GEOMETRICALLY DERIVED TIMESCALES FOR STAR FORMATION IN SPIRAL GALAXIES

D. Tamburro¹, H.-W. Rix¹, F. Walter¹, E. Brinks², W. J. de Blok², R. C. Kennicutt⁴, and M.-M. Mac Low⁵,⁶

¹Max-Planck-Institut für Astronomie, Königstuhl 17, D-69117 Heidelberg, Germany; tamburro@mpia.de, rix@mpia.de, walter@mpia.de
²Centre for Astrophysics Research, University of Hertfordshire, College Lane, Hatfield AL10 9AB, UK; e.brinks@herts.ac.uk
³Department of Astronomy, University of Cape Town, Private Bag X3, Rondebosch 7701, South Africa; cedeblok@circinus.ast.uct.ac.za
⁴Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK; robk@ast.cam.ac.uk
⁵Department of Astrophysics, American Museum of Natural History, 79th Street and Central Park West, New York, NY 10024-5192, USA; mordecai@amnh.org

Received 2007 September 17; accepted 2008 July 4; published 2008 November 18

ABSTRACT

We estimate a characteristic timescale for star formation in the spiral arms of disk galaxies, going from atomic hydrogen (H I) to dust-enshrouded massive stars. Drawing on high-resolution H I data from The H I Nearby Galaxy Survey and 24 μm images from the Spitzer Infrared Nearby Galaxies Survey, we measure the average angular offset between the H I and 24 μm emissivity peaks as a function of radius, for a sample of 14 nearby disk galaxies. We model these offsets assuming an instantaneous kinematic pattern speed, Ωp, and a timescale, tH I→24 μm, for the characteristic time span between the dense H I phase and the formation of massive stars that heat the surrounding dust. Fitting for Ωp and tH I→24 μm, we find that the radial dependence of the observed angular offset (of the H I and 24 μm emission) is consistent with this simple prescription; the resulting corotation radii of the spiral patterns are typically R cor ≃ 2.7 R*, consistent with independent estimates. The resulting values of tH I→24 μm for the sample are in the range 1–4 Myr. We have explored the possible impact of non-circular gas motions on the estimate of tH I→24 μm and have found it to be substantially less than a factor of 2. This implies a short timescale for the most intense phase of the ensuing star formation in spiral arms, and implies that a considerable fraction of molecular clouds exist only for a few Myr before forming stars. However, our analysis does not preclude that some molecular clouds persist considerably longer. If much of the star formation in spiral arms occurs within this short interval tH I→24 μm, then star formation must be inefficient, in order to avoid the short-term depletion of the gas reservoir.

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

1. INTRODUCTION

Roberts (1969, hereafter R69) was the first to develop the scenario of spiral-arm-driven star formation in galaxy disks. In this picture a spiral density wave induces gravitational compression and shocks in the neutral hydrogen gas, which in turn leads to the collapse of (molecular) gas clouds that results in star formation. This work already pointed out the basic consequences for the relative geometry of the dense cold gas reservoir and the emergent young stars: when viewed from a reference frame that corotates with the density wave, the densest part of the atomic hydrogen (H I) lies at the shock (or just upstream from it), while the young stars lie downstream from the density wave. Using H I and Hα as the tracers of the cold gas and of the young stars, respectively, R69 found a qualitative support in the data available at the time. In this picture, the characteristic timescale for this sequence of events is reflected in the typical angular offset, at a given radius, between tracers of the different stages of spiral-arm-driven star formation.

While this qualitative picture has had continued popularity, quantitative tests of the importance of spiral density waves as star-formation trigger (Lin & Shu 1964) and of the timescales for the ensuing star formation have proven complicated. First, it has become increasingly clear that even in galaxies with grand-design spiral arms, about half of the star formation occurs in locations outside the spiral arms (Elmegreen & Elmegreen 1986). Second, stars form from molecular clouds (not directly from H I) and very young star clusters are dust ensheathed at first. Moreover, the actual physical mechanism that appears to control the rate and overall location of star formation in galaxies is the gravitational instability of the gas and existing stars (e.g., Li et al. 2005). Stars only form above a critical density (Martin & Kennicutt 2001) which is consistent with the predicted Toomre (1964) criterion for gravitational instability as generalized by Rafikov (2001). Although, in galaxies with prominent spiral structure local gas condensations are governed by magneto-rotational instabilities—spiral arms are regions of low shear where the transfer of angular momentum is carried out by magnetic fields (Kim & Ostriker 2002, 2006). Obtaining high-resolution, sensitive maps of all phases in this scenario (H I, molecular gas, dust-enshrouded young stars, unobscured young stars) has proven technically challenging.

If the star formation originates from direct collapse of gravitationally unstable gas, and if the rotation curve and approximate pattern speed of the spiral arms are known, the geometric test suggested by R69 provides a timescale for the end-to-end (from H I to young stars) process of star formation. Of course, there are other ways of estimating the timescales that characterize the evolutionary sequence of the interstellar medium (ISM), based on other physical arguments. However, other lines of reasoning have led to quite a wide range of varying lifetime estimates as discussed below.

Offsets between components such as CO and Hα emission in the disks of spiral galaxies have indeed been observed (Vogel et al. 1988; Garcia-Burillo et al. 1993; Rand & Kulkarni 1990; Scoville et al. 2001). Mouschovias et al. (2006) remarked that
the angular separation between the dust lanes and the peaks of 
Hα emission found for nearby spiral galaxies (e.g., observed by Roberts 1969; Rots 1975) implied timescales of the order of 10 Myr. More recently Egusa et al. (2004), using the angular offset between CO and Hα in nearby galaxies, derived \( t_{\text{CO} \rightarrow \text{Hα}} \approx 4.8 \) Myr.

Observationally, the H\( \text{I} \) surface density is found to correlate well with sites of star formation and emission from molecular clouds (Wong & Blitz 2002; Kennicutt 1998). The conversion timescale of H\( \text{I} \) \( \rightarrow \) H\( \alpha \) is a key issue since it determines how well the peaks of H\( \alpha \) emission can be considered as potential early stages of star formation. H\( \alpha \) molecules only form on dust grain surfaces in dusty regions that shield the molecules from ionizing UV photons. Their formation facilitates the subsequent building up of more complex molecules (e.g., Williams 2005). Within shielded clouds the conversion timescale \( \text{H} \text{I} \rightarrow \text{H} \alpha \) is given by \( \tau_{\text{H} \text{I}} \approx 10^6 / n_0 \) yr, where \( n_0 \) is the proton density in cm\(^{-3}\) (Hollenbach & Salpeter 1971; Jura 1975; Goldsmith & Li 2005; Goldsmith et al. 2007). Given the inverse proportionality with \( n_0 \), the conversion timescale can vary from the edge of a molecular cloud (\( \tau \approx 4 \times 10^5 \) yr, \( n_0 \approx 10^6 \)) to the central region (\( \tau \approx 10^5 \) yr, \( n_0 \approx 10^7 \)) where the density is higher. Local turbulent compression can further enhance the local density, and thus decrease the conversion timescale (Glover & Mac Low 2007). Thus, even short cloud-formation timescales remain consistent with the H\( \text{I} \) \( \rightarrow \) H\( \alpha \) conversion timescale.

The subsequent evolution (see, e.g., Beuther et al. 2007, for a review) involves the formation of cloud cores (initially starless) and then star cluster formation through accretion onto protostars, which finally become main sequence stars. High-mass stars evolve more rapidly than low-mass stars. Stars with \( M \geq 5 \; M_\odot \) reach the main sequence quickly, in less than 1 Myr (Hillenbrand et al. 1993; Palla & Stahler 1999), while they are still deeply embedded and actively accreting. The O and B stars begin to produce an intense UV flux that photoionizes the surrounding dust heated by UV and are therefore good indicators of recent star formation (Thronson & Telesco 1986).

A different scenario is suggested by Allen (2002), in which young stars in the disks of galaxies produce H\( \text{I} \) from their parent H\( \text{II} \) clouds by photodissociation. According to this scenario, the H\( \text{I} \) should not be seen furthest upstream in the spiral arm, but rather between the CO and UV/H\( \alpha \) regions. Allen et al. (1986) indeed report observation of H\( \text{I} \) downstream of dusty regions in M83.

Several lines of reasoning, however, point toward longer star-formation timescales and molecular cloud lifetimes, much greater than 10 Myr. Krumholz & McKee (2005) conclude that the star-formation rate in the solar neighborhood is low. In fact, they point out that the star-formation rate in the solar neighborhood is \( \sim 100 \) times smaller than the ratio of the masses of nearby molecular clouds to their free-fall time \( M_{\text{MC}} / \tau_{\text{ff}} \), which also indicates the rate of compression of molecular clouds. Individual dense molecular clouds have been argued to stay in a fully molecular state for about 10–15 Myr before their collapse (Tassis & Mouschovias 2004), and to transform about 30% of their mass into stars in \( \geq 7 \tau_{\text{ff}} \approx 10^8 \) yr, e.g., considering the mass of the Orion Nebula Cluster, ONC, Tan et al. (2006). Large molecular clouds have been calculated to survive 20–30 Myr before being destroyed by the stellar feedback by Krumholz et al. (2006). Based on observations, Pallà & Stahler (1999, 2000) argue that the star-formation rate in the ONC was low 10\(^9\) yr ago, and that it increased only recently. Blitz et al. (2007), using a statistical comparison of cluster ages in the Large Magellanic Cloud (LMC) to the presence of CO, found that the lifetime for giant molecular clouds is 20–30 Myr.

