imply that other sources inject energy into the ISM (see following sections), or that the dissipation timescales are shorter than we assume. In the next sections, we examine alternative mechanisms to explain the line width in these regions.

### 5.2. Thermal Broadening

The temperature of the warm phase of the H\textsc{i} is maintained by UV heating. However, neutral gas never reaches temperatures high enough to explain line widths as high as 10 km s\textsuperscript{-1}, which are instead attributed to supersonic turbulent motions (Wolfire et al. 2003; Lacour et al. 2005). As $\sigma_{HI} \gtrsim 10$ km s\textsuperscript{-1} for $r \lesssim r_{25}$ for all our sample galaxies, we argue that thermal effects can be neglected within the star-forming radius. In regions of active star formation, stellar winds and ionizing radiation from stars appear less effective together than the SNe from the same stellar population at driving turbulence (Mac Low & Klessen 2004). Thus, SN-driven turbulence looks likely to dominate there.

In the outer regions of H\textsc{i} disks, on the other hand, the velocity dispersion approaches its thermal value. There, the warm neutral atomic phase temperature is typically $\sim 5000$ K, as measured, e.g., in the solar neighborhood (Heiles & Troland 2003; Redfield & Linsky 2004), where the SFR is a few $\times 10^{-9}$ $M_\odot$ yr\textsuperscript{-1} pc\textsuperscript{-2}. This temperature gives a thermal width of $\sigma_{HI} \sim 6$ km s\textsuperscript{-1}.

Typical temperatures of the warm medium can even be as high as $\sim 8500$ K (corresponding to $\sim 8$ km s\textsuperscript{-1}; Wolfire et al. 1995). If thermal broadening is effective, the observed $\sigma_{HI} \sim 6$ km s\textsuperscript{-1} outside the star-forming radius does not necessarily involve turbulence. However, such temperature levels, especially at $r \gtrsim 2 \times r_{25}$, where the SFR is below $10^{-10}$ $M_\odot$ yr\textsuperscript{-1} pc\textsuperscript{-2} (see Figure 1), still require a continuous UV background source warming up the H\textsc{i} disks of galaxies. At $r > r_{25}$, the source of such UV radiation is presumably not local; it could be extragalactic.

The local thermal pressure estimate and the actual velocity dispersion in the outer parts of H\textsc{i} disks are consistent with the existence of a warm phase for the gas. For example, Leroy et al. (2008) estimate a local pressure $P/k \sim 300$ K cm\textsuperscript{-3} at $r \simeq 2 \times r_{25}$ for the galaxy NGC 4214, assuming hydrostatic equilibrium (see Elmegreen 1989). At a radius $2 \times r_{25}$, the H\textsc{i} velocity dispersion in NGC 4214 is $\sim 7$ km s\textsuperscript{-1}, corresponding to a temperature of $\sim 5900$ K, which, solving $P \propto n \sigma^2$, yields a density $n \simeq 0.05$ cm\textsuperscript{-3}. This is consistent with the gas in a warm phase according to Figure 7 in Wolfire et al. (2003), where a pressure of $\sim 300$ K cm\textsuperscript{-3} corresponds to $n \sim 0.04$ cm\textsuperscript{-3}, at least for the outer parts ($r \sim 15–18$ kpc) of the Milky Way, which likely have a similar UV background. For pressure values lower than 300 K cm\textsuperscript{-3}, all the gas is warm.

### 5.3. MRI Energy

If external UV heating is insufficient to maintain a warm phase, then a nonstellar energy source is needed to explain the observed turbulence (Section 4.2). MRI is a plausible candidate. It develops in differentially rotating disks with angular velocity
decreasing outward, as in all but the smallest galactic disks, as long as some weak magnetic field threads the disk. It has been argued to sustain both the interstellar gas turbulence and the galactic magnetic field to a few \( \mu G \) (Piontek & Ostriker 2005, 2007). MRI requires a minimum magnetic field as low as \( 10^{-25} \) G to originate, which is much lower than the seed galactic magnetic fields (Kitchatinov & Rüdiger 2004).

