Measurements of the CO-to-H$_2$ Conversion Factor and Dust-to-Gas Ratio in Nearby Galaxies

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Collaborators: Adam Leroy, Fabian Walter, KINGFISH team, HERACLES team

Galactic Scale Star Formation
Heidelberg - August 1, 2012
Measuring the CO-to-H$_2$ Conversion Factor.

\[ \Sigma_{\text{H}_2} = \alpha_{\text{CO}} \, I_{\text{CO}} \]

\[ \alpha_{\text{CO}} = 4.35 \, \text{M}_\odot \, \text{pc}^{-2} \, (\text{K} \, \text{km} \, \text{s}^{-1})^{-1} \]

\[ X_{\text{CO}} = 2 \times 10^{20} \, \text{cm}^{-2} \, (\text{K} \, \text{km} \, \text{s}^{-1})^{-1} \]

*note: $\alpha_{\text{CO}}$ defined here for unresolved clouds, includes He*

To measure $\alpha_{\text{CO}}$:
1. observe CO
2. use another tracer to get total amount of molecular gas
3. compare with observed CO

Other ways to trace the total amount of molecular gas:

- **Dynamics** (i.e. virial masses)
- $\gamma$-rays
- **Modeling Line Emission**
- **Dust**
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- **γ-rays**
- **Modeling Line Emission**
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**Necessary assumptions:**
molecular cloud is virialized, no CO-free layer of H$_2$

Need to resolve GMCs. *Hard to do outside the Local Group.*

Previous results find little variation away from MW $\alpha_{\text{CO}} \sim 4.35$

**GMCs in center of NGC 6946** have $\alpha_{\text{CO}} \sim \alpha_{\text{CO,MW}}/2$

*(Donovan Meyer et al. 2012)*
Other ways to trace the total amount of molecular gas:

<table>
<thead>
<tr>
<th>Dynamics (i.e. virial masses)</th>
<th>( \gamma )-rays</th>
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<th>Dust</th>
</tr>
</thead>
</table>

**Necessary assumptions:**

distribution of cosmic rays

Need to observe \( \gamma \)-rays.

*Hard to do outside the Local Group.*

Measure MW disk \( \alpha_{\text{CO}} \approx 4.35 \), MW center \( \alpha_{\text{CO}} \) 5× lower.
Other ways to trace the total amount of molecular gas:

**Dynamics** (i.e. virial masses)  \( \gamma \)-rays  **Modeling Line Emission**  Dust

**Necessary assumptions:**
number of different gas components, velocity/density structure of cloud, etc.

Need to observe multiple molecular gas lines.

Measure galaxy center \( \alpha_{\text{CO}} \) 5-10× lower than MW.
(e.g. Israel 2009a,b)
Other ways to trace the total amount of molecular gas:

**Dynamics** (i.e. virial masses)  

**γ-rays**  

**Modeling Line Emission**  

**Dust**

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**Necessary assumptions:**
- Dust & gas are well mixed, DGR & emissivity don’t change with atomic/molecular phase.
- Need to observe dust mass tracer (typically far-IR + SED modeling).
- Widely applied with various techniques...

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**Figure 6.**

*The Astrophysical Journal*

α measurepments. In detail, our measurements (circles) yield lower trends in α compared to previous IR-based studies. We suspect that this is perhaps because of higher ionization fractions inside clouds. Magnetic support becomes very strong at low metallicities, virial masses even at fairly small scales. They suggest that an alternative view is argued by Bot et al. ([2010](#)), Rosolowsky ([2007](#)), and Bolatto et al. ([2008](#)) suggest that the ratio of CO-to-H₂ and NGC 6822. We also thank Julia Roman-Duval, Michele John Cannon, and Fabian Walter for sharing their data on M 31 systems, an actual numerical prescription for the regions of interest in a uniform way across a heterogeneous sample we improve on literature studies of individual galaxies.

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Equation (5).

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Extended H₂ to be higher in the dense gas close to molecular complexes, Equation (5).

