A CONSTANT MOLECULAR GAS DEPLETION TIME IN NEARBY DISK GALAXIES

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ABSTRACT

We combine new sensitive, wide-field CO data from the HERACLES survey with ultraviolet and infrared data from GALEX and Spitzer to compare the surface densities of H2, ΣH2, and the recent star formation rate, ΣSFR, over many thousands of positions in 30 nearby disk galaxies. We more than quadruple the size of the galaxy sample compared to previous work and include targets with a wide range of galaxy properties. Even though the disk galaxies in this study span a wide range of properties, we find a strong, and approximately linear correlation between ΣSFR and ΣH2 at our common resolution of 1 kpc. This implies a roughly constant median H2 consumption time, τH2 = ΣH2/ΣSFR, of ~2.35 Gyr (including heavy elements) across our sample. At 1 kpc resolution, there is only a weak correlation between ΣH2 and τDep over the range ΣH2 ≈ 5–100 M⊙ pc−2, which is probed by our data. We compile a broad set of literature measurements that have been obtained using a variety of star formation tracers, sampling schemes, and physical scales and show that overall, these data yield almost exactly the same results, although with more scatter. We interpret these results as strong, albeit indirect evidence that star formation proceeds in a uniform way in giant molecular clouds in the disks of spiral galaxies.

Key words: galaxies: evolution – galaxies: ISM – radio lines: galaxies – stars: formation

1. INTRODUCTION

Giant molecular clouds (GMCs) are the sites of star formation in the Milky Way (e.g., Blitz 1993). Therefore, it is not surprising that a strong correlation is observed between tracers of molecular gas and recent star formation (e.g., Rownd & Young 1999; Wong & Blitz 2002; Leroy et al. 2008; Bigiel et al. 2008), while the correlation between atomic gas and recent star formation is found to be weak or absent within galaxies (e.g., Kennicutt 1998; Rownd & Young 1999; Murgia et al. 2002; Blum et al. 2010). Finally, the relationship between star formation and molecular gas – traced by CO emission – to recent star formation – traced by ultraviolet and infrared emission – at 1 kpc resolution across a large sample of 30 nearby galaxies. This sample is significantly larger and more diverse than that of Bigiel et al. (2008, hereafter B08). From 2007 to 2010, the HERA CO-Line Extragalactic Survey (HERACLES, first maps are presented in Leroy et al. 2009) Collaboration used the IRAM 30 m telescope to construct maps of CO J = 2 → 1 emission from 48 nearby galaxies. Because the targets overlap surveys by Spitzer (mostly SINGS; Kennicutt et al. 2003) and GALEX (mostly the NGS; Gil de Paz et al. 2007), excellent multimwavelength data are available for most targets.

2. METHOD

We study all galaxies meeting the following criteria: (1) a HERACLES map containing a robust CO J = 2 → 1 detection, (2) GALEX far-UV (FUV) and Spitzer infrared data at 24 μm (IR), and (3) an inclination ≤ 75°. The first condition excludes low-mass galaxies without CO detections. The second map.
removes a few targets with poor Spitzer 24 μm data. The third disqualifies a handful of edge-on galaxies. We are left with 30 disk galaxies listed in Table 1 along with distances adopted from Walter et al. (2008), LEDA, and NED. This sample is more than four times larger than that of B08 and spans a substantial range in metallicities (8.36 ≤ z ≤ 8.93) and mass (8.9 ≤ log(M∗) ≤ 11.0).

We follow the approach of B08 with only a few modifications. B08 compared the first seven HERACLES maps to FUV, IR, and Hα emission to infer the relationship between the surface density of H2, ΣH2, and the star formation rate surface density, ΣSFR. As in B08, we estimate ΣH2 from HERACLES CO J = 2 → 1 emission. We assume a Galactic XCO = 2 × 1020 cm−2 (K km s−1)−1, correct for inclination, include helium in our quoted surface densities (a factor of 1.36, a difference from B08), and adopt a CO line ratio I(2−1)/I(1−0) = 0.7 (note that B08 used a ratio of 0.8).