Following the same line of reasoning as Section 5.1, if we assume that a fraction, \( \epsilon_{\text{MRI}} \leq 1 \), of the MRI energy is transformed into kinetic energy, then in steady state the observed kinetic energy must equal the MRI energy input within the turbulence decay time: \( E_k = \epsilon_{\text{MRI}} \bar{E}_{\text{MRI}} \tau_{\text{MRI}} \). Theoretical calculations (Sellwood & Balbus 1999; Mac Low & Klessen 2004; Mac Low 2008) estimate the production energy rate of MRI to be

\[
\dot{E}_{\text{MRI}} = 3.7 \times 10^{-8} \text{ erg cm}^{-2} \text{ s}^{-1} \times \left( \frac{h_z}{100 \text{ pc}} \right) \left( \frac{B}{6 \mu \text{G}} \right)^2 \times \frac{\Omega}{(220 \text{ Myr})^{-1}},
\]

where \( \Omega \equiv v/r \) is the angular velocity, \( h_z \) is the vertical thickness of the \( \text{H}\text{\footnotesize{I}} \) disk, and \( B \) is the magnetic field. In our analysis, we can assume a constant thickness \( h_z = 100 \) pc for all galaxies. This is appropriate for the inner Milky Way out to the solar circle (Wolfire et al. 2003), although in the outer regions of disks and in dwarf galaxies \( h_z \) may be higher (up to \( \sim 300 \) pc; Walter & Brinks 1999). We also assume a constant magnetic field, \( B = 6 \mu\text{G} \), as a typical galactic magnetic field (Beck et al. 1996; Heiles & Troland 2005). Taking the turbulent decay timescale again to be \( \tau_{\text{MRI}} \) \( \equiv 9.8(\lambda_{100}/\sigma_{10}) \) Myr, we can estimate the driving scale, \( \lambda = \lambda_c \). The critical wavelength for the fastest MRI growth (Balbus & Hawley 1998)

\[
\lambda_c = 2\pi v_A \left[ -\frac{3 + \alpha}{4} \frac{d\Omega^2}{dr} \right]^{-1/2},
\]

where \( \alpha \equiv d\ln v_A/d\ln r \), and the Alfvén velocity, \( v_A^2 = B^2/4\pi \rho \).

For a typical galactic magnetic field of \( B = 6 \mu\text{G} \) and a density of \( 2 \times 10^{-24} \text{ g cm}^{-3} \), \( \lambda_c \sim 10^5 \) pc.

In Figure 3, we compare the energy produced by MRI within a decay time of turbulence, \( \epsilon_{\text{MRI}} \bar{E}_{\text{MRI}} \tau_{\text{MRI}} \), with the observed kinetic energy, \( E_k \), as a function of radius for different values of \( \tau_{\text{MRI}} \). Note that although both \( \bar{E}_{\text{MRI}} \) and \( \tau_{\text{MRI}} \) are functions of radius, the MRI energy input only decreases with radius slowly, not exponentially as \( E_k \). In Figure 3, we show a comparison between the SN energy (Section 5.1) and the MRI energy plotted as a function of radius, and indicated with green and blue solid lines, respectively. We also plot in the pixel-by-pixel \( E_k \) versus \( \Sigma_{\text{SFR}} \) plot of Figure 4 the average value of the MRI for pixels with each \( \Sigma_{\text{SFR}} \), for \( \epsilon_{\text{MRI}} = 1 \).

While SNe can be identified as the dominant source of energy at \( \Sigma_{\text{SFR}} > -9 M_\odot \text{ yr}^{-1} \text{ pc}^{-2} \), the MRI contribution becomes important at \( \Sigma_{\text{SFR}} < -9 M_\odot \text{ yr}^{-1} \text{ pc}^{-2} \) and dominant at large galactocentric radii. On the other hand, the kinetic energy of turbulence within \( r_{25} \) is much higher than the predicted MRI energy, indicating that MRI cannot account for the observed gas turbulence in regions of active star formation.

The observed \( E_k \) is higher than the SN energy for the dwarf galaxies Holmberg II and, more significantly, IC 2574. In these two cases, the gas turbulence cannot be explained by SNe (see Stanimirović & Lazarian 2001; Dib & Burkert 2005; Pasquali et al. 2008); still, the MRI could account for the observed regime of turbulence. Our analysis suggests that MRI could dominate regions of low SFR and rules out MRI as an effective turbulence driving mechanism at high SFR.