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If the additional H₂ diverge in the SMC. This divergence is most easily understood about the metallicity of M 33 or the LMC, and then strongly if the additional H₂ diverge in the SMC. This divergence is most easily understood about the metallicity of M 33 or the LMC, and then strongly.

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Rubio et al. ([1997](#)) in the SMC. The seen envelope should perhaps because of higher ionization fractions inside clouds. Magnetic support becomes very strong at low metallicities, virial masses even at fairly small scales. They suggest that an alternative view is argued by Bot et al. ([2010](#)), Rosolowsky ([2007](#)), and Bolatto et al. ([2008](#)) suggest that the ratio of CO-to-H₂ and NGC 6822. We also thank Julia Roman-Duval, Michele John Cannon, and Fabian Walter for sharing their data on M 31 systems, an actual numerical prescription for the regions of interest in a uniform way across a heterogeneous sample we improve on literature studies of individual galaxies.

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Measuring the Conversion Factor with Dust.

\[
\text{DGR} = \frac{\Sigma_D}{(\Sigma_{\text{HI}} + \alpha_{\text{CO}} I_{\text{CO}})}
\]

- Fix DGR based on some model or expected DGR.
- Fix DGR based on nearby HI-only line-of-sight.
- \textit{Solve for both DGR & } \alpha_{\text{CO}} \textit{ using spatially resolved measurements.}
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- Fix DGR based on nearby HI-only line-of-sight.
- Solve for both DGR & \( \alpha_{\text{CO}} \) using spatially resolved measurements.

Assumption: DGR constant on kpc scales.
Our Technique: Minimizing Scatter in DGR on kpc scales

\[ \text{DGR} = \frac{\Sigma_{\text{dust}}}{\Sigma_{\text{HI}} + \alpha_{\text{CO}} I_{\text{CO}}} \]

- both CO and H I are detected
  \[ \rightarrow \text{Need good S/N maps of CO & HI.} \]
- a range of \( I_{\text{CO}}/\Sigma_{\text{HI}} \) values are present
  \[ \rightarrow \text{Need many resolution elements.} \]
- region is small, ok to assume DGR & \( X_{\text{co}} \sim \) constant
  \[ \rightarrow \text{Must select small chunk of galaxy, so need high resolution.} \]
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cartoon of what happens to DGR when \( \alpha_{\text{CO}} \) is adjusted

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- region is small, ok to assume DGR & Xco ~ constant
  → Must select small chunk of galaxy, so need high resolution.

$$DGR = \frac{\Sigma_{\text{dust}}}{\Sigma_{\text{HI}} + \alpha_{\text{CO}} I_{\text{CO}}}$$

cartoon of what happens to DGR when $\alpha_{\text{CO}}$ is adjusted
Example of the Technique
Example of the Technique
1. Measure CO, HI & dust at each point in region.

2. Measure scatter in DGR at various $\alpha_{\text{CO}}$.

3. Find minimum in scatter.

4. Minimum scatter = most "uniform" DGR in region = best-fit $\alpha_{\text{CO}}$ & DGR
DGR = $\Sigma_D/(\Sigma_{HI} + \alpha_{CO} I_{CO})$

KINGFISH
Key Insights into Nearby Galaxies:
A Far-IR Survey with Herschel

70-500 µm imaging & spectroscopy of 62 nearby galaxies with Herschel
Kennicutt et al. 2011

3.6 - 24 µm from SINGS and LVL.
(Kennicutt et al. 2003, Dale et al. 2009)

To get $\Sigma_D$: SED modeling from 3.6 - 350 µm (Aniano+ 2012)
(preserves SPIRE 350 µm’s 25” resolution while still covering the peak of the dust SED)
The Observations

\[
\text{DGR} = \frac{\Sigma_D}{(\Sigma_{\text{HI}} + \alpha_{\text{CO}} I_{\text{CO}})}
\]

HI survey of 34 nearby galaxies with the VLA
Walter et al. (2008)

Resolution of \(~12"\)

