Star Formation Scaling Relations: The Local Truth

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The SFR is the primary metric for describing galaxy evolution over cosmic time.

Bouwens et al. 2010
What are the physical processes that set the SFR and control galaxy evolution?

Bouwens et al. 2010
Schmidt’s Conjecture:

“It would seem most probable that the rate of star formation depends on the gas density and we shall assume that the number formed per unit interval of time varies with a power of the gas density ...” Schmidt (1959)

\[ \Sigma_{\text{SFR}} = \kappa (\Sigma_g)^\beta \quad (M_\odot \text{ pc}^{-2}) \]

“It is rather tempting to try to estimate the effects of star formation...in galaxies as a whole.”
Determining SFRs and Gas Masses in External Galaxies

SFRs: population synthesis modelling

Gas Mass HI: \( M_{\text{gas}} = \alpha_{\text{HI}} L_{\text{HI}} \)

Gas Mass \( \text{H}_2 \): \( M_{\text{gas}} = \alpha_{\text{CO}} L_{\text{CO}} \)

Conroy C. 2013.
$\Sigma_{\text{SFR}} = A \left( \Sigma_{\text{gas}} \right)^{1.6}$

Schmidt-Kennicutt Scaling Law

$Z = 0$
Galaxies
Giant Molecular Clouds
Giant Molecular Clouds

**THE LOCAL TRUTH:**

SFRs: *Direct Counting* of YSOs and measured ages.

Masses: Resolved measurements of dust column densities and an assumed gas-to-dust ratio

Does a Schmidt Law exist for MW GMCs?
Giant Molecular Clouds

A Schmidt Law does NOT exist between GMCs
A Schmidt Law does NOT exist between GMCs

Well known scaling relation of Larson (1981)

\[ M = \Sigma_c R^2 \]

\[ \Sigma_c = 41 M_\odot \text{pc}^{-2} \]

Lombardi et al. 2010
Does a Schmidt Law exist *within* GMCs, on sub-cloud scales?
Schmidt Law in Orion

\[ \Sigma_\ast(A_K) = \kappa A_K^\beta \]

\( \beta = 2 \)

Orion A

Orion A

\[ \Sigma_\ast(A_K) \text{ [stars pc}^{-2}] \]

\[ A_K \text{ [mag]} \]

Lada et al. 2013
A Schmidt Law Exists within GMCs

Schmidt Law in Giant Molecular Clouds

Results:

\[ \Sigma_* = \kappa (A_K)^\beta \]

<table>
<thead>
<tr>
<th></th>
<th>Orion</th>
<th>Taurus</th>
<th>California</th>
<th>Perseus</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \beta )</td>
<td>2.0 ± 0.05</td>
<td>2.1 ± 0.1</td>
<td>3.1 ± 0.2</td>
<td>2.4 ± 0.6</td>
</tr>
<tr>
<td>( \kappa )</td>
<td>1.1 ± 0.1</td>
<td>2.1 ± 0.3</td>
<td>0.8 ± 0.2</td>
<td>0.2 ± 0.1</td>
</tr>
</tbody>
</table>

Gutermuth et al. 2011
Giant Molecular Clouds

A Schmidt Law within clouds does NOT explain variations in SFRs between clouds.
Schmidt Law and Star Formation in GMCs

\[ N_*(>A_K) = \Sigma_*(>A_K) \times S(>A_K) \]
Cloud structure plays critical role in determining the SFR in clouds!

Surface Area Distribution Function, $S(>A_K)$
Scaling Law of Surface Areas

\[ S(> A_K) \sim \Sigma^{-n}_{gas} \]
Connecting Cloud Structure to Star Formation
Dense Gas fraction varies between clouds!
And is correlated with the level of star formation
Dense Gas and Star Formation

90% of Protostars at $A_K > 1.0$ mag

Orion A

Local Dark Cloud Sample

Lada et al. 2013

Evans et al. 2014
Consider Protostars and Dense Gas

Orion A

Lombardi et al. 2014

Herschel: 250 µm
Star Formation Scaling Laws *Between* Local GMCs
The Dense Gas Scaling Law for Local Star Formation

A linear scaling relation for integrated quantities!