### 5.4. Robustness of the Approach

Three major sources of uncertainty enter our analysis. The first and largest of these are the empirical conversions from UV and IR emission to \( \Sigma_{\text{SFR}} \), which may introduce up to a 40% uncertainty (Section 3.4). The conversion from \( \Sigma_{\text{SFR}} \) to SN rate relying on a universal IMF introduces an additional 30% uncertainty (Section 5.1). A second uncertainty enters from the reliance on numerical simulation to evaluate the driving scale of SN-driven turbulence and thus the dissipation timescale, \( \tau_{\text{SN}} \). The simulations give a 30% error for their estimate of the driving scale (Joung & Mac Low 2006; Avillez & Breitschwerdt 2007). The dissipation timescale also depends on the mean velocity dispersion, which, of course, not constant as assumed in our estimate. A third uncertainty enters in our estimates of MRI energy, where we assume a constant magnetic field and vertical thickness of the disk for all the galaxies of the sample, which may not be the case. The vertical thickness of the gaseous component in galaxies increases outward and may double the value assumed in our analysis of \( h_z = 100 \) pc. The typical strength of magnetic fields observed in the Milky Way and other galaxies declines slowly as a function of galactocentric distance, although the variations of the magnetic field can be much larger azimuthally than radially (Fletcher et al. 2004; Han et al. 2006; Beck 2007). These three sources of errors could in principle explain those data points lying near \( \epsilon_{\text{SN}} \leq 1 \) and \( \epsilon_{\text{MRI}} \geq 1 \).

Aside from the potential sources of uncertainties, if we were to interpret our empirical finding by taking into account only SNe explosions and MRI, still a minor part of the observed turbulence would require \( \epsilon_{\text{SN}} \) and \( \epsilon_{\text{MRI}} \) efficiencies uncomfortably high, as high as 100%. Therefore, we do not exclude that other mechanisms could be efficiently driving some turbulence in the gas. Potentially, within the star-forming radius (\( \lesssim r_{25} \)) stellar winds could be the most effective, while in the outermost regions of \( \text{H}\text{\footnotesize{I}} \) disks, i.e., \( r > 2 \times r_{25} \), where the SNe and the star formation effects are not likely to produce feedback, a floor level of \( H\text{\footnotesize{I}} \) velocity dispersion of \( \sim 6 \text{ km s}^{-1} \) could be attributed to thermal broadening. Observation of the \( \text{H}\text{\footnotesize{I}} \) in absorption at large galactocentric radii might ultimately help in determining whether the gas is cold and turbulent or warm (see Dickey & Brinks 1993).

### 5.5. Is \( \Sigma_{\text{H}\text{\footnotesize{I}}} \) Controlling the \( E_k \) Versus \( \Sigma_{\text{SFR}} \) Relation?

The gas kinetic energy, \( E_k \), is the correct physical quantity to study the energy balance in the ISM. However, gas surface density and SFR are well known to correlate (e.g., Kennicutt 1998; Bigiel et al. 2008), so one may wonder whether this drives our observed correlation between \( E_k \) and \( \Sigma_{\text{SFR}} \). In other words, the observed covariation between \( E_k \) and \( \Sigma_{\text{SFR}} \) might result from the two facts: at higher gas mass density, galaxies form stars at higher rate, and higher gas mass bears higher kinetic energy. In order to verify that the correlation between \( E_k \) and \( \Sigma_{\text{SFR}} \) is not controlled by \( \Sigma_{\text{H}\text{\footnotesize{I}}} \), we remove the effect of \( \Sigma_{\text{H}\text{\footnotesize{I}}} \) on the \( E_k \) versus \( \Sigma_{\text{SFR}} \) relation by calculating the partial correlation coefficient:

\[
\rho_{12,3} = \frac{\rho_{12} - \rho_{13} \rho_{23}}{\sqrt{(1 - \rho_{13}^2)(1 - \rho_{23}^2)}},
\]