We estimate ΣSFR (inclination corrected) using a combination of FUV emission and 24 μm emission. FUV emission traces photospheric emission from mainly O and B stars, with a typical age of ~20–30 Myr (Leitherer et al. 1999; Salim et al. 2007) but sensitive to populations up to 100 Myr of age. Infrared emission at 24 μm comes from dust mainly heated by young stars. This emission correlates closely with other signatures of recent star formation, especially Hα emission, and so has been used to correct optical and UV tracers for the effects of extinction (Calzetti et al. 2007; Kennicutt et al. 2007). Leroy et al. (2008) motivated this FUV–IR combination, showing that it reproduces other estimates of ΣSFR with ~50% accuracy down to ΣSFR < 10−3 M⊙yr−1kpc−2.

For 24 galaxies, we use FUV maps from the Nearby Galaxy Survey (NGS; Gil de Paz et al. 2007), for five targets from the All-sky Imaging Survey and for one galaxy we use a map from the Medium Imaging Survey. We use maps of IR emission at 24 μm from the Spitzer Infrared Nearby Galaxies Survey (SINGS; Kennicutt et al. 2003) and the Local Volume Legacy Survey (LVL; Dale et al. 2009). Handling of the maps follows B08.

We convolve the IR and FUV maps to the 13″ (FWHM) resolution of the HERACLES data. Given the wide distance range of our sample, 13″ resolution corresponds to physical scales from 180 pc to 1.7 kpc. To avoid being influenced by physical resolution, we create a second set of maps at a common physical resolution of 1 kpc (FWHM), appropriate to carry out a uniform analysis. Five galaxies are too distant to reach 1 kpc resolution. We include them in our “kpc” analysis at their native resolution, 1.4 kpc on average (excluding them does not change our conclusions).

The HERACLES maps are masked to include only significant emission (Leroy et al. 2009). The exact completeness of each map in mass surface density depends on the inclination and, for fixed spatial resolution, the distance of the target. A typical noise level is 25 mK per 5.2 km s−1 channel at 13″ resolution. For the most distant, face-on systems this limits ICO > 0.8 K km s−1 or 5 M⊙pc−2 for our adopted XCO and line ratio. Closer or more inclined systems will be complete to lower ΣH2.

We sample both sets of maps, one at 13″ and one at 1 kpc resolution, using a hexagonal grid spaced by one half-resolution element. We keep only sampling points inside the B-band 25th magnitude isophotal radius, r25, and where the HERACLES mask includes emission. At 13″ resolution, this yields ΣSFR and ΣH2 estimates for a total of ~27,000 points (~5000 independent measurements) in 30 nearby star-forming galaxies. At 1 kpc resolution, this number drops to ~12,000 (~2000 independent measurements).

### 3. RESULTS

Figure 1 shows our data in ΣSFR–ΣH2 space. The upper panels present measurements at a common angular resolution of 13″ and the lower panels show results for a common physical scale of 1 kpc. The left panels show contours indicating the density of data with each galaxy weighted equally. The right panels directly show each data point. Dotted lines in each plot indicate constant molecular gas depletion times, tDepl = ΣH2/ΣSFR, i.e., fixed ratios of H2-to-SFR.

To make the contour plots, we divide the ΣSFR–ΣH2 space into 0.1 dex wide cells to grid the data. During gridding, we assign each data point a weight inversely proportional to the number of data points for the galaxy that it was drawn from. This assigns the same total weight to each galaxy, ensuring that a few large galaxies do not drive the overall distribution. Contours indicate the density of sampling points in each cell.

The scatter plots on the right treat all measurements equally, which leads large galaxies to dominate the distribution. While the contour plots treat a galaxy as the fundamental unit, the scatter plots treat each region as a key independent measurement. The red points show a running median in ΣSFR as a function of ΣH2. Though treating ΣH2 as an independent variable is not rigorous, this binning is a useful way to guide the eye. We only bin where ΣH2 > 5 M⊙pc−2 and we are confident of being complete.

