How galactic-scale gas motions regulate the structure of molecular gas and star formation

Sharon E. Meidt (MPIA)
molecular gas

star formation
(sub-)kpc star formation relation

Bigiel et al. (2008;2011)

\( \tau_{\text{dep}} = 2.5 \text{ Gyr} \)

\( \tau_{\text{dep}} = \frac{\Sigma_{\text{H}_2}}{\Sigma_{\text{SFR}}} \)

\( \tau_{\text{dep}} = \text{SFE}^{-1} \)

\( \text{molecular gas depletion time} \)

\( \Sigma_{\text{SFR}} \sim \Sigma_{\text{H}_2}^n \)

\( n = 1 \)

\( \neq 1.4 - 1.5 \)

universal molecular gas depletion time ??

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Krumholz, Dekel & McKee (2011)

2 modes of SF?

MW clouds

z=2 starbursts

Local SF law, log n = 1, 3, 5 [cm^{-3}]
Daddi starbursts (top), disks (bottom)
Heiderman f_{dense}=1 (top), f_{dense} \propto \Sigma^{0.4} (bottom)

MW clouds

z = 0 disks

z = 0 starbursts

High z disks

High z starbursts
gas kinematics in spiral potentials

stellar feedback

gas organization

star formation

GMC formation + evolution

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gas kinematics in spiral potentials

global stability, shear, shocks

stellar feedback

gas organization

star formation

GMC formation + evolution
gas kinematics in spiral potentials

global stability, shear, shocks: stellar feedback

gas organization

non-circular motions:
dynamical coupling of clouds to environment
CO(1–0) in central 9 kpc at 
**GMC resolution (40 pc, 10^5 M_\text{sun})**

**IRAM**
30m: 40 hr 
PdBI: 170 hr

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IRAM
Molecular Gas disk of M51

Schuster et al. (2007)

single dish (~ 500 pc)
Molecular Gas disk of M51

PAWS (PI: Schinnerer)

IRAM
30m: 40 hr
PdBI: 170 hr

CO(1–0) in central 9kpc at GMC resolution (40pc, \(10^5\)M\(_{\odot}\))

see also Koda et al. (2011)

~100pc resolution
Molecular Gas disk of M51

Colombo et al. (in prep.)

Velocity field

~50 km s\(^{-1}\) non-circular streaming motions!

bar twist

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Molecular Gas disk of M51

Colombo et al. (in prep.)

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Molecular Gas disk of M51

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30m: 40 hr
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CO(1–0) in central 9kpc at
GMC resolution (40pc, $10^5 M_{\odot}$)

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Spatial Relation b/n Gas and Star Formation
Schinnerer et al. (in prep.)
Spatial Relation b/n Gas and Star Formation
Schinnerer et al. (in prep.)

and see Mentuch Cooper et al. 2012
Spatial Relation b/n Gas and Star Formation
Schinnerer et al. (in prep.)

and see Mentuch Cooper et al. 2012

PACS 70μm

In gas depletion time

‘universal’ time (Bigiel et al. 2008)

and see Mentuch Cooper et al. 2012
GMC Stabilization in M51

*what shuts off star formation?*

support *not* entirely from

- **spiral arm shear**
  (Oort A; cf. Dib & Helou 2012)
- preferentially enhanced turbulent motions
  (regular σ along spiral)
- **stellar feedback** (little Hα, UV, clusters <70Myr)

*Meidt et al. (2013)*
Pressure Stabilization

Hughes et al. (2013a)

\[ \log(P_{\text{int}}/k_B \ [K \ cm^{-3}]) \]

\[ \log(P_{\text{ext}}/k_B \ [K \ cm^{-3}]) \]

log molec. gas surf. dens. \((M_{\text{sol}} \ pc^{-2})\)

Radius (arcsec)

prop. to \log (Pressure) \((P \sim G \Sigma^2)\)

average

arm

clouds

surface pressure important
Pressure Stabilization

ambient $P$ comparable to internal cloud $P$

cloud

surface pressure important

$log$ molec. gas surf. dens. $(M_{\text{sol}} \text{ pc}^{-2})$

Radius (arcsec)

prop. to $log$ (Pressure) $(P \sim G \Sigma^2)$

clouds

M51

average

arm

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ambient P comparable to internal cloud P
c
cloud
surface pressure important

what happens if we perturb the cloud surface in the presence of (relative) motion?