where \( \rho_{12,3} \) is the partial correlation between \( x_1 = \log \Sigma_{\text{SFR}} \) and \( x_2 = \log E_k \) while controlling for \( x_3 = \log \Sigma_{\text{H}\text{\footnotesize{I}}} \), and \( \rho_{ij} \)
is the Pearson's correlation coefficient between two data sets, \(x_i\) and \(x_j\). Here, considering the quantities in logarithmic scale is convenient as they are correlated as power laws. Retaining only data points above a fiducial value for the H\(_i\) mass density, i.e., \(\Sigma_{\text{H}i} \geq 3 M_\odot\) (see Bigiel et al. 2008), we obtain the values listed in Table 2 for our sample galaxies. If the correlations between \(E_k\) and \(\Sigma_{\text{SFR}}\) were completely controlled by \(\Sigma_{\text{H}i}\) we would expect \(\rho_{12.3} = 0\). Yet, we find that \(0.2 \leq \rho_{12.3} \leq 0.6\) for our sample galaxies, indicating that the correlation between \(E_k\) and \(\Sigma_{\text{SFR}}\) is real. Equivalently, we show that the correlation, \(E_k\) versus \(\Sigma_{\text{SFR}}\), at constant \(\Sigma_{\text{H}i}\), holds a positive slope in Figure 5, in which we remove the contribution from \(\Sigma_{\text{H}i}\) to \(E_k\) by subtracting the average \((E_k)_{\Sigma\text{H}i}\) within bins of \(\Sigma_{\text{H}i}\). The residuals \(E_k - (E_k)_{\Sigma\text{H}i}\) versus \(\Sigma_{\text{SFR}}\) exhibit a positive correlation, indicating that it is not \(\Sigma_{\text{H}i}\) alone that determines the observed \(E_k\) versus \(\Sigma_{\text{SFR}}\) correlation. Positive slopes in Figure 5 and positive partial correlation coefficients imply that there is a real, physical relationship between \(E_k\) and SFR even at fixed \(\Sigma_{\text{H}i}\). The relatively weak slopes in Figure 5 indicate that higher gas mass density correlates indeed with higher kinetic energy, simply because it generates more star formation. Figure 5 and the partial correlation coefficients allow us to detect a relationship between \(E_k\) and SFR that is independent of \(\Sigma_{\text{H}i}\). Comparing Figures 4 and 5, however, it is clear that most of the correlation between \(E_k\) and SFR in Figure 5 closely involves \(\Sigma_{\text{H}i}\) (the distributions in Figure 5 are very flat compared to those in Figure 4). The basic effect seems to be that higher \(\Sigma_{\text{H}i}\) results in higher SFR, which creates more \(E_k\). Also, note that if the turbulence, as traced by \(E_k\), were effectively suppressing star formation, we would have observed a negative correlation here.

### 5.6. Does Turbulence Drive Stochastic Star Formation?

The data analysis suggests that the SFR drives the H\(_i\) turbulence through SN feedback. However, the observed correlation could also be interpreted in the opposite logical direction, i.e., that the turbulence is driving star formation. In fact, as it has been argued (Mac Low & Klessen 2004), turbulence in the ISM has a dual role: (1) to quench star formation by providing pressure support to the ISM and preventing collapse and

![Figure 5](image-url)
(2) to promote star formation by generating stochastic super-critical density enhancements. If the turbulence were to drive substantial stochastic star formation, we would indeed expect a positive correlation between $\Sigma_{\text{H} \alpha}$ and $\Sigma_{\text{SFR}}$. However, Figure 1 shows that $\Sigma_{\text{H} \alpha}$ and $\Sigma_{\text{SFR}}$ occupy quite different dynamic ranges. While the $\Sigma_{\text{SFR}}$ ranges over several orders of magnitude, $\Sigma_{\text{H} \alpha}$ ranges from $\sim 20$ to $\sim 5$ km s$^{-1}$ and is characterized by large azimuthal variations. Although $\Sigma_{\text{SFR}}$ positively correlates with $\Sigma_{\text{H} \alpha}$, on galactic scales, the large azimuthal variations imply that $\Sigma_{\text{SFR}}$ is not well defined for any given value of $\Sigma_{\text{H} \alpha}$.

This does not preclude turbulent induction of star formation in individual regions, but does suggest that this process does not dominate over large scales. The physical explanation might be that supercritical density fluctuations are often dispersed on timescales shorter than the free-fall time, arresting the collapse (Klessen et al. 2000; Elmegreen 2002; Joung & Mac Low 2006).

6. EFFECTS OF SPIRAL ARM KINEMATICS AND TIDAL INTERACTIONS

In the following, we discuss other possible mechanisms to produce ISM turbulence, such as spiral arm kinematics, tidal interactions, and streamers.

Table 1, which lists the morphological types of the galaxies of our sample, shows that there is no evident trend of the mean velocity dispersion, $<\sigma>$, among individual galaxies or morphological type. Spiral galaxies with strong spiral pattern, e.g., NGC 628 and NGC 3184, have similar values of typical H $\alpha$ velocity dispersion as galaxies with no clear spiral structure, e.g., Holmberg II and IC 2574. Since the spiral arm strength should vary within the sample, we argue that the spiral arm kinematics in our sample galaxies are not an important effect in driving turbulence into the ISM.

Although the galaxies Holmberg II and IC 2574 belong to the M81 group, they do not show signatures of tidal distortion. In our sample, only NGC 5194 is an interacting galaxy. The H $\alpha$ velocity dispersion in NGC 5194 is significantly higher than the average for the galaxies in the sample (see Figure 2). On the basis of our results, we speculate that the tidal interaction with the companion NGC 5195 enhanced the SFR in the disk of NGC 5194, which has consequently driven the velocity dispersion in the H $\alpha$ gas to higher values.