HI column density determined directly from 21cm line.
The Observations

$$DGR = \frac{\Sigma_D}{(\Sigma_{HI} + \alpha_{CO} I_{CO})}$$

HERACLES
HERA CO-Line Emission Survey

CO J=(2-1) survey of 48 nearby galaxies with HERA on the IRAM 30m.
Leroy et al. (2009)

Resolution of ~13”

Assume (2-1)/(1-0) = 0.7 average for HERACLES sample
(Rosolowsky et al., in prep)
NGC0628 Results
NGC0628 Results

Log($\alpha_{\text{CO}}$)

$\Delta\alpha_{\text{CO}}$ (dex)

$01^\text{h}37^\text{m}0^\text{s}36^\text{m}50^\text{s}$

$15^\circ42'0''$
NGC0628 Results
NGC3938 Results
NGC3938 Results
NGC3938 Results

![Graph showing the relationship between Log(α_c) and Deprojected Radius (r_{26}) with Δα_{CO} (dex) scale.](image)
NGC6946 Results
NGC6946 Results

![Graph showing Log(α_20) vs Deprojected Radius (r_20) with color scale indicating Δα_20 (dex).]
Variations we see in $\alpha_{\text{CO}}$

- MW $\alpha_{\text{CO}}$, no trend with radius.
- Flat MW $\alpha_{\text{CO}}$ profile + central unresolved dip.
- Overall gradient in $\alpha_{\text{CO}}$ with radius.
- Low $\alpha_{\text{CO}}$ everywhere, no clear radial trend.

illustrated with a few examples of ~face-on, highly resolved galaxies
The right panel shows observed intensities (in MJy sr$^{-1}$) of our SFR tracers—H$\alpha$, FUV, 24$\mu$m, and 70$\mu$m emission.

REFERENCES

Figure A1. Atlas of radial profiles, see Figure 4 for details. (A color version of this figure is available in the online journal.)

Calzetti for helpful comments. We thank the anonymous referee for thoughtful comments that improved the paper. The work of A.S. was supported by the Deutsche Forschungsmeinschaft (DFG) Priority Program 1177. Support for A.K.L. was provided by NASA through Hubble Fellowship grant HST-HF-51258. Awarded by the Space Telescope 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 the National Research Foundation. This research made use of the NASA/IPAC Extragalactic Database (NED), which is operated by the JPL/Caltech, under contract with NASA, NASA’s Astrophysical Data System.
Figure A1. (Continued)

The color of the CO point indicates the significance with which we could determine the integrated CO intensities: green for high significance measurements, orange for measurements of marginal significance, and red for 3σ upper limits. To have H2 and HI on the same mass surface density scale, we multiplied the observed 21 cm line intensities by a factor of 312.5 (the ratio of Equations (1) and (2)). We also plot the SFR surface density (M⊙ yr⁻¹ kpc⁻²) determined from Hα + 24 µm and FUV + 24 µm. Black solid dashed lines show our exponential fit to the radial CO profile. We fit all high significance data excluding galaxy centers, defined as the inner 30', which often exhibit breaks from the overlap profile (Regan et al. 2001; Helfer et al. 2003). The derived exponential scale lengths (in units of r25, the radius of the 25th magnitude B-band isophote), appear in the lower left corner.

NGC 3184 radial profiles from Schruba+ 2011

0.2 dex
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The right panel shows observed intensities (in MJy sr$^{-1}$) of our SFR tracers—H$\alpha$, FUV, 24 µm, and 70 µm emission.

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NGC 4321 radial profiles from Schruba+ 2011

NGC 4321

$I_{c0} = 0.27 \, r_{25}$

NGC 4321 (M100)
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Figure A1. (Continued)

The color of the contour lines indicates the significance with which we could determine the integrated CO intensities: green for high significance measurements, orange for measurements of marginal significance, and red for 3σ upper limits. To have H$_2$ and H$_i$ on the same mass surface density scale, we multiplied the observed 21 cm line intensities by a factor of 3.5 (the ratio of Equations (1) and (2))). We also plot the SFR surface density (M$_\odot$ yr$^{-1}$ kpc$^{-2}$) determined from H$\alpha$ + 24 µm and FUV + 24 µm. Black solid dashed lines show our exponential fit to the radial CO profile. We fit all high significance data excluding galaxy centers, defined as the inner 30′′, which often exhibit breaks from the overall profile (Regan et al. 2001; Helfer et al. 2003). The derived exponential scale lengths (in units of $r_{25}$, the radius of the 25th magnitude B-band isophote), appear in the lower left corner.