However, other studies conclude that the timescales for star formation are rather short. Hartmann (2003) pointed out that the Palla–Stahler model is not consistent with observations since most of the molecular clouds in the ONC are forming stars at the same high rate. The stellar age or the age spread in young open stellar clusters is not necessarily a useful constraint on the star-formation timescale: the age spread, for example, may result from independent and non-simultaneous bursts of star formation (Elmegreen 2000). Ballesteros-Paredes & Hartmann (2007) pointed out that the molecular cloud lifetime must be shorter than the value of \( \tau_{\text{MC}} \approx 10 \) Myr suggested by Mouschovias et al. (2006). Also subsequent star formation must proceed very quickly, within a few Myr (Vázquez-Semadeni et al. 2005; Hartmann et al. 2001). Prescott et al. (2007) found strong association between 24\( \mu \text{m} \) sources and optical H\( \alpha \) regions in nearby spiral galaxies. This provides constraints on the lifetimes of star-forming clouds: the break out time of the clouds and their parent clouds is less or at most of the same order as the lifetime of the H\( \alpha \) regions, therefore a few Myr. Dust and gas clouds must dissipate on a timescale no longer than 5–10 Myr.

In conclusion, all the previous studies listed aim to estimate the lifetimes of molecular clouds or the timescales separation between the compression of neutral gas and newly formed stars. Most of these studies are based on observations of star-forming regions both in the Milky Way and in external galaxies, and in all cases the derived timescales lie in a range between a few Myr and several tens of Myr.

In this paper, we examine a new method (Section 2) for estimating the timescale to proceed from H\( \text{I} \) compression to star formation in nearby spiral galaxies. We compare Spitzer Space Telescope/MIPS 24\( \mu \text{m} \) data from the Spitzer Near Infrared Galaxies Survey (SINGS; Kennicutt et al. 2003) to 21 cm maps from The H\( \alpha \) Nearby Galaxy Survey (THINGS; Walter et al. 2008). The proximity of our targets allows for high spatial resolution. In Section 3 we give a description of the data. The MIPS bands (24, 70, and 160\( \mu \text{m} \)) are tracers of warm dust heated by UV and are therefore good indicators of recent star-formation activity (see, for example, Dale et al. 2005). We used the band with the best resolution, 24\( \mu \text{m} \), which has been recognized as the best of the Spitzer bands for tracing star formation (Calzetti et al. 2005, 2007; Prescott et al. 2007); the 8\( \mu \text{m} \) Spitzer/IRAC band has even higher resolution but is contaminated by PAH features that undergo strong depletion in the presence of intense UV radiation (Dwek 2005; Smith et al. 2007). In Section 4 we describe how we use azimuthal cross-correlation to compare the H\( \alpha \) and 24\( \mu \text{m} \) images and derive the angular offset of the spiral pattern. This algorithmic approach minimizes possible biases introduced by subjective assessments. We describe our results in Section 5 where we derive \( t_{\text{H} \alpha \rightarrow 24 \mu \text{m}} \) for our selection of objects. Finally, we discuss the implications of our results in Section 6 and draw conclusions in Section 7.

2. METHODOLOGY

The main goal of this paper is to estimate geometrically the timescales for spiral-arm-driven star formation using a simple kinematic model, examining the R69 arguments in light of state-of-the-art data. Specifically, we set out to determine the relative geometry of two tracers for different stages of star-formation
sequence in a sample of nearby galaxies, drawing on the SINGS and THINGS data sets (see Section 3): the 24 μm and the H\textsubscript{I} emission.

While the angular offset between these two tracers is an empirical model-independent measurement, a conversion into a star-formation timescale assumes (a) that peaks of the H\textsubscript{I} trace material that is forming molecular clouds and (b) that the peaks of the 24 μm emission trace the very young, still dust-shrouded star clusters, where their UV emission is absorbed and re-radiated into the mid- to far-infrared wavelength range (~5 μm to ~500 μm). The choice of these particular tracers was motivated by the fact that they should tightly bracket the conversion process of molecular gas into young massive stars, and by the availability of high-quality data from the SINGS and THINGS surveys. Note that a number of imaging studies in the near-IR have shown (e.g., Rix & Zaritsky 1995) that the large majority of luminous disk galaxies have a coherent, dynamically relevant spiral arm density perturbation. Therefore, this overall line of reasoning can sensibly be applied to a sample of disk galaxies.

We consider a radius in the galaxy disk where the spiral pattern can be described by a kinematic pattern speed, \( \Omega_p \), and the local circular velocity \( v_c(r) \equiv \Omega(r) \times r \). Then two events separated by a time \( t_{24-\mu m} \) will have a phase offset of

\[
\Delta \phi(r) = (\Omega(r) - \Omega_p) t_{24-\mu m},
\]

where \( t_{24-\mu m} \) denotes the time difference between two particular phases that we will study here. If the spiral pattern of a galaxy indeed has a characteristic kinematic pattern speed, the angular offset between any set of tracers is expected to vary as a function of radius in a characteristic way. Considering the chronological sequence, defining the angular phase difference \( \Delta \phi \equiv \phi_{24\mu m} - \phi_{H\text{I}} \) and adopting the convention that \( \phi \) increases in the direction of rotation, we expect the qualitative radial dependence plotted in Figure 1: \( \Delta \phi > 0 \) where the galaxy rotates faster than the pattern speed, otherwise \( \Delta \phi < 0 \). Where \( \Omega(R_{\text{cm}}) = \Omega_p \), at the so-called corotation radius, we expect the sign of \( \Delta \phi \) to change.

In practice, the gaseous and stellar distribution is much more complex than in the qualitative example of Figure 1, since the whole spiral network, even for galaxies where the spiral arms are well defined such as in grand-design galaxies, typically exhibits a full wealth of smaller scale sub-structures both in the arms and in the inter-arm regions. The optimal method to measure the angular offset between the two observed patterns is therefore through cross-correlation (Section 4). We treat the timescale \( t_{24-\mu m} \) and the present-day pattern speed \( \Omega_p \) as global constants for each galaxy, although these two parameters might, in principle, vary as a function of galactocentric radius. Note that we need not rely on the assumption that the spiral structure is quasi-stationary over extended periods, \( t \geq t_{\text{dyn}} \). Even if spiral arms are quite dynamic, continuously forming and breaking, and with a pattern speed varying with radius, our analysis will hold approximately.

3. DATA

The present analysis is based on the 21 cm emission line maps, a tracer of the neutral atomic gas for the 14 disk galaxies listed in Table 1, which are taken from THINGS. These high-quality NRAO* Very Large Array observations provide data cubes with an angular resolution of \( \simeq 6'' \) and spectral resolution of 2.6 or 5.2 km s\(^{-1}\). Since the target galaxies are nearby, at distances of 3–10 Mpc, the linear resolution of the maps corresponds to 100–300 pc. The H\textsubscript{I} data cubes of our target galaxies are complemented with near-IR images, which are public data. In particular, the majority of the THINGS galaxies (including all those in Table 1) have also been observed within the framework of the SINGS and we make an extensive use of the 24 μm MIPS images (see Section 4.2). Figure 2 illustrates our data for two of the sample galaxies, NGC 5194 and NGC 2841. The 24 μm band image is shown in color scale, and the contours show the H\textsubscript{I} emission map. To obtain the exponential scale length of the stellar disk (see Section 4), we use 3.6 μm Infrared Array Camera (IRAC) images when available, otherwise we use H\textsuperscript{\star} band images taken from the Two Micron All Sky Survey (2MASS; Jarrett et al. 2003). To check the consistency of our results, we use CO maps from the Berkeley-Illinois-Maryland Association Survey of Nearby Galaxies (BIMA-SONG, Helfer et al. 2003) for some of our target galaxies.

4. ANALYSIS

All analysis in this paper started from fully reduced images and data cubes. On this data we carry out two main steps. First, we derive the rotation curve \( v_c(r) \) of the H\textsubscript{I} and the geometrical parameterization of the galaxy disk, and use these parameters to deproject the maps of the galaxies to face-on orientation (see Table 1). Second, we sample the face-on maps in concentric annuli. For each annulus we cross-correlate the corresponding pair of H\textsubscript{I} and 24 μm fluxes, in order to derive the angular offset between the H\textsubscript{I} and the 24 μm patterns as a function of radius.

For three of the galaxies listed in Table 1 (NGC 628, NGC 5194, and NGC 3627), we also measure the angular offset between the CO and 24 μm emission maps. If the ISM evolves sequentially from atomic into molecular gas, and then subsequently initiates the formation of stars, considering the kinematics expressed in Equation (1), we expect the CO emission to lie in between the H\textsubscript{I} and the 24 μm.