Extended streamers characterize the galaxies NCG 4736 and NGC 5055. Their radial profiles of the H $\alpha$ velocity dispersion exhibit a local increase outside the radius of active star formation, i.e., at $r \sim 4'$ ($\sim r_{25}$) for NCG 4736 and at $r \sim 9'$ ($\sim 1.5 r_{25}$) for NGC 5055. However, these local peaks in $\sigma_{\text{H} \alpha}(r)$ and the streamers have different galactocentric locations, corresponding to $r \sim 8'$ and $r \sim 11'$ for NCG 4736 and NGC 5055, respectively. Therefore, we argue that the presence of extended streamers is not likely to be connected to higher H $\alpha$ velocity dispersion.

7. CONCLUSIONS

Combining high-quality maps of H $\alpha$ column density and line width provided by THINGS for a sample of dwarf and spiral galaxies, we obtain the following results.

1. The H $\alpha$ velocity dispersion, $\sigma_{\text{H} \alpha}$, declines uniformly as a function of galactocentric distance in all analyzed galaxies.
2. At $r_{25}$, the edge of the star-forming region, the H $\alpha$ velocity dispersion $\sigma(r_{25}) \simeq 10 \pm 2$ km s$^{-1}$, which is consistent with the mass-weighted median H $\alpha$ velocity dispersion $<\sigma>$.

These findings are independent of the dynamical mass of the galaxy and of their morphological type.

3. Within the radius of active star formation ($r \leq r_{25}$), the estimated SN rate and the corresponding energy input rate are sufficient to account for the bulk of observed kinetic energy of turbulence. For those galaxies of the sample with considerable H$_2$ gas, the SNe can well account for the combined H $\alpha$ and H$_2$ gas turbulence. In this region, the observed instantaneous kinetic energy of the H $\alpha$ gas is consistent with the balance between the energy input from the total number of SNe calculated from the observed SFR and the turbulent dissipation predicted by numerical models. The proportionality between gas $E_{\text{g}}$ and SN energy input rate derived from the SFR provides direct evidence that H $\alpha$ turbulence comes from SNe in regions of active SFR. The resulting SN feedback efficiencies are typically $\epsilon_{\text{SN}} \times (10^7 \text{ yr} / \tau_D) \approx 0.1$ at SFR levels $\Sigma_{\text{SFR}} > 10^{-9}$ $M_\odot$ yr$^{-1}$ pc$^{-2}$, with the dissipation timescale of turbulence $\tau_D \approx 10^7$ yr.

4. Within the star-forming disk ($r \leq r_{25}$), neither thermal broadening nor MRI can produce the observed H $\alpha$ velocity dispersion. At low SFR, $\Sigma_{\text{SFR}} < 10^{-9}$ $M_\odot$ yr$^{-1}$ pc$^{-2}$, corresponding to large radial distances ($r > r_{25}$), an additional mechanism driving the H $\alpha$ velocity dispersion is required to avoid SN efficiencies, $\epsilon_{\text{SN}} > 1$.

5. The thermal broadening of the spectral lines, associated to a temperature of $\sim 5000$ K, may be able to explain the observed $\sigma_{\text{H} \alpha} \sim 6$ km s$^{-1}$ in the outermost regions of H $\alpha$ disks in our sample galaxies, if the required UV radiation to maintain these temperatures is present. The energy input from MRI can account for the kinetic energy observed in regions of low SFR, $\Sigma_{\text{SFR}} < 10^{-9}$ $M_\odot$ yr$^{-1}$ pc$^{-2}$, at large galactocentric distances.

6. We cannot unambiguously separate the temperature of the warm and nonturbulent neutral medium from the effect of MRI stirring the ISM. Both mechanisms are equivalently plausible drivers of the H $\alpha$ velocity dispersion observed in the outer parts ($r > r_{25}$) of galaxy disks. We suggest that testing the H $\alpha$ line profiles of the gas against a bright background source could ultimately clarify whether the gas in regions of weak star formation is uniformly warm, or contains a cold, turbulent phase, presumably stirred by MRI. If the gas is actually turbulent, the gas kinetic energy for both high and low star-forming regions is consistent in all cases with realistic values of $\epsilon_{\text{SN}}$ and $\epsilon_{\text{MRI}}$ efficiencies, suggesting that the feedback provided by both SN explosions and MRI is sufficient to drive the bulk of the observed H $\alpha$ turbulence.

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