Dynamically regulated star formation: the role of gas flows on ISM structure

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with

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stellar mass  molecular gas

SINGS
Kennicutt et al. (2003)

HERACLES
Leroy et al. (2008)

slide following A. Leroy
SINGS
Kennicutt et al.
(2003)

HERACLES
Leroy et al.
(2008)

SFR
molecular gas

NGC 6946

NGC 3184

NGC 4321

slide following A. Leroy
high gas surface density, little star formation

NGC 4303
high gas surface density, little star formation
spatially-resolved star formation relation

Bigiel et al. (2008;2011)

\[ \Sigma_{\text{SFR}} = \Sigma_{\text{H}_2} \]

10s-100s clouds per resolution element

1 kpc resolution
Equal weighting per point.

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spatially-resolved star formation relation

Bigiel et al. (2008;2011)

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

constant molecular gas depletion time

$T_{\text{dep}} = \frac{\Sigma_{\text{H}_2}}{\Sigma_{\text{SFR}}}$
spatially-resolved star formation relation

Bigiel et al. (2008;2011)

10s-100s clouds per resolution element

constant molecular gas depletion time

$T_{\text{dep}} = \frac{\Sigma \text{H}_2}{\Sigma \text{SFR}}$

Is there a ‘universal cloud’?

cloud scaling relations
spatially-resolved star formation relation

Bigiel et al. (2008; 2011)

\[ \tau_{\text{dep}} = \frac{\Sigma_{\text{H}_2}}{\Sigma_{\text{SFR}}} \]

Is there a ‘universal cloud’?

Cloud scaling relations

is there a mix of active and non-active clouds?
spatially-resolved star formation relation

Bigiel et al. (2008;2011)

\[
\sum_{\text{SFR}} = \sum_{\text{H}_2}
\]

Is there a ‘universal cloud’?

\[
\tau_{\text{dep}} = \frac{\sum_{\text{H}_2}}{\sum_{\text{SFR}}}
\]

constant molecular gas depletion time

- Is there a mix of active and non-active clouds?
- What is the role of dynamical environment?
CO(1–0) in central 9kpc at GMC resolution (40pc, \(10^5\)M\(_{\text{sun}}\))
PAWS: Highest resolution map of M51

PAWS (PI: Schinnerer)

IRAM
30m: 40 hr
PdBI: 170 hr

CO(1-0) in central 9kpc at cloud resolution (40pc, $10^5 M_{\odot}$)

see also Koda et al. (2011)
~100pc resolution
PAWS: Highest resolution map of M51

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CO(1-0) in central 9kpc at cloud resolution (40pc, $10^5 M_{\text{Sun}}$)

see also Koda et al. (2011)
~100pc resolution
cloud properties depend on environment!

CPROPS decomposition
Rosolowsky & Leroy (2006)
catalog of >1000 clouds!

Hughes, Meidt et al. (2013a)
Colombo et al. (2014a)
cloud properties depend on environment!

PAWS
Hughes, Meidt et al. (2013a)
Colombo et al. (2014a)

CPROPS decomposition
Rosolowsky & Leroy (2006)
catalog of >1000 clouds!

clouds in ARM are
• brighter,
• more massive,
• higher gas surface density

compared to inter-ARM
cloud properties depend on environment!  

*the role of spiral arms*

Colombo et al. (2014a)

*spiral arms* sweep up material, aid in formation via instability

mass spectrum: formation/destruction

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cloud properties depend on environment! **the role of spiral arms**

Colombo et al. (2014a)

**spiral arms** sweep up material, aid in
- formation via instability  **number**
- cloud mass growth via collision/agglomeration  **high mass end**

clouds destroyed via shear and feedback in interarm

mass spectrum: formation/destruction
cloud properties depend on environment! 

cloud ‘scaling relations’

Hughes, Meidt et al. (2013a)
cloud properties depend on environment! "cloud ‘scaling relations’"

$\Sigma$ and $<\sigma>/R$ vary with galactic environment
Cloud properties depend on environment! *Cloud ‘scaling relations’*

- Clouds in M51 are brighter, more massive, and have a higher gas surface density compared to in low-mass galaxies.