4.1. Analysis of the H\textsubscript{I} Kinematics

For each object we apply the same general approach: we first perform adaptive binning of the H\textsubscript{I} data cube regions with low signal-to-noise (S/N) ratio using the method described by Cappellari & Copin (2003). From the resulting spatially binned data cubes we fit the 21 cm emission lines with a single Gaussian profile and use the parameterization to derive (1) the line-of-sight velocity map \( v(x, y) \), given by the line centroid, and (2) the flux maps \( \mu_l(x, y) = a(x, y)/(\sqrt{2\pi} \sigma(x, y)) \), where \( a \) and \( \sigma \) are the Gaussian peak amplitude and width, respectively. Since we do not need to derive the rotation curve with high accuracy for the purpose of this paper, we limit our model to a co-planar rotating disk with circular orbits described by

\[
v(x, y) = v_{\text{sys}} + v_c(r) \sin i \cos \psi,
\]

where \( v(x, y) \) is the observed velocity map along the line of sight (see Begeman 1989). For simplicity, we assume here that the orbits are circular, though we address the issue of non-circular motions in Section 4.5. By \( \chi^2 \) minimization fitting\(^9\) of the model function in Equation (2) to the observed velocity map \( v(x, y)\),

\(^*\) The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

\(^9\) The fitting has been performed with the mpfit IDL routine found at the URL: http://cow.physics.wisc.edu/~craigm/idl/fitting.html
we obtain the systemic velocity $v_{sys} = \text{const}$, the inclination $i$ and the position angle (P.A.) of the geometric projection of the disk on to the sky. Here, $\psi$ is the azimuthal angle on the plane of the inclined disk (not the sky) and is a function of $i$ and P.A. The line where $\psi = 0$ denotes the orientation of the line of nodes on the receding side of the disk. The kinematic center $(x_0, y_0)$ is fixed a priori and is defined as the central peak of either the IRAC 3.6 $\mu$m or the 2MASS $H$ band image. The positions of the dynamical centers used here are consistent with those derived in Trachternach et al. (2008). We parameterize the deprojected rotation curve $v_c$ with a four-parameter arctan-like function (e.g., Rix et al. 1997)

$$v_c(r) = v_0(1 + x)^\gamma (1 + x^{-\gamma})^{-1/\gamma},$$

where $x = r/r_0$. Here, $r_0$ is the turn-over radius, $v_0$ is the scale velocity, $\gamma$ determines the sharpness of the turnover, and $\beta$ is the asymptotic slope at larger radii.

The values for the projection parameters $i$, and P.A., the systemic velocity $v_{sys}$, and the asymptotic velocity that have been obtained applying the approach described above, are consistent with the values reported in Table 1. From the maximum value of Equation (3) we obtain the maximum rotational velocity $v_{max}$, which is listed for all the sample galaxies in Table 1.

### 4.2. Azimuthal Cross-Correlation

The central analysis step is to calculate by what angle $\Delta \phi$ the patterns of H I and 24 $\mu$m need to be rotated with respect to each other in order to best match. We use the kinematically determined orientation parameters, $i$ and P.A., to deproject both the H I and 24 $\mu$m images to face-on. To estimate the angular separation between the two components is exaggerated and simplified for clarity. We measured the deprojected phase difference $\Delta \phi(r)$ between the H I and the 24 $\mu$m emission, with $\phi$ increasing in the direction of rotation. The sketch shows part of a face-on galaxy rotating anti-clockwise, with the center as indicated. The solid curved lines represent the two components within one spiral arm, namely the H I and the heated dust. The angular separation between the two components is exaggerated for clarity. We measured the deprojected phase difference $\Delta \phi(r)$ at a given radius. Inside corotation, $R_{cor}$, the material is rotating faster than the pattern speed and the 24 $\mu$m emission lies ahead of the H I ($\phi_{24\mu m} < \phi_{HI}$). At corotation the two patterns coincide, and outside $R_{cor}$ the picture is reversed since the pattern speed exceeds the rotation of the galaxy.

minimizing as a function of the phase shift $\ell$ (also defined as $lag$) the quantity

$$\chi^2_{x,y}(\ell) = \sum_k [x_k - y_{k-\ell}]^2,$$

where the sum is calculated over all the $N$ elements of $x$ and $y$ with $k = 0, 1, 2, \ldots, N - 1$. Specifically here, for a given radius $r = \hat{r}$ we consider for all discrete values of azimuth $\phi$:

$$x_k = f_{HI}(\phi_k | \hat{r})$$

and

$$y_{k-\ell} = f_{24\mu m}(\phi_{k-\ell} | \hat{r}).$$

Expanding the argument of the sum in Equation (4) one obtains that $\chi^2(\ell)$ is independent of the terms $\sum_k x_k^2$ and $\sum_k y_{k-\ell}^2$, and

### Table 1

| Obj. Name | Alt. Name | $R_{25}$ (') | $R_i$ (') | Band | $i$ (°) | P.A. (°) | $D$ (Mpc) | $v_{max}$ (km s$^{-1}$) |
|-----------|-----------|---------------|-----------|------|--------|----------|----------|-------------------|
| NGC 2403  |           | 9.98          | 1.30°     | $H$  | 63     | 124      | 3.22     | 128              |
| NGC 2841  |           | 3.88          | 0.92°     | $H$  | 74     | 153      | 14.1     | 331              |
| NGC 3031  | M81       | 10.94         | 3.63 ± 0.2| $H$  | 59     | 330      | 3.63     | 256              |
| NGC 3184  |           | 3.62          | 0.92 ± 0.09| $H$  | 16     | 179      | 11.1     | 260              |
| NGC 3351  |           | 3.54          | 0.86 ± 0.03| $H$  | 41     | 192      | 9.33     | 210              |
| NGC 3521  |           | 4.8           | 0.74 ± 0.02| $H$  | 73     | 340      | 10.05    | 242              |
| NGC 3621  |           | 5.24          | 0.80°     | $H$  | 65     | 345      | 6.64     | 144              |
| NGC 3627  | M66       | 4.46          | 0.95°     | $H$  | 62     | 173      | 9.25     | 204              |
| NGC 5055  | M63       | 6.01          | 1.16 ± 0.05| $H$  | 59     | 102      | 7.82     | 209              |
| NGC 5194  | M51       | 3.88          | 1.39 ± 0.11| $H$  | 42     | 172      | 7.77     | 242              |
| NGC 628   | M74       | 4.77          | 1.10 ± 0.09| $H$  | 7      | 20       | 7.3      | 220              |
| NGC 6946  |           | 5.35          | 1.73 ± 0.07| $H$  | 32.6   | 242      | 5.5      | 201              |
| NGC 7793  |           | 5.0           | 1.16 ± 0.05| $H$  | 50     | 290      | 3.82     | 109              |
| NGC 925   |           | 5.23          | 1.43°     | $H$  | 66     | 286      | 9.16     | 121              |

**Notes.** (1) Semi-major axis of the 25 mag arcsec$^{-2}$ isophote in the $B$ band obtained from the LEDA database (URL: http://leda.univ-lyon1.fr); (2) exponential scale length derived in this paper as described in Section 4 using either IRAF or galfit (values tagged with *), where the error bars are $\delta R/R < 1\%$; (3) image band used (2MASS H or IRAC 3.6 $\mu$m band) to derive $R_i$; (4) and (5) kinematic inclination and P.A., respectively; (6) adopted distance; (7) maximum amplitude of the rotation velocity corrected for inclination obtained from the rotation curve $v_c$ derived in Section 4.1. The values in Columns (4) to (6) are adopted from de Blok et al. (2008).
\[ \chi^2 \text{ is minimized by the maximization of} \]
\[ cc_{x,y}(\ell) = \sum_x [x_k y_{\ell-x}], \] (6)
which is defined as the CC coefficient. Here we used the normalized CC
\[ cc_{x,y}(\ell) = \frac{\sum_k [(x_k - \bar{x})(y_{k-\ell} - \bar{y})]}{\sqrt{\sum_k (x_k - \bar{x})^2 \sum_k (y_{k} - \bar{y})^2}} \] (7)
where \( \bar{x} \) and \( \bar{y} \) are the mean values of \( x \) and \( y \), respectively. Here, the slow, direct definition has been used and not the fast Fourier transform method. The vectors are wrapped around to ensure the completeness of the comparison. With this definition, the CC coefficient would have a maximum value of unity for the two patterns best match at zero azimuthal phase shift. The error bars for \( \delta\ell_{\text{max}} \) have been evaluated through a Monte Carlo approach, adding normally distributed noise and assuming the expectation values of \( \ell_{\text{max}} \) and \( \delta\ell_{\text{max}} \) as the mean value and the standard deviation, respectively, after repeating the determination \( N = 100 \) times.

Our analysis is limited to the radial range between low \( S/N \) regions at the galaxy centers and their outer edges. In the H\textsc{i} emission maps the \( S/N \) is low near the galaxy center, where the H\textsc{i} is converted to molecular H\textsubscript{2}, whereas for the 24 \( \mu \)m band the emission map has low \( S/N \) near \( R_{25} \) (and in most cases already at \( \sim 0.8 R_{25} \)). Regions with \( S/N < 3 \) in either the H\textsc{i} or 24 \( \mu \)m images have been clipped. We also ignore those points \( \ell_{\text{max}} \) with a coefficient \( cc(\ell_{\text{max}}) \) lower than a threshold \( cc \lesssim 0.2 \). We further neglect any azimuthal ring containing less than a few hundred points, which occurs near the image center and near \( R_{25} \). The resulting values \( \Delta \phi(r) \) are shown in Figure 4.

4.3. Disk Exponential Scale Length

We also determine the disk exponential scale length \( R_s \) for our sample using the galfit\textsuperscript{11} algorithm (Peng et al. 2002). In particular, we fit an exponential disk profile and a de Vaucouleurs profile to either the IRAC 3.6 \( \mu \)m or to the 2MASS \( H \) band image. As galfit underestimates the error on \( R_s \) (as recognized by the author of the algorithm), typically \( \delta R_s/R_s < 1\% \), we therefore also use the IRAF task ellipse (Jedrzejewski 1987) to derive the radial surface brightness profile and fit \( R_s \). After testing the procedure on a few objects, we note only small differences (of the order of the error bars) in Table 1 when deriving \( R_s \) from the \( H \) band and the 3.6 \( \mu \)m band.

