Star Formation Regulation on Cloud Scales

Eva Schinnerer (MPIA)
What regulates star formation?

universe
- dark matter \rightarrow \text{structure evolution}

- galaxies
  - dark, baryonic matter \rightarrow \text{molecular gas}

- GMC (Giant Molecular Cloud)
  - GMC, molecular gas \rightarrow \text{dense gas}

- dense gas
  - dense gas fraction \rightarrow \text{dense cores}

- dense core
  - dense core \rightarrow \text{formation of stars}
What regulates star formation?

universe → dark matter → structure evolution

galaxies

dark,baryonic matter → molecular gas

GMC (Giant Molecular Cloud)

GMC,molecular gas → dense gas

dense gas

dense gas fraction → dense cores

dense core

dense core → formation of stars
What regulates star formation?

- universe
  - dark matter → structure evolution
- galaxies
  - dark, baryonic matter → molecular gas
- GMC (Giant Molecular Cloud)
  - GMC, molecular gas → dense gas
- dense gas
  - dense gas fraction → dense cores
- dense core
  - dense core → formation of stars
What regulates star formation?

universe
  dark matter $\rightarrow$ structure evolution

galaxies
  dark, baryonic matter $\rightarrow$ molecular gas

GMC (Giant Molecular Cloud)
  GMC, molecular gas $\rightarrow$ dense gas

dense gas
  dense gas fraction $\rightarrow$ dense cores

dense core
  dense core $\rightarrow$ formation of stars
What regulates star formation?

universe
- dark matter → structure evolution

galaxies
- dark, baryonic matter → molecular gas

GMC (Giant Molecular Cloud)
- GMC, molecular gas → dense gas

dense gas
- dense gas fraction → dense cores

dense core
- dense core → formation of stars
What regulates star formation?

Impact of galactic structure?

- Universe
  - Dark matter → Structure evolution
- Galaxies
  - Dark, baryonic matter → Molecular gas
  - GMC (Giant Molecular Cloud)
    - GMC, molecular gas → Dense gas
  - Dense gas
    - Dense gas fraction → Dense cores
- Dense core
  - Dense core → Formation of stars
Stars form in molecular gas... with roughly constant efficiency (a.k.a 'SF law').

Results from 40 nearby galaxies, resolution: 1 kpc.

(Schuruba et al. 2011)
PdBI Arcsecond Whirlpool Survey

http://www.mpi-a.de/PAWS

data cubes, moment maps, GMC catalog
@ 1", 3", 6" resolution for $^{12}\text{CO}(1-0)$
22" resolution for $^{12}\text{CO}(1-0), ^{13}\text{CO}(1-0)$ for entire M51a

GMC resolution (40 pc, $10^5 M_{\odot}$)

$M_* = 3.6 \times 10^{10} M_\odot$
$\mu_{\text{mol}} = 0.17$
$\mu_{\text{gas}} = 0.25$
molecular gas disk of M51 - resolution is key

Schuster et al. (2007)

single dish telescope (~ 500 pc)
typical 'survey quality'

resolution element
of previous studies
molecular gas disk of M51 - resolution is key

Schinnerer et al. (2013)
mm-interferometer (~ 40 pc)

now
Molecular gas and star formation in spiral galaxies

#1: 3D distribution of molecular gas differs from atomic gas one.

#2: Giant Molecular Cloud properties are set by environment.

#3: Conversion of molecular gas into stars is complex process.
Molecular gas and star formation in spiral galaxies

#1: 3D distribution of molecular gas differs from atomic gas one

#2: Giant Molecular Cloud properties are set by environment

#3: Conversion of molecular gas into stars is complex process
molecular gas is more clumped than atomic gas ...
... small scale distributions can vary significantly

Leroy et al. (2013)
Molecular & atomic gas are distributed differently

molecular gas is more clumped than atomic gas ...
... small scale distributions can vary significantly

Leroy et al. (2013)

molecular and atomic gas kinematics are not the same ...
... molecular and atomic phase probe different gas distributions

Colombo et al. (2014b)

residual velocity fields

pixel-by-pixel comparison

molecular gas (PAWS)  atomic gas (THINGS)
Extra-planar molecular gas in M51

Pety et al. (2013)

interferometer = spatial filter:
- **PdBI+30m**: all scales
- **PdBI-only**: small scales
- ‘missing flux’: large scales

\[ \sim 50\% \text{ of emission from } >1.3\text{kpc} \]
Extra-planar molecular gas in M51

Pety et al. (2013)

interferometer = spatial filter:

**PdBI+30m** : all scales
**PdBI-only** : small scales
‘missing flux’ : large scales

\[ \sim 50\% \text{ of emission from scales } > 1.3 \text{kpc} \]

\[ \theta = 6'' \]

\[ T \text{ (K)} \]

\[ \text{Equivalent FHWM (km/s)} \]

\[ \text{Radius (arcsec)} \]

in dynamically hot, thick disk
Extra-planar molecular gas

in M51:
evidence for extended extra-planar (~250pc scale height) molecular gas
Pety et al. (2013)
in 12 nearby galaxies:
similar CO(2-1) and HI line widths suggest presence of extra-planar gas
Caldu Primo et al. (2013)
in M51: evidence for extended extra-planar (~250pc scale height) molecular gas

in 12 nearby galaxies: similar CO(2-1) and HI line widths suggest presence of extra-planar gas