All four plots reveal a strong correlation between ΣSFR and ΣH2. In this Letter, we focus our quantitative analysis on the right-hand plots, which weight every measurement equally. The Spearman rank correlation coefficient across all data is r = 0.8 at 1 kpc resolution, indicating a strong correlation between ΣSFR and ΣH2.
Figure 1. Star formation rate surface density, $\Sigma_{\text{SFR}}$, estimated from FUV+24 $\mu$m emission as a function of molecular gas surface density, $\Sigma_{\text{H}_2}$, estimated from CO $J = 2 \rightarrow 1$ emission for 30 nearby disk galaxies. The left panels show data density with equal weight given to each galaxy. Purple, red, orange, and green contours encompass the densest 25%, 50%, 75%, and 90% of the data. The right panels show each measurement individually as a black dot. The red points indicate running medians in $\Sigma_{\text{SFR}}$ as a function of $\Sigma_{\text{H}_2}$ and the error bars show the 1 $\sigma$ log scatter in each $\Sigma_{\text{H}_2}$ bin. In both panels, dotted lines indicate fixed $\Sigma_{\text{H}_2}$ depletion times in years. Measurements in the top panels are on a common angular scale of 13$''$, those in the bottom panels are on a common physical scale of 1 kpc. All panels show a strong correlation between $\Sigma_{\text{SFR}}$ and $\Sigma_{\text{H}_2}$ with the majority of data having $\tau_{\text{H}_2, \text{Dep}} \sim 2.35$ Gyr.

It is common to parameterize relationships between gas and star formation using power-law fits. This can be problematic physically, because data from widely varying environments are often not well described by a single power law (B08; Bigiel et al. 2010b). It is also challenging practically, because of, e.g., issues of completeness and upper limits (see Blanc et al. 2009), zero-point uncertainties (compare Rahman et al. 2011) or a correct treatment of the uncertainties associated with physical parameter estimation. Bearing these caveats in mind, a rough parameterization may still be useful to the reader. If we apply a simple linear regression in log space and fit the function $\Sigma_{\text{SFR}} = A \times (\Sigma_{\text{H}_2}/10 M_\odot \text{ pc}^{-2})^N$ to the binned kpc data (red points in the lower right panel of Figure 1), we find $A \approx 4.4 \times 10^{-3} M_\odot \text{ yr}^{-1} \text{ kpc}^{-2}$ and $N \approx 1.0$. This is not rigorous: we have treated the observable $\Sigma_{\text{H}_2}$ as an independent variable and we discarded information in the process of binning. However, the fit does reasonably bisect the data. We find similar results fitting the individual measurements where we are complete with $N$ varying by $\pm 0.2$ and $A$ varying by $\sim 30\%$, depending mainly on how the fit is constructed.

The results of this fitting can be distilled to what is immediately apparent from the plot: a characteristic $\tau_{\text{H}_2, \text{Dep}} \sim 2.3$ Gyr and a power-law index close to unity, so that the data extend parallel to the dashed lines of fixed $\tau_{\text{H}_2, \text{Dep}}$ in Figure 1. The index close to unity implies that the ratio of $\Sigma_{\text{H}_2}$ to $\Sigma_{\text{SFR}}$ does not change much as a function of $\Sigma_{\text{H}_2}$ across our data. We quantify this by comparing $\tau_{\text{H}_2, \text{Dep}}$ to $\Sigma_{\text{H}_2}$ where we are complete ($\Sigma_{\text{H}_2} > 5 M_\odot \text{ pc}^{-2}$). Figure 2 plots the individual...
measurements along with a running median and scatter; both show little or no systematic variation of $r_{\text{Dep}}^{H_2}$ as a function of $\Sigma_{\text{H}_2}$ across the range studied. The rank correlation coefficient relating $r_{\text{Dep}}^{H_2} = \Sigma_{\text{H}_2}/\Sigma_{\text{SFR}}$ to $\Sigma_{\text{H}_2}$ is $r = 0.09 \pm 0.01$ in our kpc data, i.e., the two quantities are only very weakly correlated.