The SFR is most directly correlated with the dense gas mass.

Star Formation Timescale in Dense Gas:

\[ t_{gc} \approx 22 \text{ Myr} \]
A Generalized Star Formation Scaling Law for Local GMCs

\[
\text{SFR} = (4.6 \times 10^{-8}) \ f_{dg} M_{\text{gas}} \ (M_\odot \ \text{yr}^{-1})
\]

Family of linear scaling relations parameterized by the dense gas fraction \( f_{dg} \)

\[
f_{dg} = \frac{M_{0.8}}{M_{\text{gas}}}
\]

Star Formation Timescale:

\[
t_{gc} \approx 22 f^{-1} \ \text{Myr}
\]
Extending SFR Scaling Relations to Nearby Galaxies
Extending SFR Scaling Relations to Nearby Galaxies

NGC 300 (ALMA)

Constant Column Density Scaling Law

$M \sim R^2$

$\Sigma = 67 \, M_\odot \, \text{pc}^{-2}$

Faesi et al. 2016
Extending SFR Scaling Relations to Nearby Galaxies

SFRs vs Total Molecular Mass

Lada et al. 2012

Total Molecular Masses

Galaxies

Local GMCs

Log(Star Formation Rate (M_☉ yr⁻¹))

Log Molecular Mass (M_☉)

Lada et al. 2012
Extending SFR Scaling Relations to Nearby Galaxies

Gaesi et al. 2014
Lada et al. 2012

Total Molecular Masses

$SFR \text{ vs Total Molecular Mass}$

![Graph showing the relationship between SFR and total molecular mass.]

- Galaxies
- Local GMCs
- NGC 300 GMCs

Faesi et al. 2014
Lada et al. 2012
Extending SFR Scaling Relations to Nearby Galaxies

SFR vs Total Molecular Mass

Total Molecular Masses

Faesi et al. 2014
Lada et al. 2012
GMCs are the fundamental building blocks of star formation in disk galaxies.
Extending SFR Scaling Relations to Nearby Galaxies

![SFRs vs Molecular Mass](image)

- **Dense Gas Mass (Ak)**
- **Galaxies**
- **ULIRGs**
- **LIRGs**
- **Disks**
- **Local GMCs**

**Log Star Formation Rate (M_☉ yr⁻¹)** vs **Log Molecular Mass (M_☉)**

- **Gao and Solomon 2004**
- **Lada et al. 2010**
The SFR is controlled by the mass of dense molecular gas within GMCs AND galaxies.
Extending SFR Scaling Relations to Nearby Galaxies

The physical process of star formation in galaxies must be very similar to that in MW GMCs

Dense gas fractions and depletion times are similar across wide range in environments from local clouds to whole galaxies.
Extending SFR Scaling Relations to Nearby Galaxies

**SFR vs Molecular Mass**

- Dense Gas Mass (HCN)
- Dense Gas Mass (Ak)
- Total Gas Mass (CO)
- Total Gas Mass (Ak)

**Early Universe: z = 2 - 4**

The physical process of star formation in distant galaxies and through much of cosmic history must be reasonably the same as it is presently in the nearest molecular clouds.
Deconstructing the Kennicutt-Schmidt Scaling Relation
Deconstructing the Kennicutt-Schmidt Law:

Galaxies

Bigiel et al. 2008 AJ 136:2846

Schruba et al. 2011 AJ 142;37
Deconstructing the Kennicutt-Schmidt Law:

Galaxies

- HI DILUTION
- CLOUD COUNTING

Bigiel et al. 2008 AJ 136:2846

Schruba et al. 2011 AJ 142:37
Deconstructing the Kennicutt-Schmidt Law:

Galaxies

Starburst Galaxies:

Bigiel et al. 2008
1. There is no Schmidt Law *between* GMCs

2. A Schmidt Law *does* exist within GMCs but it does not provide a complete description of a cloud’s star formation activity.

3. The structure of a cloud plays a pivotal role in setting its global SFR and the overall level of its star formation activity.

4. The integrated SFR scales *linearly* with, and is most reliably traced by, the dense gas mass in a star forming region.