**Cloud 'scaling relations'**

\[ \Sigma \text{ and } \frac{<\sigma>}{R} \text{ vary with galactic environment} \]

Completely unexpected: NO ‘Universal’ cloud. Clouds ‘know’ about their environment.
Role of External Pressure

Hughes, Meidt et al. (2013a)

KEY: surface pressure important!

clouds coupled to surroundings
Impact of (dynamical) environment
Impact of (dynamical) environment

- dynamical suppression/regulation of star formation via pressure changes in flows
  - test: M51 cloud stability, pressure + gas motions
  - implications for universal SF relation
Role of gas flows:

not all gas forms stars equally:

**disk structures** drive gas **flows**

gas flows REDUCE external pressure, 
**increase cloud stability**
Role of gas flows:

not all gas forms stars equally:

**disk structures** drive gas **flows**

gas flows **REDUCE** external pressure, **increase cloud stability**

**RESULT:**

lower star formation rate, increase in gas depletion time
dynamical pressure

Meidt et al. (2013)
dynamical pressure

Meidt et al. (2013)
dynamical pressure

Bernoulli: gas in motion, reduced pressure

Meidt et al. (2013)
dynamical pressure

- Bernoulli: gas in motion, reduced pressure
- increased cloud stable mass (bigger before collapse)
- fewer collapse-unstable clouds
- lower star formation, longer $\tau_{\text{dep}}$

Meidt et al. (2013)
Projected velocity field of M51

~50 km s$^{-1}$ non-circular streaming motions!

Colombo, Meidt et al. (2014b)
Projected velocity field of M51

Colombo, Meidt et al. (2014b)

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

Approaching

Receding

~50 km s\(^{-1}\) non-circular streaming motions!
Projected velocity field of M51

Colombo, Meidt et al. (2014b)

~50 km s\(^{-1}\) non-circular streaming motions!
Projected velocity field of M51

~50 km s$^{-1}$ non-circular streaming motions!

Colombo, Meidt et al. (2014b)
large variations in gas streaming motions
large variations in gas streaming motions
Molecular Gas disk of M51

PAWS (PI: Schinnerer)

IRAM
30m: 40 hr
PdBI: 170 hr

CO(1-0) in central 9 kpc at cloud resolution (40 pc, $10^5 M_{\text{Sun}}$)
Molecular Gas vs. UV

white contours: CO
Molecular Gas vs. obscured SF

PACS 70μm

white contours: CO
Molecular Gas vs. obscured SF

\[ \frac{\Sigma_{\text{mol. gas}}}{\Sigma_{\text{SFR}}} \]

'universal' time (Bigiel et al. 2008)
GMC Stabilization in M51

what shuts off star formation?

support *not* from the usual suspects:

Meidt et al. (2013)
GMC Stabilization in M51

what shuts off star formation?

support *not* from the usual suspects:

- spiral arm shear

Meidt et al. (2013)
GMC Stabilization in M51
what shuts off star formation?

support *not* from the usual suspects:

- spiral arm shear
- enhanced turbulent motions

*Meidt et al. (2013)*
GMC Stabilization in M51
what shuts off star formation?

support not from the usual suspects:

• spiral arm shear

• enhanced turbulent motions

• stellar feedback (little Hα, UV, clusters <70Myr)
dynamical pressure  A Quantitative approach

cloud mass spectrum

dN/dM \propto M^\gamma

Meidt et al. (2013)
A Quantitative approach

dynamical pressure

cloud mass spectrum

\[ \text{stable} \quad \text{unstable} \]

\[ \log N_{cl} \frac{(m>M)}{kpc^2} \]

\[ \log M_{\text{lum}} [M_{\text{sun}}] \]

power-law with

\[ \frac{dN}{dM} \propto M^\gamma \]

Meidt et al. (2013)
dynamical pressure

A Quantitative approach

Cloud mass spectrum

$\log N_{cl} [(m>M)/kpc^2]$ vs $\log M_{lum} [M_{\odot}]$

- Stable
- Unstable

Power-law with

$\frac{dN}{dM} \propto M^\gamma$

With $v_{\text{stream}}$

Pressure decreased, stable mass raised

Meidt et al. (2013)
A Quantitative approach

dynamical pressure

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

\( \text{cloud mass spectrum} \)

\[ \log N_{\text{cl}} \left( \frac{m > M}{\text{kpc}^2} \right) \]

\[ \log M_{\text{lum}} \left[ M_{\odot} \right] \]

stable

unstable

With a power-law mass spectrum

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

Pressure decreased, stable mass raised

Meidt et al. (2013)
dynamical pressure

A Quantitative approach

cloud mass spectrum

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

power-law with \( dN/dM \propto M^\gamma \)

with \( v_{\text{stream}} \)

pressure decreased, stable mass raised

depletion time

\[
\tau_{\text{dep}} = \frac{\Sigma \text{H}_2}{\Sigma \text{SFR}}
\]