These results extend those found by B08 and Leroy et al. (2008), who also found a roughly constant ratio $\Sigma_{\text{H}_2}/\Sigma_{\text{SFR}}$ for a smaller, less diverse sample. Based on detailed studies of Local Group galaxies (e.g., Blitz et al. 2007; Bolatto et al. 2008; Bigiel et al. 2010a; Fukui & Kawamura 2010), they speculated that the approximately linear $\Sigma_{\text{SFR}} \sim \Sigma_{\text{H}_2}$ relation arises because star formation in disk galaxies takes place in a relatively uniform population of GMCs. Given typical GMC masses of $\sim 10^4 - 10^6 M_\odot$ and sizes of $\sim 50$ pc, each of our resolution elements likely averages over at least a few—and often many—GMCs. Thus, in this scenario the relationship between $\Sigma_{\text{H}_2}$ and $\Sigma_{\text{SFR}}$ reduces to a counting exercise: $\Sigma_{\text{H}_2}$ corresponds to a different number of GMCs inside different resolution elements, rather than to changing physical conditions in the molecular gas. This also naturally explains the weak dependence of our results on spatial scale, which merely determines the number of GMCs per resolution element but leaves the average fixed constant $r_{\text{Dep}}^{H_2}$ intact (compare B08 for a detailed discussion).

This scenario does not contradict earlier results finding that $r_{\text{Dep}}^{H_2}$ depends on $\Sigma_{\text{H}_2}$ or $\Sigma_{\text{SFR}}$; the strongest measurements of variable $r_{\text{Dep}}^{H_2}$ come from LIRGs and ULIRGs (e.g., Kennicutt 1998; Gao & Solomon 2004), systems with $H_2$ surface densities significantly exceeding those studied here and where the assumption of a uniform GMC population likely breaks down. Departures are also expected on scales of individual molecular clouds, where only a small fraction of the molecular gas actively forms stars (e.g., Heiderman et al. 2010). We will show in the next section, however, that for normal disk galaxies and on scales greater than a few 100 pc our results agree remarkably well with previous measurements of $r_{\text{Dep}}^{H_2}$.

4. COMPARISON TO LITERATURE DATA

As described in Section 1, many studies have examined the relationship between molecular gas and star formation in nearby disk galaxies over the last decade. The emphasis on power-law fits has somewhat obscured the basic question of whether these data fundamentally agree or disagree regarding which part of $\Sigma_{\text{H}_2} - \Sigma_{\text{SFR}}$ space is occupied by local disk galaxies. To address this point, Figure 3 shows our binned data (big black points with error bars) along with a wide compilation of recent measurements.

We adjust all literature measurements to share our adopted $X_{\text{CO}}$ and stellar IMF (Kroupa), but otherwise leave the data unchanged. These points therefore reflect a wide range of star formation tracers, sampling schemes, and physical scales.

We plot averages over whole galaxies as triangles. These include 57 normal spiral galaxies (green) and 15 starburst galaxies (blue) from Kennicutt (1998). Kennicutt (1998) estimates $\Sigma_{\text{SFR}}$ from H/α for normal spirals and IR emission for starbursts. We also show 236 pointings toward spirals from Murgia et al. (2002) (purple) and toward 80 small nearby spirals and dwarfs from Leroy et al. (2005, red)15. Both data sets have $\sim 50''$ resolution, corresponding to $\sim 1$–4 kpc, and use 1.4 GHz radio continuum (RC) emission to estimate $\Sigma_{\text{SFR}}$.

Filled diamonds indicate radial profile measurements. Data for seven nearby spirals from Wong & Blitz (2002) are shown in red, those for M51 from Schuster et al. (2007) in green, and those for NGC 6946 from Crosthwaite & Turner (2007) in purple. Wong & Blitz (2002) derive $\Sigma_{\text{SFR}}$ from H/α emission, Schuster et al. (2007) from RC emission, and Crosthwaite & Turner (2007) from FIR emission.