100 NGC 3351 radial profiles from Schruba+ 2011

NGC 3351 [K km s$^{-1}$]

Integrated Intensity

$\Delta \alpha_{\text{CO}}$ (dex)
Variations we see in $\alpha_{\text{CO}}$

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REFERENCES


22 NGC 3627
radial profiles from Schruba+ 2011
NGC 3627
HI
$H_2$
SFR(FUV+24)
SFR(H$\alpha$+24)

$l_{co} = 0.16 \, r_{25}$
What drives variations in $\alpha_{CO}$?

*Metallicity?*

**NGC 0628**

Large metallicity gradient.

**NGC 6946**

Small metallicity gradient.

~ an order-of-magnitude lower than MW disk!
α_{CO} & Metallicity

uniform metallicity selection from Moustakas et al. 2010

strong-line metallicities with Pilyugin & Thuan 2005 calibration measurements from HII region spectra

General trend for higher α_{CO} at low Z.

but...

significant scatter in α_{CO} at given Z.
Dust-to-Gas Ratio

Linear trend with $Z$.

Less than a factor of 2 scatter.

Constant fraction of metals locked up in dust.
Metallicity isn’t everything...

Is this what we expect?

- dust shielding controls C+/C/CO transition

- in MW only 30-50% of gas H$_2$ not in CO layer
  (Fermi Collab. 2010, Planck Collab. 2011)

![Diagram of decreasing metallicity and DGR](image)

e.g. Maloney & Black 1988, Bolatto et al. 1999, Wolfire et al. 2010, Glover & Mac Low 2011
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What drives variations in $\alpha_{CO}$?
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$\alpha_{CO} \propto \Sigma^{-0.5}$
Azimuthal Variations in NGC 6946

Lower $\alpha_{CO}$ along the spiral arms.
Azimuthal Variations in NGC 6946

Lower $\alpha_{\text{CO}}$ along the spiral arms.
Disagreement with Virial Mass $\alpha_{\text{CO}}$
Measurements in the centers

Virial masses give \textasciitilde MW or higher $\alpha_{\text{CO}}$ in centers of 2976, 4736 and 6946.

4 Galaxies with virial mass based $\alpha_{\text{CO}}$
Disagreement with Virial Mass $\alpha_{\text{CO}}$
Measurements in the centers

4 Galaxies with virial mass based $\alpha_{\text{CO}}$

Virial masses give $\sim$MW or higher $\alpha_{\text{CO}}$ in centers of 2976, 4736 and 6946.

Several galaxies with multi-line modeling $\alpha_{\text{CO}}$

Modeling suggests low $\alpha_{\text{CO}}$ in some galaxy centers

NGC 6946 5-10 times lower than MW - Israel & Baas 2001, Walsh et al. 2002, Meier & Turner 2004
Our conversion factors make some galaxy centers have high star-formation efficiency.

Depletion Time:  \( \tau_{\text{DEP}} = 1 / \text{SFE} = \Sigma_{\text{H}_2} / \Sigma_{\text{SFR}} \)

Leroy et al. 2012b, submitted
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Leroy et al. 2012b, submitted
Summary

• $\alpha_{\text{CO}}$ can vary by factor of 10 in nearby galaxies - especially low in their centers.

• Metallicity not a key driver of $\alpha_{\text{CO}}$ at $Z \sim Z_\odot$ and above. Expected if main effect is to change dust shielding and alter “CO-dark” gas layer.

• Low measured $\alpha_{\text{CO}}$ enhances SFE in some galaxy centers over predictions with fixed conversion factor.

• Temperature & velocity dispersion of molecular gas are probably crucial drivers of $\alpha_{\text{CO}}$. 