prop. to log (Pressure) \( P \sim G \Sigma^2 \)

Radius (arcsec)

log molec. gas surf. dens. \( (M_{\text{sol}} \, \text{pc}^{-2}) \)

M51

average

arm
change in stable mass threshold: dynamical pressure

Meidt et al. (2013)

cf. Jog (2013, in prep.)
change in stable mass threshold: *dynamical pressure*

Meidt et al. (2013)  
*cf.* Jog (2013, in prep.)

clouds in motion in arm:

1. **reduced surface pressure**  
   (Bernoulli)
2. **increased** (Bonnor-Ebert)  
   **stable mass**
3. **reduced collapse-unstable fraction**
4. **lower SFE**
change in stable mass threshold: *dynamical pressure*

*Meidt et al. (2013)*

*cf. Jog (2013, in prep.)*

clouds in motion in arm:

1). reduced surface pressure (Bernoulli)
2). increased (Bonnor-Ebert) stable mass
2b). reduced collapse-unstable fraction
3). lower SFE
change in stable mass threshold: \textit{dynamical pressure}  

Meidt et al. (2013)  

\textit{cf.} Jog (2013, in prep.)

clouds in motion in arm:

1). \textbf{reduced surface pressure} (Bernoulli)

2). \textbf{increased} (Bonnor-Ebert) stable mass

2b). reduced collapse-unstable fraction

3). \textbf{lower SFE}

$$\ln \tau_{\text{dep}} \approx -(\gamma + 1) \frac{V_{\text{stream}}^2}{4\sigma^2}$$

for $dN/dM \propto M^\gamma$

\begin{itemize}
\item log $N_c$ [(m $>$ M)/kpc$^2$]
\item log $M_{\text{lum}}$ [M$_{\text{sun}}$]
\end{itemize}
non-circular gas motions: Present-day Torques

$S^4G$
stellar
mass
surface
density

Meidt et al. (2012a,b)
Eskew, Zaritsky & Meidt (2012)
non-circular gas motions: 
*Present-day Torques*

\[
M_{\odot} \, \text{pc}^{-2}
\]

\[S^4G\]
stellar mass
surface density

Meidt et al. (2012a,b)
Eskew, Zaritsky & Meidt (2012)
Present-day Torques

Inertial torques $R \times \nabla \Phi$

Outflow inflow

Radius = proxy for environment (bar, spiral)

$\langle \mathbf{\Gamma} \rangle (R)$

Azimuthal bins

Torque profile

PAWS CO
Present-day Torques

$\langle \Gamma \rangle (R)$

Azimuthal bins

Consistent with Meidt et al. 2008
Spiral arm Torques

from PAWS kinematics
inflow=large

\(|V_{\text{stream}}|\)

<\Gamma>(R)

azimuthal bins

T_{\text{dep}}

(arb. units)
Spiral arm Torques

from PAWS
kinematics
inflow=large
$|V_{\text{stream}}|$
Spiral arm Torques

from PAWS kinematics
inflow=large $|V_{\text{stream}}|$

$<\Gamma>(R)$
azimuthal bins $T_{\text{dep}}$
(arb. units)

cf. Knapen et al. (1992)
\[
\ln \tau_{\text{dep}} \approx -(\gamma + 1) \frac{|v_{\text{stream}}|^2}{4 \sigma^2} \ln \tau_{\text{dep},0}
\]

for \( dN/dM \propto M^\gamma \)

fit predicts

slope of mass spectrum \( \gamma \)

intersection w/ y-axis: \( \tau_{\text{dep},0} \)
\[ \ln \tau_{\text{dep}} \approx -(\gamma + 1) \frac{|V_{\text{stream}}|^2}{4 \sigma^2} + \ln \tau_{\text{dep},0} \]

for \( dN/dM \propto M^\gamma \)
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for \( \frac{dN}{dM} \propto M^\gamma \)

Radius (arcsec) vs. \( \frac{V_{\text{stream}}^2}{4\sigma^2} \)
\[ \ln \tau_{\text{dep}} \approx -(\gamma + 1) \frac{|v_{\text{stream}}|^2}{4\sigma^2} + \ln \tau_{\text{dep},0} \]

for \( \frac{dN}{dM} \propto M^\gamma \)