Meidt et al. (2013)
dynamical pressure  A Quantitative approach

cloud mass spectrum

\[
\log N_{\text{cl}} [(m>M)/kpc^2] \quad \log M_{\text{lum}} [M_{\odot}]
\]

stable \hspace{1cm} unstable

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

depletion time
\[
\tau_{\text{dep}} = \frac{\Sigma H_2}{\Sigma SFR}
\]

slope of cloud mass spectrum
\[-1.3 < \gamma < -1.7\]

Meidt et al. (2013)
dynamical pressure

A Quantitative approach

cloud mass spectrum

power-law with
\( \frac{dN}{dM} \propto M^\gamma \)

with \( v_{\text{stream}} \)

pressure decreased, stable mass raised

\[
\ln \left( \frac{\Sigma H_2}{\Sigma SFR} \right) \approx -(\gamma + 1) \frac{v_{\text{stream}}^2}{4\sigma^2}
\]

depletion time
\( \tau_{\text{dep}} = \frac{\Sigma H_2}{\Sigma SFR} \)

measure from observed kinematics

slope of cloud mass spectrum
\(-1.3 < \gamma < -1.7\)

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Meidt et al. (2013)
\( \ln \tau_{\text{dep}} \approx -(\gamma + 1) \frac{|v_{\text{stream}}|^2}{4\sigma^2} + \ln \tau_{\text{dep},0} \)

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

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Meidt et al. (2013)
\[ \ln \tau_{\text{dep}} \approx -(\gamma + 1) \left( \frac{V_{\text{stream}}}{4\sigma^2} \right)^2 + \ln \tau_{\text{dep}, 0} \]

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only where \(|\gamma| > 1\)

streaming motions lengthen gas depletion time

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Meidt et al. (2013)
Scatter in star formation relation: gas motions

The scatter in the star formation relation can be attributed to gas motions. Streaming lengthens \( \tau_{\text{dep}} \) to 2 Gyr, as shown in the diagram. The data points represent lines of constant gas depletion time, with the green points indicating different timescales.

\( \log (\text{molecular surface density}) \) vs. \( \log (\text{SFR surf. dens.}) \)

Meidt et al. (2013)
Clouds in their *dynamical* environment

- clouds *coupled* to environment: external + internal pressures similar!
Clouds in their *dynamical* environment

- clouds **coupled** to environment: external + internal pressures similar!

- pressure **reduced** due to streaming motions
Clouds in their *dynamical* environment

- clouds *coupled* to environment: external + internal pressures similar!
- pressure *reduced* due to streaming motions
- clouds stabilized, *star formation suppressed*
Clouds in their *dynamical* environment

- clouds **coupled** to environment: external + internal pressures similar!
- pressure **reduced** due to streaming motions
  - clouds stabilized, *star formation suppressed*

*explains:*
- scatter in `1 kpc` star formation relation
- range in depletion times between galaxies, from present-day to starbursts and disks at high-z
Star Formation Relation

spirals, starbursts from Kennicutt (1998)
Star Formation Relation

Two modes of star formation?adopted in cosmological simulations, Krumholz, Dekel & McKee (2011)

'Starbursts'

'Spirals, starbursts' from Kennicutt (1998)
• gas forms stars in a **single** fundamental mode

• departures from this mode due to presence of gas motions

• **clouds prevented from forming stars**
Star Formation Relation

are ‘normal’ spirals really normal??

'normal disks'

short $\tau_{\text{dep}}$

long $\tau_{\text{dep}}$

'starbursts'

M51

early late

$\log \Sigma_{\text{SFR}} \left( M_{\odot} \text{ kpc}^{-2} \text{ yr}^{-1} \right)$

$\log \Sigma_{\text{H}_2} \left( M_{\odot} \text{ pc}^{-2} \right)$
Star Formation Relation

are ‘normal’ spirals really normal??

are ‘normal’ spirals really normal??

M51

‘normal disks’

‘starbursts’

long $T_{\text{dep}}$

short $T_{\text{dep}}$

early late

$\Sigma_{\text{SFR}}$ ($M_{\text{sol}}$ kpc$^{-2}$ yr$^{-1}$)

$\Sigma_{\text{H2}}$ ($M_{\text{sol}}$ pc$^{-2}$)
Star Formation Relation

are ‘normal’ spirals really normal??

'Starbursts'

'M51'

'Short $\tau_{dep}$'

'Long $\tau_{dep}$'

'Normal disks'

early late

$\log \Sigma_{SFR} (M_{sol} kpc^{-2} yr^{-1})$

$\log \Sigma_{H2} (M_{sol} pc^{-2})$
Trends with disk morphology

since gas motions are larger in more massive disks, $\tau_{\text{dep}}$ larger in more massive disks

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*Leroy et al. 2013*

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**strong streaming**

**weak streaming**

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Trends with disk morphology

since gas motions are larger in more massive disks, \( \tau_{\text{dep}} \) larger in more massive disks

Leroy et al. 2013

Young et al. (1996)

…IR

…H\( \alpha \)

‘starburst’

strong streaming

Morphology weak streaming

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COLD GASS:
Saintonge et al. (2013)
Take Away

is there a universal cloud?
Take Away

is there a universal cloud?