5. RESULTS

5.1. Angular Offset

With the angular offset \( \Delta \phi(r) \equiv (\phi_{24\mu m} - \phi_{\text{H}i})(r) \), where \( \phi \) increases in the direction of rotation, and the rotation curve

\textsuperscript{11} http://www.python.org

\textsuperscript{11} http://zwicky.as.arizona.edu/~cyp/work/galfit/galfit.html
Figure 3. Representative examples for the determination of the azimuthal H\texttextsubscript{1}–24\mu m offset: shown is the cross-correlation \(cc(\ell)\) of the two functions \(f_{H_1}(\phi_i, \hat{r})\) and \(f_{24\mu m}^{\phi \omega_i}(\phi_i, \hat{r})\), as a function of azimuth offset \(\phi\) at a fixed radius \(\hat{r}\). The present example shows the \(cc(\Delta \phi)\) profile calculated for NGC 628 at \(\hat{r} \approx 2\) (\(\pm 4.2\) kpc) and NGC 5055 at \(\hat{r} \approx 2.6\) (\(\pm 6.4\) kpc), in the left and right columns, respectively. Top panel: the \(cc(\Delta \phi)\) profile in the entire range \([-180^\circ, 180^\circ]\); bottom panel: a zoom of the range \([-30^\circ, 30^\circ]\). We considered an adequate range greater than the width of the range \([-180^\circ, 180^\circ]\).}

\[v(r)\] for each radial bin, we can rewrite Equation (1) as

\[\Delta \phi(r) = \left(\frac{v(r)}{r} - \Omega_p\right) \times \tau_{H_1-24\mu m},\]

where \(\Omega(r) \equiv v(r)/r\). Since \(\Omega(r) > \Omega_p\) inside the corotation radius \(R_{cor}\), and \(\Omega(r) < \Omega_p\) outside corotation, we expect \(\Delta \phi(r) > 0\) for \(r < R_{cor}\) and \(\Delta \phi(r) < 0\) for \(r > R_{cor}\). At corotation, where \(\Delta \phi(R_{cor}) = 0\), the two components \(H_1\) and \(24\mu m\) should have no systematic offset. We assume \(\tau_{H_1-24\mu m}\) and \(\Omega_p\) to be constant for any given galaxy, and that all the spirals are trailing, since the only spiral galaxies known to have a leading pattern are NGC 3786, NGC 5426, and NGC 4622 (Thomasson et al. 1989; Byrd et al. 2002). By \(x^2\) fitting the model prediction of Equation (8) to the measured angular offsets \(\Delta \phi(r)\) in all radial bins of a galaxy, we derive best-fit values for \(\tau_{H_1-24\mu m}\) and \(\Omega_p\).

The \(\Delta \phi(r)\) data and the resulting best fits are shown in Figure 4, with the resulting best-fit values listed in Table 2. In Figure 4 we plot for all objects the radial profile of the angular offsets \(\Delta \phi(r)\). The solid line represents the best-fit model proscripted by Equation (8). The square symbols in the plot represent the fitted data points from Section 4.2. Looking at the ensemble results in Figure 4, two points are noteworthy: (1) the geometric offsets are small, typically a few degrees and did need high-resolution maps to become detectable, (2) the general radial dependence follows overall the simple prescription of Equation (8) quite well.

5.2. \(\tau_{H_1-24\mu m}\) and \(R_{cor}\)

Because \(\Delta \phi(r)\) is consistent with (and follows) the predictions of the simple geometry and kinematics in Equation (8), the procedure adopted here turns out to be an effective method to derive the following: (1) the time lag \(\tau_{H_1-24\mu m}\), which should bracket the timescale needed to compress the molecular gas, trigger star formation, and heat the dust; it therefore represents also an estimate for the lifetime of star-forming molecular clouds, (2) the kinematic pattern speed \(\Omega_p\) of the galaxy spiral pattern and, equivalently, the corotation radius \(R_{cor}\).

We now look at the ensemble properties of the resulting values for \(\tau_{H_1-24\mu m}\) and \(R_{cor}\). The scatter of the individually fitted \(\Delta \phi\) points is significantly larger than their error bars (as shown in Figure 4), which may be due to the galactic dynamics being more complex than our simple assumptions. For example, the pattern speed may not be constant over the entire disk or there may be multiple corotation radii and pattern speeds, as, for instance, found by numerical simulations (Sellwood & Sparke 1988) and observed in external galaxies (Hernández et al. 2005).

Even though a considerable intrinsic scatter characterizes \(\Delta \phi(r)\) for most of our sample galaxies, and the error bars of \(\tau_{H_1-24\mu m}\) listed in Table 2 are typically \(\gtrsim 15\%\), the histogram of the characteristic timescales \(\tau_{H_1-24\mu m}\) in Figure 5 shows overall a relatively small spread for a sample of 14 galaxies of different Hubble types: the timescales \(\tau_{H_1-24\mu m}\) occupy a range between 1 and 4 Myr for almost all the objects.

The solid curve in Figure 4, representing the prescription of Equation (8), intersects the horizontal axis at the corotation radius \(R_{cor}\), which can be formally derived by inverting Equation (8) at \(\Delta \phi = 0\). We report in Table 2 the ratio between \(R_{cor}\) and the exponential scale length \(R_e\) for each object and show this result in Figure 6. Comparisons of our pattern speed \(\Omega_p\) measurements with other methodologies (e.g., Tremaine & Weinberg 1984) are listed in Table 2. The differences with our results may arise since the Tremaine–Weinberg method assumes the continuity condition of the tracer, which may break down for the gas as it is easily shocked, it changes state, and it is converted into stars (Hernández et al. 2005; Rand & Wallin 2004), or it can be obscured by dust (Gerssen & Debattista 2007).
Figure 4. Radial profiles for the angular offset $H_1 \rightarrow 24 \mu m$ for the entire sample, obtained by sampling face-on $H_1$ and 24 $\mu m$ maps concentric rings and cross-correlating the azimuthal profiles for each radius. The solid line is the best-fit model to the observed data points, denoted by squared symbols, which has been obtained by $\chi^2$ minimization of Equation (8); the solid curve intersects the horizontal axis at corotation (defined as $\Delta \phi = 0$). The solid and dashed vertical lines indicate the 2.7 $R_\odot \simeq R_{cor}$ value and error bars, derived by Kranz et al. (2003).

Table 2
Characteristic Timescales $t_{H_1 \rightarrow 24 \mu m}$ and Pattern Speed $\Omega_p$ Resulting from a $\chi^2$ fit of the Observed Angular Offset via Equation (1)

| Obj. Name | Alt. Name | $t_{H_1 \rightarrow 24 \mu m}$ (Myr) | $\Omega_p$ (km s$^{-1}$ kpc$^{-1}$) | $R_{cor}/R_\odot$ | $\Omega_p$ (km s$^{-1}$ kpc$^{-1}$) |
|-----------|-----------|---------------------------------|-------------------------------|------------------|---------------------------------|
| NGC 2403  |           | 1.4 ± 0.5                       | 30 ± 4                        | 2.8 ± 0.3        |                                 |
| NGC 2841  |           | 4.4 ± 0.5                       | 42 ± 2                        | 2.8 ± 0.1        |                                 |
| NGC 3031  | M81       | 0.5 ± 0.3$^{\dagger}$           | 27 ± 13$^{\dagger}$           | 2.3 ± 1.4        | 24$^a$                          |
| NGC 3184  |           | 1.8 ± 0.4                       | 38 ± 5                        | 2.3 ± 0.5        |                                 |
| NGC 3351  | M95       | 2.2 ± 0.3                       | 38 ± 3                        | 2.3 ± 0.4        |                                 |
| NGC 3521  |           | 2.9 ± 0.4                       | 32 ± 2                        | 3.6 ± 0.2        |                                 |
| NGC 3621  |           | 2.3 ± 1.3$^{\dagger}$           | 31 ± 11$^{\dagger}$           | 2.8 ± 1.0        |                                 |
| NGC 3627  | M66       | 3.1 ± 0.4                       | 25 ± 4                        | 3.0 ± 0.5        |                                 |
| NGC 5055  | M63       | 1.3 ± 0.3                       | 20 ± 5                        | 3.8 ± 1.5        | 30–40$^b$                       |
| NGC 5194  | M51       | 3.4 ± 0.8                       | 21 ± 4                        | 1.5 ± 0.6        | 38 ± 7$^c$, 40 ± 8$^d$          |
| NGC 6268  | M74       | 1.5 ± 0.5                       | 26 ± 3                        | 2.2 ± 0.4        | 32 ± 2$^e$                      |
| NGC 6946  |           | 1.3 ± 0.3$^{\dagger}$           | 36 ± 4$^{\dagger}$           | 1.7 ± 0.4        | 39 ± 9$^e$, 42 ± 6$^d$          |
| NGC 7793  |           | 1.2 ± 0.5$^{\dagger}$           | 40 ± 10$^{\dagger}$          | 2.5 ± 0.9        |                                 |
| NGC 925   |           | 5.7 ± 1.6                       | 11 ± 1.0                      | 2.1 ± 0.2        | 7.7$^f$                        |

Notes. The error bars are evaluated via a Monte Carlo method. The timescales $t_{H_1 \rightarrow 24 \mu m}$ listed in this table are summarized in the histogram in Figure 5. The corotation radius to exponential scale radius $R_{cor}/R_\odot$ ratios are summarized in Figure 6. We list for comparison in the last column other measurements of the pattern speed:
(a) Westpfahl (1991); (b) Thornley & Mundy (1997); (c) Zimmer et al. (2004); (d) Hernández et al. (2004); (e) Sakhibov & Smirnov (2004); (f) Elmegreen et al. (1998). Addressing to the discussion on pattern speeds in Section 6.2, we tag as bad fit those galaxies (indicated with the $\dagger$ symbol) where the fit is not reliable.
timescales range between 1 and 4 Myr for almost all galaxies.