Small points represent aperture data. Blue points show 520 pc sized aperture measurements from Kennicutt et al. (2007) of star-forming regions in the spiral arms of NGC 5194 (M51). They infer $\Sigma_{\text{SFR}}$ from a combination of H/α and 24 $\mu$m emission. Green points show 500 pc apertures from Rahman et al. (2011), who sample mainly the spiral arms of NGC 4254. The points shown here reflect $\Sigma_{\text{SFR}}$ as derived from FUV and 24 $\mu$m emission. Red points indicate 170 pc apertures covering the central $4.1 \times 4.1$ kpc$^2$ of NGC 5194 (M51) from Blanc et al. (2009). They infer $\Sigma_{\text{SFR}}$ from extinction corrected H/α emission using integral field unit observations. The left panel of Figure 3 labels these various studies and overplots our data.

Figure 3 shows that these measurements sweep out a distinct part of $\Sigma_{\text{SFR}} - \Sigma_{\text{H}_2}$ space. Most data scatter between $r_{\text{Dep}}^{H_2} = 10^7$ and $10^{10}$ yr and our measurements lie near the center of the distribution. The right panel in Figure 3 shows this most clearly: we take the simplistic approach of treating all of the literature data equally (shown as gray points) and construct the same running median that we use on our own data. The literature average (red points) agrees strikingly well with our measurements (black points). This implies that our results are robust with respect to the choice of tracers or experimental setup. The literature sample as a whole also suggests that $r_{\text{Dep}}^{H_2} \approx 2.3$ Gyr in nearby disks and that $r_{\text{Dep}}^{H_2}$ is a fairly weak function of $\Sigma_{\text{H}_2}$.

5. SUMMARY

Using new IRAM 30 m CO $J = 2 \rightarrow 1$ maps from the HERACLES survey, we determine the relation between $H_2$

15 These studies compile measurements from Young et al. (1995), Taylor et al. (1998), Elfhag et al. (1996), and Böker et al. (2003).
surface density, $\Sigma_{H_2}$, and SFR surface density, $\Sigma_{SFR}$, in 30 nearby disk galaxies. This significantly extends the number of galaxies (by more than a factor of four) and the range of galaxy properties probed compared to Bigiel et al. (2008). We present our main results for a common physical resolution of 1 kpc. We find a remarkably constant molecular gas consumption time $\tau_{H_2} \approx 2.35$ Gyr (including helium) with a 1σ scatter of 0.24 dex ($\approx 75\%$) and little dependence of $\tau_{H_2}$ on $\Sigma_{H_2}$ over the range $\Sigma_{H_2} \sim 5$–100 $M_\odot$ pc$^{-2}$.

This extends and reinforces the conclusions of Bigiel et al. (2008) and Leroy et al. (2008) that the star formation rate per unit $H_2$ in the disks of massive star-forming galaxies is, to first order, constant. We interpret this as strong, yet indirect, evidence that the disks of nearby spiral galaxies are populated by GMCs forming stars in a relatively uniform manner. We caution that these results are specific to disk galaxies and scales on which we average over many GMCs—they may be expected to break down at very high surface densities and on small scales. Taken as a whole, a broad compilation of literature data on disk galaxies from the last decade yields impressively similar results.

We thank the GALEX NGS, SINGS, and LVL teams for making their outstanding data sets available. We thank Karl Gordon for the kernel used on the MIPS 24 $\mu$m data and Nurur Rahman for sharing his data. We thank the staff of the IRAM 30 m telescope for their assistance carrying out the survey. F.B., A.K.L., and F.W. gratefully acknowledge the Aspen Center for Physics, where part of this work was carried out. Support for A.K.L. was provided by NASA through Hubble Fellowship grant HST-HF-51258.01-A awarded by the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., for NASA, under contract NAS 5-26555. 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.
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