\( v_{\text{stream}}^2 / 4\sigma^2 \)
\[ \ln \tau_{\text{dep}} \approx -(\gamma + 1) \frac{|v_{\text{stream}}|^2}{4\sigma^2} + \ln \tau_{\text{dep,0}} \]

for \( dN/dM \propto M^\gamma \)
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for \( dN/dM \propto M^\gamma \)

fit predicts

slope of mass spectrum \( \gamma \)

intersection w/ y-axis: \( \tau_{\text{dep,0}} \)

\(<\gamma> = -1.6 \pm 0.5 \)
\(<\gamma> = -1.7 \pm 0.25 \)

direct fits to spectra (Hughes et al. 2012)

\(<\tau_{\text{dep,0}}> \sim 1\text{Gyr} \)
\(<\tau_{\text{dep}}> = 2.5\text{Gyr} \)

~ ‘universal’ depletion time (Bigiel et al. 2008)
are the ‘normal’ spiral galaxies really normal?

- dynamical pressure in the presence of streaming motions driven by torques

- comparable to dwarfs with Galactic $X_{\text{CO}}$, starbursts?

![Graph showing molecular surface density and star formation rate](image)

- symbol size $\sim$ streaming$^{1/2}$
- lines of constant $\tau_{\text{dep}}$
- streaming lengthens $\tau_{\text{dep}}$ to 2 Gyr

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are the ‘normal’ spiral galaxies really normal?

\[ \sum_{SFR} = \sum_{gas} \frac{e^{(Y+1) \frac{v_s^2}{\sigma^2}}}{\tau_{dep,0}} \]

- K98 ‘normal’ spirals
  - dark:light
  - early late

lines of constant \( \tau_{dep} \)
Trends with Morph. type

\[ v_{\text{stream}} \sim m (\Omega - \Omega_p) R \tan \theta \frac{\Sigma}{\Sigma_0} \]
\[ \sim m V_c \tan \theta \frac{\Sigma}{\Sigma_0} \]
\[ \sim \frac{V_c}{m} \frac{\Sigma}{\Sigma_0} \]

\{ \text{away from CR} \}

\[ \rightarrow \text{early type spirals have longer globally-averaged } T_{\text{dep}} \]

\( i_p = \text{pitch angle} \)
\( V_c = \text{rot. velocity} \)
\( m\text{-armed symmetry} \)
Trends with Morph. type

\[ V_{\text{stream}} \sim m (\Omega - \Omega_p) R \tan i_p \frac{\Sigma}{\Sigma_0} \]
\[ \sim m V_c \tan i_p \frac{\Sigma}{\Sigma_0} \]
\[ \sim \frac{V_c}{m} \frac{\Sigma}{\Sigma_0} \}

away from CR

\[ \rightarrow \] early type spirals have longer globally-averaged \( T_{\text{dep}} \)

\( i_p = \)pitch angle
\( V_c = \)rot. velocity
\( m\)-armed symmetry

\[ \text{‘starburst’} \]
COLD GASS:
Saintonge et al. (2013)
implications, locally and at high-z

- **early-type spirals** have *longest* depletion times
- **dwarfs, starbursts** (little spiral-driven streaming): *short* depletion times
- *why 2 Gyr? because spirals typically drive streaming* $v_s = 10-15 \text{ km s}^{-1}$

Meidt et al. (2013)
implications, locally and at high-z

- **early-type spirals** have *longest* depletion times
- **dwarfs, starbursts** (little spiral-driven streaming): *short* depletion times
- *why 2 Gyr? because spirals typically drive streaming*
  \(v_S = 10-15 \text{ km s}^{-1}\)
- **at high-z** high gas fraction: *short* depletion time

\[
\tau_{\text{dep}} \propto \frac{V_S}{\sigma} \propto \left(\frac{2\beta+1}{Q_F g}\right)^{1/2}
\]

\(\tau_{\text{dep}}\) linked to gas fraction
(high \(F_g\) --> weakened sensitivity to environment-decoupling)

*RC shape*  
*gas fraction*  
*Meidt et al. (2013)*
Daddi et al. (2010) gas fraction

cf. Tacconi et al. (2010); Combes et al. (2013)
Take Away

- non-circular streaming motions suppress star formation and lengthen depletion time
- star-forming disk galaxies have $\tau_{\text{dep}}=2$ Gyr (in contrast to nominal 1 Gyr in systems without non-axisymmetric structures)