Comparison of the observed non-axisymmetric motions with hydrodynamical models based on the actual stellar mass distribution (Kranz et al. 2003) have found a characteristic value of $R_{\text{cor}}/R_e = 2.7 \pm 0.4$ value found by Kranz et al. (2003). The galaxies in the plot are sorted by asymptotic rotation velocity (see Table 1), giving no indication of a correlation between dynamical mass and the $R_{\text{cor}}/R_e$ ratio.

5.3. Comparison With CO Data

If the basic picture outlined in the introduction is correct, then the molecular gas traced by the CO, as an intermediate step in the star-formation sequence, should lie in between and have a smaller offset from the H I than the 24 $\mu$m does, but in the same direction. To check this qualitatively, we retrieve the BIMA-SONG CO maps (Helfer et al. 2003) for the galaxies NGC 628, NGC 5194, and NGC 3627. For comparison, we derive the angular offset between the CO emission and the H I, and CO $\mu$ (triangles) for the galaxies NGC 628, NGC 5194, and NGC 3627. CO maps are taken from the BIMA-SONG survey. The solid vertical line in each panel indicates the position of corotation as obtained by $\chi^2$ fitting of Equation (1) for the H I. These results are qualitatively consistent with a temporal star-formation sequence H I $\leftrightarrow$ CO $\leftrightarrow$ 24 $\mu$m.

Figure 7. Comparison of the angular offsets obtained for H I $\leftrightarrow$ 24 $\mu$m (squares) and CO $\leftrightarrow$ 24 $\mu$m (triangles) for the galaxies NGC 628, NGC 5194, and NGC 3627. CO maps are taken from the BIMA-SONG survey. The solid vertical line in each panel indicates the position of corotation as obtained by $\chi^2$ fitting of Equation (1) for the H I. These results are qualitatively consistent with a temporal star-formation sequence H I $\leftrightarrow$ CO $\leftrightarrow$ 24 $\mu$m.

5.4. Analysis of Non-Circular Motions

So far we have carried out an analysis that is based on the assumption of circular motions. We quantify here non-circular motions and determine to what extent their presence affects the estimate of the timescales $t_{\text{HI} \rightarrow 24 \mu m}$, which scale with $\Delta \phi$. In the classic picture (e.g., R69), the radial velocity of the gas is reversed around the spiral shock, so that the material is at nearly the same galactocentric radius before and after the shock. Gas in galaxies with dynamically important spiral arms does not move on circular orbits, though. Shocks and streaming motions transport gas inwards, and gas orbits undergo strong variations of the error bars, make estimates of $I_{\text{CO} \rightarrow 24 \mu m}$ and $R_{\text{cor}}$ rather uncertain. Therefore, we simply focus on $\Delta \phi_{\text{HI} \rightarrow 24(r)}$ versus $\Delta \phi_{\text{HI} \rightarrow 24(r)}$, which is shown in Figure 7. This figure shows that the values of $\Delta \phi_{\text{CO} \rightarrow 24}$ all lie closer to zero than the values of $\Delta \phi_{\text{HI} \rightarrow 24}$.

Hence this check shows that the peak location of the molecular gas is consistent with the evolutionary sequence where the H I represents an earlier phase than the CO. In this picture the H I has a larger spatial separation with respect to the hot dust emission, except at corotation, where the three components are expected to coincide. However, it is clear that higher sensitivity CO maps are needed to improve this kind of analysis.
we actually estimate in our data analysis, and which is shorter than the actual line spiral pattern, the two horizontal lines denoted with \( \triangle \phi \) and \( \triangle \phi' \), it implies that in the rest frame of the spiral arm, the change in the velocity components of the gas in the arm frame, respectively, that if the radial and tangential components of the gas velocity, and the pitch angle of the \( \text{H I} \) spiral arms are known, the actual value of \( \Delta \phi \) can be calculated by applying the correction factor

\[
k(r) \equiv \frac{\cos \beta}{\cos(\beta + \alpha)}
\]

(12)
to the directly measured quantity \( \Delta \phi' \). Note from Figure 8 that if \( \alpha \to 90\degree \), then \( k(r) \to \infty \), but in this case also \( \Delta \phi' \to 0 \), resulting in a finite value for \( \Delta \phi \) through Equation (9), and for the timescale, since \( t_{\text{H I} \sim 24 \mu m} \propto \Delta \phi \).

5.4.1. Methodology

In these circumstances, if spiral arms in galaxies are dynamically affecting the gas kinematics, then it is sensible to test the effects of non-circular motions especially in strong arm spiral galaxies from our sample. We select, NGC 5194 (M51), NGC 628, and NGC 6946. Therefore we examine the extreme case, calculating along a narrow region along spiral arms how much the streaming motions affect our angular offset measurements, thus the derivation of the timescales \( t_{\text{H I} \sim 24 \mu m} \). Subsequently, we generalize the procedure accordingly with our specific methodology by averaging these effects over the product of \( \text{H I} \times 24 \mu m \) fluxes, which is the weighting function of the cross-correlation.

The radial and tangential velocity components are difficult to separate unambiguously. The radial component is accurately measured along the minor axis, while however information on the azimuthal component are lost. The opposite occurs along the major axis. Therefore, we follow the prescriptions for non-circular streaming motions analysis from Section 3 of S07, to separate the velocity components \( v_R \) and \( v_\phi \) from the observed \( \text{H I} \) velocity field \( v_{\text{obs}} \), adopting

\[
v_{\text{obs}}(R, \phi) = v_{\text{sys}} + (v_R(R, \phi) \sin \phi + v_\phi(R, \phi) \cos \phi) \sin i
\]

(13)
as a generalization of Equation (2). Knowing \( v_R \) and \( v_\phi \), we then obtain the geometry of the orbits using Equations (10) and (11). Specifically, the \( \text{H I} \) column density and velocity map are deprojected and resampled into a polar coordinate system \((R, \phi)\) for simplicity, so that the azimuthal phase of the spiral arms can be described by a logarithmic spiral \( \psi = \phi_{\text{arm}} - \theta_0 = \ln(R_{\text{arm}}/R_0) \), for a given fiducial radius \( R_0 \). We extract the observed velocity \( v_{\text{obs}} \), along logarithmic lines as illustrated in Figure 9, which best represent the arm phase. Though these logarithmic lines are drawn by eye, on top of the spiral arms, we obtain reasonable results, e.g., for the case of NGC 5194 we find a logarithmic slope of 26\degree, similar to the 21\degree found by S07. Assuming \( v_R \) and \( v_\phi \) to be constant along equal arm phases, we fit Equation (13) to the observed velocities extracted at each arm phase \( \psi \in [\phi_{\text{arm}}, \phi_{\text{arm}} + 2\pi] \). The fitting gives \( v_R \) and \( v_\phi \) as a function of \( \psi \) and therefore as a function of radius through Equation (11) (see also S07). Provided the angles \( \alpha \) and \( \beta \) from Equations (10) and (11), we straightforwardly calculate the actual value of the angular offset \( \Delta \phi \) given \( \Delta \phi' \) from circular orbits assumption using Equations (9) and (12).
In particular, for NGC 5194, where $\mu_24=\phi_{\text{obs}} - \phi_0 = \ln(R_{\text{arm}}/R_0)$ where the observed velocity $v_{\text{obs}}$ is extracted in order to be fitted to Equation (13) and obtain the $v_R$ and $v_\phi$ velocity components (see Section 5.4). The top and bottom panels represent the projection into a polar coordinates system $(R, \phi)$ of the observed H I line-of-sight velocity field and the H I column density map, respectively, for the galaxy NGC 5194. The solid lines represent logarithmic spiral arms with phases $\psi = \phi_{\text{arm}}$ and $\psi = \phi_{\text{arm}} \pm 180^\circ$. In the top panel, the gray scale image of the velocity field indicates velocity values from $-90$ km s$^{-1}$ (dark) to $+90$ km s$^{-1}$ (light). The velocity map in figure is not deprojected for inclination effects, which are instead taken into account in Equation (13). The coordinate $\phi = 0$ represents the kinematic position angle of the galaxy.

Consistently with Gómez & Cox (2002) and S07, we find in the three considered galaxies that the locations of the spiral arms coincide with a net drop-off of the tangential velocity and negative radial velocity, possibly indicating that near the arms the orbits bend inwards. We then calculate, using Equation (12), the correction $k(r)$ at the position of the arms, indicated in Figure 9, where we expect the largest variations for $v_R$ and $v_\phi$. Even so, we find for the three considered galaxies that $k(r)$ results near unity for all radii, except where $v_\phi$ approaches zero, which does not necessarily coincide with corotation, but rather where the division in Equation (10) diverges and the error bars are large. In particular, for NGC 5194, where $|\alpha| < 20^\circ$ for all $r$, the correction $k(r)$ ranges between 0.7 and 1.2, and for both NGC 628 and NGC 6946 $k(r)$ ranges between 0.9 and 1.5, as indicated in Figure 10. After calculating the corrected offsets $\Delta \phi$ from Equation (9), and fitting Equation (8) to the values $\Delta \phi$, we find that the timescale $t_{H I-24 \mu m}$ and the pattern speed $\Omega_p$ do not change significantly—the differences are below the error bars for the three galaxies. Note that the data points where $v_\phi = 0$, that is where Equation (10) diverges, are not excluded from the fit. The results of these fits are listed in Table 3 and plotted in Figure 10. We also find that the radial displacements,

$$dr \simeq r \tan[\Delta \phi'(r)][k(r) \sin(\alpha(r))],$$

are typically as small compared to the radial steps of $\Delta \phi'$, i.e. $|dr| < 70$ pc for all $r$ for NGC 5194. In Section 4.2 we calculated $\Delta \phi'$ through Equation (7), hence not only within the spiral arms, but also as intensity-weighted mean across all the azimuthal values. If we were to calculate the angle-averaged value $\Delta \phi'$ from the average $\langle v_R \rangle$ and $\langle v_\phi \rangle$ weighted by the product $H I \times 24 \mu m$, which is the weighting function of the cross-correlation, we find $\alpha \simeq 0$ for all radii and a correction $k(r)$ even closer to unity than over a region limited to the arms. With this approach we obtain $0.95 < k(r) < 1.05$ for NGC 5194.