5. The *amount of dense gas sets the SFR* in systems ranging from individual GMCs to entire galaxies.

6. The Kennicutt-Schmidt law for galaxies is largely the result of unresolved measurements of GMCs and not a result of any underlying physical law of star formation.
Conclusion

The physical process of star formation in distant galaxies and through much of cosmic history may be reasonably the same as it is presently in the nearest molecular clouds.
Supplementary Material
Star Formation Scaling Laws

Depletion Time vs Dense Gas Fraction

- Local Clouds
- Galaxies

Log($t_{\text{depletion}}$) vs Log(Dense Gas Fraction)
SF Scaling Laws for Dense Gas

Wu et al. 2005

Jackson et al. 2015

Galaxies

Milky Way GMCs

IRAS is incomplete

MALT90 Data (Year 1 & 2)

Galaxy Data (Gao & Solomon 2004)
Deconstructing the Kennicutt-Schmidt Law:

A Puzzling Discrepancy:

Galaxies: $t_{\text{depletion}} = 2$-3 Gyrs

MW GMCs: $t_{\text{depletion}} = 220$ Myrs

N300 GMCs: $t_{\text{depletion}} = 270$ Myrs

Diffuse, inert CO clouds? SFR Calibrations? Both?

Bigiel et al. 2008
\[ \Sigma_{\text{SFR}} = 4.6 \times 10^{-8} f_{\text{dense}} \Sigma_{\text{gas}} \]

\[ f_{\text{dense}} \sim (\Sigma_{\text{gas}})^{0.5} \]
Implications for Modelling Star Forming Galaxies

SF threshold density: $n_{\text{gas}} > 50 \text{ cm}^{-3}$
$t_{sf} = \text{Constant}$

\[ \rho_{\text{SFR}} = A(\rho_{\text{gas}})^{1.0} \]
\[ \Sigma_{\text{SFR}} = B(\Sigma_{\text{gas}})^{1.4} \]

\[ f_{\text{dense}} \sim (\Sigma_{\text{gas}})^{0.4} \]
A Linear Scaling Law for Galaxies

Young & Scoville 1991, ARAA 32, 581

\[ \log \text{SFR} \ (M_\odot \ yr^{-1}) + 9.28 \]
A Linear Scaling Law at High Z

Schinnerer et al. 2016
The Star Formation Rate In Molecular Gas

Greater than an order of magnitude variation, independent of cloud mass!

$\tau_{gc} \approx 220$ Myr
## Inventory of Local GMC Masses

<table>
<thead>
<tr>
<th>Cloud</th>
<th>Mass ($10^4 M_\odot$)</th>
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<tbody>
<tr>
<td>Orion A</td>
<td>6.77</td>
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<tr>
<td>Orion B</td>
<td>7.18</td>
</tr>
<tr>
<td>California</td>
<td>9.99</td>
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<tr>
<td>Perseus</td>
<td>1.84</td>
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<tr>
<td>Taurus</td>
<td>1.49</td>
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<tr>
<td>Ophiuchus</td>
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</tr>
<tr>
<td>RCrA</td>
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<tr>
<td>Pipe</td>
<td>0.79</td>
</tr>
<tr>
<td>Lupus 3</td>
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<td>Lupus 3</td>
<td>0.14</td>
</tr>
<tr>
<td>Lupus 4</td>
<td>0.08</td>
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</table>
# Inventory of YSOs in Local Clouds

<table>
<thead>
<tr>
<th>Cloud:</th>
<th>YSOs</th>
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<tbody>
<tr>
<td>Orion A</td>
<td>2862</td>
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<tr>
<td>Orion B</td>
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<td>California</td>
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<tr>
<td>Perseus</td>
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<tr>
<td>Taurus</td>
<td>335</td>
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<td>Ophiuchus</td>
<td>316</td>
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<tr>
<td>RCrA</td>
<td>100</td>
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<tr>
<td>Pipe</td>
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<tr>
<td>Lupus 1</td>
<td>13</td>
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<tr>
<td>Lupus 3</td>
<td>69</td>
</tr>
<tr>
<td>Lupus 4</td>
<td>12</td>
</tr>
</tbody>
</table>
The Timescales for Star Formation

\[ \tau_{sf} \approx 1-3 \text{ Myr} \]