No
Take Away

is there a universal cloud?  
**No**

is there a mix of active + non-active clouds?

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Take Away

is there a universal cloud?  No

is there a mix of active + non-active clouds?  Yes!
Take Away

- is there a universal cloud? **No**
- is there a mix of active + non-active clouds? **Yes!**

- conversion of gas to stars impacted by galactic dynamics
Take Away

is there a universal cloud?  
No

is there a mix of active + non-active clouds?  
Yes!

• conversion of gas to stars impacted by galactic dynamics
Take Away

- conversion of gas to stars impacted by galactic dynamics
- non-circular streaming motions suppress star formation and lengthen depletion time

is there a universal cloud? **No**
is there a mix of active + non-active clouds? **Yes!**
Take Away

- conversion of gas to stars impacted by galactic dynamics

- non-circular streaming motions suppress star formation and lengthen depletion time

is there a universal cloud?  
No

is there a mix of active + non-active clouds?  
Yes!

S. E. Meidt, 3D2014, March 10
Take Away

is there a universal cloud? is there a mix of active + non-active clouds?
No Yes!

• conversion of gas to stars impacted by galactic dynamics

• non-circular streaming motions suppress star formation and lengthen depletion time

• physical interpretation for scatter in ‘Kennicutt-Schmidt’ star formation relation + a smooth link to high-z star formation
Impact of environment

- dynamical suppression/regulation of star formation
  - test: M51 cloud stability, pressure + gas motions
  - implications for universal SF relation

- cloud lifetimes

- internal cloud structure
Cloud lifetimes

- clouds destroyed by shear, star formation feedback
- processes can be isolated in M51
  - in one radial zone: only shear (no feedback)

\textit{natural limit to timescale to convert gas in to stars}
Cloud lifetimes

natural limit to timescale to convert gas in to stars

Meidt et al. (2014, in prep.)
Cloud lifetimes

natural limit to timescale to convert gas in to stars

Meidt et al. (2014, in prep.)

S. E. Meidt, 3D2014, March 10
Cloud lifetimes

natural limit to timescale to convert gas in to stars

finite lifetime, number decreases

Meidt et al. (2014, in prep.)
Cloud lifetimes

natural limit to timescale to convert gas in to stars

finite lifetime, number decreases

\[
\frac{N_{\text{up}}}{N_{\text{down}}} = \frac{T_{\text{GMC}}}{T_{\text{travel}}}
\]

Meidt et al. (2014, in prep.)
natural limit to timescale to convert gas in to stars

“unstable” susceptible to Coriolis forces

“stable” against Coriolis forces

Meidt et al. (2014, in prep.)
Cloud lifetimes

- More clouds in zone I (unstable to Coriolis forces)
- More clouds in zone II (stable to Coriolis forces)
Cloud lifetimes

Zone I
- More clouds
- Unstable to Coriolis forces

Zone II
- More clouds
- Stable to Coriolis forces
split inter-arm in half

constant $\tau$

Shear

Feedback

$M > M_{\text{crit}}$

$M < M_{\text{crit}}$

$N_r / N_i$

Radius (arcsec)

constant $\tau$

S. E. Meidt, 3D2014, March 10
split inter-arm in half
split inter-arm in half

unstable to Coriolis forces

stable to Coriolis forces

$\tau$

constant
Cloud lifetimes

\[ \frac{N_{\text{Up}}}{N_{\text{Down}}} \times T_{\text{travel}} \]

consistent with Dobbs 2006; Fukui & Kawamura (2010) in LMC
Scatter in the Star Formation relation

Bigiel et al. (2008)
Scatter in the Star Formation relation

- 2 modes of star formation?
- scale-dependent scatter: ‘discreteness + stochasticity’:
  - temporal & spatial decoupling of gas and stars
  - stellar feedback--cloud dispersal/destruction

Bigiel et al. (2008)

S. E. Meidt, 3D2014, March 10
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log(star formation rate)

log(gas surface density)

250pc 500pc 750pc

Bigiel et al. (2008)
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250pc 500pc 750pc

Bigiel et al. (2008)
Scatter in the Star Formation relation

- 2 modes of star formation?
- scale-dependent scatter: ‘discreteness + stochasticity’:
- galaxy dynamics

Bigiel et al. (2008)
Dobbs & Pringle (2013)