After exploring the two extreme cases, (1) simple model of circular orbits and (2) streaming motions near spiral arms for galaxies with prominent spiral structure—where these effect are supposed to be the largest—we find that the implied timescales $t_{H I-24 \mu m}$ do not vary significantly. By estimating the streaming motions in three galaxies from our data set, we find that the correction $k(r)$ which we must apply to the angular offset measurements in the scheme of circular orbits is generally near unity. Non-circular motions do not greatly affect the offset measurements $\Delta \phi$ for the galaxies with the most prominent spiral arms of our data set, where we expect indeed the highest deviations from circular orbits, suggesting that, since $t_{H I-24 \mu m} \propto \Delta \phi$, the timescales $t_{H I-24 \mu m}$ will not vary by more than a factor of 1.5.

However, these conclusions should be viewed cautiously, since (1) we are assuming that $v_R$ and $v_\phi$ can be obtained by fitting Equation (13), and (2) we do not account for beam effects. While the presence of non-circular motions produces apparent radial variations of inclination and position angle, our estimates are suggesting that these effects do not influence much the determination of the timescales. Yet, tidal interactions could ensure physical variations of inclination and position angle, thus of the actual geometry of the observed velocities. Although we note that among the sample galaxies only NGC 3031 (M81),

| Obj. Name | Alt. Name | $t_{H I-24 \mu m}$ (Myr) | $\Omega_p$ (km s$^{-1}$ kpc$^{-1}$) |
|-----------|-----------|--------------------------|----------------------------------|
| NGC 5194  | M51       | $3.3 \pm 0.6$            | $20 \pm 3$                       |
| NGC 628   | M74       | $1.4 \pm 0.5$            | $26 \pm 3$                       |
| NGC 6946  |           | $1.1 \pm 0.3$            | $36 \pm 4$                       |

**Notes.** The best fits and the corrections are plotted in Figure 10. In comparison with the values listed in Table 2, $t_{H I-24 \mu m}$ and $\Omega_p$ differ by less than their corresponding error bars.
NGC 3627, NGC 5055, and NGC 5194 are affected by tidal interaction. Moreover, we do not consider extra-planar motions due to the implied numerical difficulties. For instance, to include a vertical velocity component \( v_z \) into Equation (13) would introduce a degeneracy while fitting \( v_R, v_\phi, \) and \( v_z \), and a degeneracy in the geometry of the motions, rendering the estimates of the timescales uncertain. However, after subtracting a circular orbit model from the observed velocity field of the galaxy NGC 3184, an inspection of the velocity residuals reveals deviations from circular motions of \( \sim 5-10 \) km s\(^{-1}\) amplitude, and about zero near the spiral arms. Considering that NGC 3184 is nearly face-on (\( i = 16^\circ \)), then vertical motions should not exceed 5–10 km s\(^{-1}\). The beam deconvolution, on the other hand, would enlarge the uncertainties on separating \( v_R \) and \( v_\phi \), but we rely on a resolution size limit which is far below the typical thickness of a spiral arm and allows us to resolve fine sub-structures within the arms. We also rely on a large number of data points—several hundred to several thousand depending on the galactocentric radius.

Figure 10. Correction factor \( k(r) \) from Equation (12), as applied to the angular offset measurement for the galaxies NGC 5194, NGC 628, and NGC 6946. Bottom panels: the solid curve represents the correction factor \( k(r) = \cos \beta / \cos(\beta + \alpha) \) as a function of radius. Top panels: the squares denote the angular offset measurements \( \Delta \phi \) of Figure 4 calculated assuming circular orbits, the circles denote \( \Delta \phi \) after correction, and the solid curve represents the model fit of Equation (8) to the corrected offset values.

NGC 3627, NGC 5055, and NGC 5194 introduce a degeneracy while fitting \( \beta/\alpha \) due to the implied numerical difficulties. For instance, to include vertical motions due to the implied numerical difficulties. Moreover, we do not consider extra-planar motions.

6. DISCUSSION

By analyzing the angular offsets between H\( \alpha \) and 24 \( \mu m \) in the context of a simple kinematic model, we found short timescales, as summarized in the histogram of Figure 5 and in Table 2. The implied characteristic timescales for almost all sample galaxies lie in the range 1–4 Myr. This result sets an upper limit to the timescale for massive star formation under these circumstances, since we are observing the time lag between two phases: (a) the atomic gas phase, which subsequently is compressed into molecular clouds and forms clusters of young, embedded, massive stars, and (b) the warm dust phase, produced by heating from young stars, whose UV radiation is reprocessed by the dust into the mid-infrared, as observed at 24 \( \mu m \). For the few objects where there are suitable CO data, we checked that this geometric picture also holds for the molecular phase.

6.1. Timescales Derived from Pattern Offsets

Egusa et al. (2004) used the same angular offset technique to compare CO and H\( \alpha \) emission. They report timescales \( t_{\text{CO-H} \alpha} \sim 4.8 \) Myr for the galaxy NGC 4254 (not in our sample). The H\( \alpha \) traces a later evolutionary stage than the warm dust emission, which can indicate the presence of a young cluster still enshrouded by dust. Therefore, the H\( \alpha \) and the dust emission are expected to be separated by the time needed to remove the dusty envelope, though they are observed to be spatially well correlated (Wong & Blitz 2002; Kennicutt 1998). Prescott et al. (2007) found a strong association between 24 \( \mu m \) sources and optical H\( \text{II} \) regions in SINGS galaxies. Also infrared sources located on top of older, UV-bright, clusters that do not have H\( \alpha \) emission are rare. Since Prescott et al. (2007) suggest that the break out time from dust clouds is short (\( \sim 1 \) Myr), we do not expect a strong offset. Egusa et al. (2004) derived the angular offset by subjective assessment of the separation of the intensity peaks. They report that this may be a source of systematic errors, since they cannot detect by eye, the angular phase differences less than a certain threshold and in turn, their results would possibly be an upper limit. Given these considerations, the timescales derived in this paper are likely consistent with the conclusions of Egusa et al. (2004).

Rots (1975) and Garcia-Burillo et al. (1993) found time lags of \( \sim 10 \) Myr for M81 and M51, respectively. In particular, Rots applied the angular offset method to the dust lanes and H\( \alpha \). This may be in part problematic since the dust absorption in the optical bands only traces the presence of dust and it is unrelated to the warm dust emission due to star-formation onset. Garcia-Burillo et al. measured the spatial separation projected on the sky between CO and H\( \alpha \) and not the azimuthal offset.

Allen (2002) has argued that H\( \text{II} \) is a photodissociation product of UV shining on molecular gas, so it should be seen between the CO and UV/H\( \alpha \) regions. Allen et al. (1986) observed H\( \text{II} \) between spiral arm dust lanes and H\( \text{II} \) regions. However, Elmegreen (2007) points out that there is no time delay between dust lanes and star formation: dust lanes may only represent a heavy visual extinction effect and may not be connected to star-formation onset. Our finding that CO is situated between H\( \text{I} \) and hot dust (i.e., Figure 7) stands in conflict with the predictions of the model proposed by Allen (2002).

The evolutionary timescales of the ISM phases, especially for star formation, are not well constrained. The observational results of the last few decades, arrive at different and, in some cases, controversial conclusions. The discrepancies might in part...
be attributed to effects of limited resolution (see Section 6.3). This suggests that higher resolution and sensitivity maps, especially for the CO emission, are needed to improve the presented technique in the future.

6.1.1. Photodissociation of H$_2$

We argue that illumination effects of UV radiation shining on molecular and dusty regions cannot photodissociate molecules in order to produce the observed peaks of H$_\text{i}$—which correspond to typical surface densities of several solar masses per pc$^2$. First, the mean free path of the UV photons is remarkably short, typically $\sim$100 pc. The presence of dust, particularly abundant in disk galaxies, is the main source of extinction in particular within spiral arms, where we observe the peak of dust emission. Second, none of the galaxies from our data set presents prominent nuclear activity, whose UV flux could ionize preferentially the inner surfaces of the molecular clouds. Also, we exclude that UV radiation from young stellar concentrations can ionize preferentially one side of the clouds causing H$_\text{i}$ and CO emissions to lie offset with respect to each other, which we instead interpret as due to an evolutionary sequence. In fact, if the light from young stars effectively produces H$_\text{i}$ by photodissociation of H$_2$, then the neutral to molecular gas fraction is expected to increase with star-formation rate per unit area, $\Sigma_{\text{SFR}}$, as a consequence of the increasing UV radiation flux. Yet, the H$_\text{i}$ to H$_2$ ratio decreases with increasing $\Sigma_{\text{SFR}}$, as also shown, for example, in Kennicutt et al. (2007) for the galaxy M51. Moreover, the H$_\text{i}$ density does not vary much as a function of $\Sigma_{\text{SFR}}$ (Kennicutt 1998).

6.2. Pattern Speeds

The results of the fits in Figure 4 are consistent with the existence of a kinematic pattern speed for the considered galaxies, and are suggesting that the spiral pattern must be metastable at least over a few Myr or, strictly speaking, quasi-stationary. If the apparent spiral structure seen in young stars were produced by stochastic self-propagating star formation (e.g., Gerola & Seiden 1978; Seiden & Gerola 1982) and shear, without an underlying coherent mass perturbation, then presumably we would not observe the systematic radial variation of the offsets, seen in Figure 4, in particular not that the offset changes sign at $R \approx 2-3 R_{\text{sp}}$. Our results, however, do not exclude the stochastic star-formation mechanism to occur, rather that this is not the dominant trigger of star formation. The spiral pattern might be the manifestation of full wealth of modes of propagating density waves, which are continuously forming and dissolving gas clouds and structures, where, i.e. the azimuthal modes for a grand-design spiral are dominant at low orders (e.g., $m = 2, 3, 4$). If the spiral structure is quasi-stationary, then it can be characterized by an instantaneous pattern speed to first order—at least over a timescale much shorter than the orbital time. This is opposed to density waves dynamically driven by bars or interaction with companions, which could last a few orbital times. Note, however, that our analysis holds approximately in both possible cases.

Some of the fits in Figure 4 do not accurately mirror the trend of the observed data points, where the scatter is so large that it renders the interpretation problematic. In particular, we could designate as a bad fit the results for the galaxies NGC 3031, NGC 3621, NGC 7793, and NGC 6946 (Table 2). We also note that the pattern speed obtained in this paper for the galaxies NGC 5055 and NGC 5194 disagree with previous independent measurements (e.g., Thornley & Mundy 1997; Zimmer et al. 2004). The fit for NGC 5055 presents large error bars due to the large scatter in the azimuthal offsets (see Figure 4), which may explain the differences. For NGC 5194 the large difference between our result and the Tremaine–Weinberg method prediction could be due, as mentioned in Section 5.2, to the assumption of continuity for the gas. In fact, Zimmer et al. (2004) find a pattern speed $\Omega_p \approx 38 \text{ km s}^{-1}\text{kpc}^{-1}$ that is much faster than the pattern speed predicted by the hydrodynamical models from Kranz et al. (2003), $\Omega_p \approx 12 \text{ km s}^{-1}\text{kpc}^{-1}$, using $R_{\text{corr}} \approx 2.7 R_\text{s}$ and $R_s \approx 1.4$. Moreover, the presence of large variations of the azimuthal offsets as a function of radius with respect to the smoother fitted curves of Figure 4 suggests that the pattern speed may not be constant over the entire disk. Instead, the spiral pattern could be described by more than one pattern speed, implying that the delay time is not exactly the same in all parts of an individual galaxy, and not necessarily the same in all the considered galaxies. However, the offsets measurements and the implied pattern speeds and timescales could be statistically pointing toward regions of high H$_\text{i}$ and 24 $\mu$m fluxes when using the weighting of Equation (7), therefore toward high $\Sigma_{\text{SFR}}$, ensuring the timescales to be comparable in all cases.

6.3. Is Star Formation Triggered by Spiral Waves?

Addressing to our results (Section 5 and Figure 4), a further aspect emerging from our analysis concerns the same general behavior displayed by an heterogeneous sample of galaxies going from grand-design (e.g., NGC 5194) to flocculent morphologies (e.g., NGC 2841 and NGC 5055, see also Figure 3 for an example comparison). Visual examination of the infrared band images for our sample galaxies (e.g., at 3.6 $\mu$m) indicates that almost all have two-arm or multi-arm coherent spiral arms; for none of these galaxies the spiral structure is so chaotic as to be characterized as flocculent. Moreover, both types of galaxies from our sample display comparable integrated star-formation rates. Grand-design density waves are not likely to be the primary trigger of star formation, since a substantial portion of stars are also formed in the inter-arm regions (Elmegreen & Elmegreen 1986). The concentration of young stellar populations near prominent spiral arms is rather an effect of kinematics (Roberts 1969). Grand-design and flocculent galaxies exhibit the same intrinsic self-similar geometry (Elmegreen et al. 2003). The difference between these two types of galaxies is only dictated by a different distribution of azimuthal modes. Large scales structures (low-order modes) are the dominant features in grand design. However, the short timescales suggest that the physical scales where star formation occurs are rather small, since this time delay cannot exceed the free-fall time. Weak density waves, those described by high-order azimuthal modes, not necessarily grand-design modes, are likely to facilitate the growth of super-critical structures which end in star-forming events. In galaxies morphologically classified as flocculent and grand design, the mechanism that triggers star formation must be the same—gravitational instability. Direct compression of gas clouds is indeed able to locally trigger star formation.

The sizes of the structures of active star formation, however, are not representative of the timescales involved. Star-forming regions are organized hierarchically according to the small-scale turbulent motions of gas and stars, where the dynamical time varies as a function of the local scale sizes (Efremov & Elmegreen 1998; Ballesteros-Paredes et al. 1999). The improved accuracy of recent observational techniques, e.g., THINGS and SINGS, allows us to observe smaller and smaller structures, which evolve thus more rapidly and are characterized by shorter
timescales. Stellar activity and turbulence limit the lifetime of molecular clouds by causing the destruction of the parent cloud and the cloud dispersal, respectively. This lifetime, typically 10–20 Myr, drops by a factor of ~10 for the star-forming clouds. Moreover, star formation begins at high rate in only a few Myr, appearing in large structures of O-B complexes—beads on a string—of few hundred pc scales, and remaining active for ~30–50 Myr, but with a gradually decreasing star-forming rate, until the complete quenching (Elmegreen 2007). The timescales measured here refer to the very initial phase of star formation, specifically when star-formation rate is the highest—traced by 24 µm peak emission. The time delay $t_{24\, \mu m} > 100$ Myr needs not to represent the average time difference between these two phases, especially if there is a gradually declining tail of star-formation activity, taking longer than $t_{H_\text{II}} = 24\, \mu m$. If much of the star formation were actually occurring within our short $t_{24\, \mu m}$ estimate, then star formation would have to be inefficient to avoid conflicts with the short-term depletion of the gas reservoir.

6.4. Can We Rule Out Timescales of 10 Myr?

Since the 24 µm emission traces the mass-weighted star-formation activity, the timescale $t_{24\, \mu m}$ measures the time for star clusters to form from H I gas, but it does not show that all molecular clouds live only ~2 Myr. It might show that the bulk of massive stars that form in disks has emerged from molecular clouds that only lived ~2 Myr, though there could still be molecular clouds that live an order of magnitude longer. The full molecular cloud lifetimes estimated for the LMC correspond to ~10 Myr (Mizuno et al. 2001; Yamaguchi et al. 2001), while star clusters are formed from molecular clouds in only few Myr. Yet, more recent observations suggest much slower evolution. In particular, Blitz et al. (2007) propose molecular cloud lifetimes for the LMC as long as 20–30 Myr. In the Milky Way this timescale is estimated to be a few Myr (e.g., Hartmann et al. 2001), but the examined cloud complexes, such as Taurus and Ophiuchus, have low star-formation rate and masses more than an order of magnitude lower than those studied by Blitz et al. (2007). Thus, it remains possible that our results and these previous arguments are all consistent. At high density star formation also occurs at higher rate. Blitz et al. (2007) also find that the timescales for the emergence of the first H II regions traced by Hα in molecular clouds is $t_{H_\text{II}} \approx 7$ Myr, which does not exclude that $t_{H_\text{II}} > t_{H_\text{II}} = 24\, \mu m$, but it could be problematic with the short break out suggested by Prescott et al. (2007), since the time delay which is required between the onset of star formation (as traced by 24 µm) from obscured H II regions) and the emergence of Hα emission would need to be large.

In conclusion, we note that the timescale $t_{H_\text{II}} = 24\, \mu m$ results from a $\chi^2$ fit to all the data, and it is treated as a global constant individually for each galaxy, so it is not a function of radius. Globally, all the characteristic timescales $t_{H_\text{II}} = 24\, \mu m$ listed in Table 2 are $\leq$4 Myr, except one single case (NGC 925). The error bars are also relatively small: $<$1 Myr for the majority of the cases. These results clearly exclude characteristic timescales $t_{H_\text{II}} = 24\, \mu m$ of the order of ~10 Myr, even for the highest value recorded in our data set which is NGC 925.

6.5. Theoretical Implications

The short timescale found here between the peak of H I emission and the peak of emission from young, dust-enshrouded stars has implications for two related theoretical controversies. First is the question of whether molecular clouds are short-lived, dynamically evolving objects (Ballesteros-Paredes et al. 1999, Hartmann et al. 2001; Elmegreen 2000, 2007; Ballesteros-Paredes & Hartmann 2007) or quasi-static objects evolving over many free-fall times (Matzner 2002; Krumholz et al. 2006). The second, related question is what the rate-limiting step for star formation in galaxies is: formation of gravitationally unstable regions in the H I that can collapse into molecular clouds (Elmegreen 2002, 2007; Kravtsov 2003; Li et al. 2005, 2006); or formation of dense, gravitationally unstable cores within quasi-stable molecular clouds (Krumholz & McKee 2005; Krumholz et al. 2006; Krumholz & Tan 2007).

The short timescales found here for the bulk of massive star formation in regions of strong gravitational instability appears to support the concept that molecular cloud evolution occurs on a dynamical time once gravitational instability has set in, and that the rate-limiting step for star formation is the assembly of H I gas into gravitationally unstable configurations. Our work does not, however, address the total lifetime of molecular gas in these regions, as we only report the separation between the peaks of the emission distributions. Molecular clouds may well undergo an initial burst of star formation that then disperses fragments of molecular gas that continues star formation at low efficiency for substantial additional time (Elmegreen 2007). Averaging over the efficient and inefficient phases of their evolution might give the overall low average values observed in galaxies (e.g., Krumholz & Tan 2007).

7. CONCLUSIONS

We have derived characteristic star-formation timescales for a set of nearby spiral galaxies, using a simple geometric approach based on the classic Roberts (1969) picture that star formation occurs just downstream from the spiral pattern, where gas clouds have been assembled into super-critical configurations. This derived timescale, $t_{24\, \mu m}$, refers to the processes from the densest H I to the molecular phase, to enshrouded hot stars heating the dust. The analysis is based on high-resolution 21 cm maps from THINGS, which we combined with 24 µm maps from SINGS. We assume that the observed spiral arms have a pattern speed $\Omega_p$. Given the rotation curve, $v_c(r) = r \Omega_p(r)$, this allows us to translate angular offsets at different radii between the H I flux peaks and the 24 µm flux peaks in terms of a characteristic time difference.

At each individual point along the spiral arm we found considerable scatter between the H I and 24 µm emission peaks. However, for each galaxy we could arrive at a global fit, using a cross-correlation technique, and derive two characteristic parameters, $t_{H_\text{II}} = 24\, \mu m$ and $R_{\text{cor}}$. For our 14 objects we found the general relation $R_{\text{cor}} = (2.7 \pm 0.2) R_e$, which is consistent with previous studies (e.g., Kranz et al. 2003) and, more importantly, we found $t_{H_\text{II}} = 24\, \mu m$ to range between 1 and 4 Myr. Even when accounting for uncertainties at the highest peak of star-formation rate timescales as long as $t_{H_\text{II}} = 24\, \mu m$ ~ 10 Myr, which have been inferred from other approaches, do not appear consistent with our findings. At least for the case of nearby spiral galaxies, our analysis sets an upper limit to the time needed to form massive stars (responsible for heating the dust) by compressing the (atomic) gas. Therefore it points to a rapid procession of star formation through the molecular cloud phase in spiral galaxies. If star formation really is as rapid as our estimate of $t_{H_\text{II}} = 24\, \mu m$ suggests, it must be relatively inefficient to avoid the short-term depletion of gas reservoirs.
We thank Henrik Beuther, Mark Krumholz, Adam Leroy, and Eve Ostriker for useful discussions and suggestions. We are also grateful to the anonymous referee, whose comments helped us to improve the manuscript. The work of W.J.G.d.B. is based upon research supported by the South African Research Chairs Initiative of the Department of Science and Technology and National Research Foundation. E.B. gratefully acknowledges financial support through an EU Marie Curie International Reintegration Grant (Contract No. MIRG-CT-6-2005-013556). M.-M.L. was partly supported by U.S. National Science Foundation grant AST 03-07854, and by stipends from the Max Planck Society and the Deutscher Akademischer Austausch Dienst. This research has made use of the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with NASA.

REFERENCES

Allen, R. J. 2002, in ASP Conf. Ser. 276, Seeing Through the Dust: The Detection of H\(_\alpha\) and the Exploration of the ISM in Galaxies, ed. A. R. Taylor, T. L. Landecker, & A. G. Willis (San Francisco, CA: ASP), 288
Allen, R. J., Atherton, P. D., & Titanus, R. P. J. 1986, Nature, 319, 296
Ballesteros-Paredes, J., & Hartmann, L. 2007, RevMexAA, 43, 123
Ballesteros-Paredes, J., Hartmann, L., & Vázquez-Semadeni, E. 1999, ApJ, 527, 825
Beigman, K. G. 1989, A&A, 223, 47
Beuther, H., Churchwell, E. B., McKee, C. F., & Tan, J. C. 2007, Protostars and Planets V (Hawaii), 165
Blitz, L., Fukui, Y., Kawamura, A., Leroy, A., Mizuno, N., & Rosolowsky, E. 2007, Protostars and Planets V (Hawaii), 81
Byrd, G., Freeman, T., & Buta, R. 2002, BAAS, 34, 1116
Calzetti, D., et al. 2005, ApJ, 633, 871
Calzetti, D., et al. 2007, ApJ, 666, 870
Cappellari, M., & Copin, Y. 2003, MNRAS, 342, 345
Dale, D. A., et al. 2005, ApJ, 635, 857
de Blok, W. J. G., Walter, F., Brinks, E., Trachternach, C., Oh, S.-H., & Kennicutt, R. C., Jr. 2008, AJ, 136, 2648
Dwek, E. 2005, in AIP Conf. Proc. 761, The Spectral Energy Distributions of Gas-Rich Galaxies: Confronting Models with Data, ed. J. D. T., et al. 2007, ApJ, 656, 770
Hillenbrand, L. A., Massey, P., Strom, S. E., & Merrill, K. M. 1993, AJ, 106, 1906
Hollenbach, D., & Salpeter, E. E. 1971, ApJ, 163, 155
Jarrett, T. H., Chester, T., Cutri, R., Schneider, S. E., & Huchra, J. P. 2003, AJ, 125, 125
Jedrzejewski, R. I. 1987, MNRAS, 226, 747
Jura, M. 1975, ApJ, 197, 575
Kennicutt, R. C., Jr., et al. 2003, PASP, 115, 928
Kennicutt, R. C., Jr., et al. 2007, ApJ, 671, 333
Kim, W.-T., & Ostriker, E. C. 2002, ApJ, 570, 132
Kim, W.-T., & Ostriker, E. C. 2006, ApJ, 646, 213
Kranz, T., Slyz, A., & Rix, H.-W. 2003, ApJ, 586, 143
Kratsov, A. V. 2003, ApJ, 590, L1
Krumholz, M. R., Matzner, C. D., & McKee, C. F. 2006, ApJ, 653, 361
Krumholz, M. R., & McKee, C. F. 2005, ApJ, 630, 250
Krumholz, M. R., & Tan, J. C. 2007, ApJ, 654, 304
Li, Y., Mac Low, M.-M., & Klessen, R. S. 2005, ApJ, 620, L19
Li, Y., Mac Low, M.-M., & Klessen, R. S. 2006, ApJ, 639, 879
Lin, C.-C., & Shu, F. H. 1964, ApJ, 140, 646
Martin, C. L., & Kennicutt, R. C., Jr. 2001, ApJ, 555, 301
Matzner, C. D. 2002, ApJ, 566, 302
Mizuno, N., et al. 2001, PASJ, 53, 971
Mouschovias, T. C., Tassis, K., & Kunz, M. W. 2006, ApJ, 646, 1043
Palla, F., & Stahler, S. W. 1999, ApJ, 525, 772
Palla, F., & Stahler, S. W. 2000, ApJ, 540, 255
Peng, C. Y., Ho, L. C., Impey, C. D., & Rix, H.-W. 2002, AJ, 124, 266
Prescott, M. K. M., et al. 2007, ApJ, 668, 182
Raikov, R. P. 2001, MNRAS, 323, 445
Rand, R. J., & Kulkarni, S. R. 1990, ApJ, 349, L43
Rand, R. J., & Wallin, J. F. 2004, ApJ, 614, 142
Rix, H.-W., Guhathakurta, P., Colless, M., & Ing, K. 1997, MNRAS, 285, 779
Rix, H.-W., & Zaritsky, D. 1995, ApJ, 447, 82
Roberts, W. W. 1969, ApJ, 158, 123
Rots, A. H. 1975, A&A, 45, 43
Sakhibov, F. K., & Smirnov, M. A. 2004, Astron. Rep., 48, 995
Scoville, N. Z., Polletta, M., Ewald, S., Stolovy, S. R., Thompson, R., & Rieke, M. 2001, AJ, 122, 3017
Seiden, P. E., & Gerola, H. 1982, Fundamentals of Cosmic Physics, 7, 241
Sellwood, J. A., & Sparke, L. S. 1988, MNRAS, 231, 25P
Shetty, R., Vogel, S. N., Ostriker, E. C., & Teuben, P. J. 2007, ApJ, 665, 1138
Smith, J. D. T., et al. 2007, ApJ, 656, 770
Tan, J. C., Krumholz, M. R., & McKee, C. F. 2006, ApJ, 641, L121
Tassis, K., & Mouschovias, T. C. 2004, ApJ, 616, 283
Thomasson, M., Donner, R. J., Sundelius, B., Byrd, G. G., Huang, T. Y., & Volk, M. J. 1989, ApJS, 66, 205
Thorley, M. D., & Mundy, L. G. 1997, ApJ, 484, 202
Thronson, H. A., Jr., & Telesco, C. M. 1986, ApJ, 311, 98
Toomre, A. 1964, ApJ, 139, 212
Trachternach, C., de Blok, W. J. G., Brinks, E., Walter, F., Kennicutt, R. C., Jr., Thorney, M., & Leroy, A. 2008, ApJ, 136, 2720
Tremaine, S., Weinberg, M. D. 1984, ApJ, 282, L5
Vázquez-Semadeni, E., Kim, J., Shadmehri, M., & Ballesteros-Paredes, J. 2005, ApJ, 618, 344
Vogel, S. N., Kulkarni, S. R., & Scoville, N. Z. 1988, Nature, 334, 402
Walter, F., Brinks, E., de Blok, W. J. G., Bigiel, F., Kennicutt, R. C., Jr., Thorney, M., & Leroy, A. 2008, ApJ, 681, 125
Westpfahl, D. 1991, in ASP Conf. Ser. 18, The Interpretation of Modern Synthesis Observations of Spiral Galaxies, ed. N. Duric & P. C. Crane (San Francisco: ASP), 175
Williams, D. A. 2005, JPhCS, 6, 1
Wong, T., & Blitz, L. 2002, ApJ, 569, 157
Yamaguchi, R., et al. 2001, PASJ, 53, 985
Zimmer, F., Rand, R. J., & McGraw, J. T. 2004, ApJ, 607, 285