Pety et al. (2013)

Caldu Primo et al. (2013)
in M51: evidence for extended extra-planar (~250pc scale height) molecular gas (Pety et al. 2013)
in 12 nearby galaxies: similar CO(2-1) and HI line widths suggest presence of extra-planar gas (Caldu Primo et al. 2013)

in models: dense gas expelled from disk by stellar feed-back (Dobbs, Burkert, Pringle 2011)
Molecular gas and star formation in spiral galaxies

#1: 3D distribution of molecular gas differs from atomic gas one

#2: Giant Molecular Cloud properties are set by environment

#3: Conversion of molecular gas into stars is complex process
Cloud properties are universal

Consistent study of 12 nearby galaxies (Bolatto et al. 2008)

GMCs are/have:

- virialized
- constant surface density

\[ \log(\text{radius}) \quad \log(\text{CO luminosity}) \]

\[ \log(\text{velocity dispersion}) \]

\[ \log(\text{velocity dispersion}) \quad \log(\text{radius}) \]
Molecular Gas Studies in Nearby Galaxies

M51
$M_*: 3.6 \times 10^{10} \, M_{\odot}$

LMC
$M_*: 2.7 \times 10^{9} \, M_{\odot}$

M33
$M_*: \sim 5 \times 10^{9} \, M_{\odot}$
Cloud properties are not universal.
Cloud properties are not universal

- Large range of gas surface densities
- GMC properties are not universal

No size-line width relation

Clouds are not (always) virialized

Large range of gas surface densities

GMC properties are not universal
Consistent conversion factor in M51

Groves et al. (in prep.)

dust-to-gas ratio  clouds’ virial mass  Large Velocity Gradient (LVG)
Consistent conversion factor in M51

Groves et al. (in prep.)

\( \alpha_{CO} \approx \) Galactic value & consistent (w/i 2x) across methods
Do spiral arms impact cloud properties?

**clouds grow across spiral arm (M51, IC342):**

- small clouds cluster/collide while crossing spiral arm (Egusa, Koda & Scoville 2010)

- small/diffuse clouds coalesce due to convergent flows and self-gravity (Hirota et al. 2011)
Do spiral arms impact cloud properties?

clouds grow across spiral arm (M51, IC342):
  - small clouds cluster/collide while crossing spiral arm
  - small/diffuse clouds coalesce due to convergent flows and self-gravity

numerical simulations:
  - more high mass clouds, but typical cloud unchanged

Egusa, Koda & Scoville (2010)
Hirota et al. (2011)
Fujimoto et al. (2014)
Galactic environments in M51
Galactic environments in M51

- Spiral arm
- Central region
- Inter-arm
Galactic environments in M51
Molecular gas structure varies with environment

PDF - Probability Distribution Function

gas density

(local) MW clouds

e.g. Federrath (2013)
Molecular gas structure varies with environment

PDF - Probability Distribution Function

Kainulainen et al. (2011)

(log-normal)

s = log T

e.g. Federrath (2013)

(local) MW clouds
gas density

(log-normal)

(turbulent)
Molecular gas structure varies with environment

**PDF - Probability Distribution Function**

(l) MW clouds

gas density

Kainulainen et al. (2011)

log-normal
(turbulent)

power law
(star forming)

\[ s = \log T \]

e.g. Federrath (2013)
Molecular gas structure varies with environment

PDF - Probability Distribution Function

Kainulainen et al. (2011)

(log-normal (turbulent))

power law (star forming)

s = log T

gas density

(local) MW clouds

e.g. Federrath (2013)
Molecular gas structure varies with environment

PDF - Probability Distribution Function

\[ s = \log(T_{mb}/[K]) \]

Hughes et al. (2013a)

PDF - Probability Distribution Function

- Nuclear bar
- Molecular ring
- Inner arm
- Material arm
- Upstream
- Downstream

Hughes et al. (2013a)
GMC properties vary with environment

Giant Molecular Cloud (GMC) mass function

Columbo et al. (2014a)
GMC properties vary with environment

Giant Molecular Cloud (GMC) mass function

Columbo et al. (2014a)

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

\[ \log M_{\text{lum}} [M_{\odot}] \]
GMC properties vary with environment

Giant Molecular Cloud (GMC) mass function

Columbo et al. (2014a)

![Graph showing GMC properties varying with environment with log Ncl vs log Mlum [Msun] and different markers for different environments such as Nuclear Bar, Nuclear Ring, Dens-Wave Arms Out, Dens-Wave Arms In, Material Arms, Upstream, and Downstream.]
GMC properties vary with environment

Giant Molecular Cloud (GMC) mass function

Columbo et al. (2014a)
GMC properties vary with environment

Giant Molecular Cloud (GMC) mass function

Columbo et al. (2014a)

**disk clouds**
- grow in spiral arm via agglomeration merging/collision
- dispelled in inter-arm star formation shear
GMC properties vary with environment

Giant Molecular Cloud (GMC) mass function

**disk clouds**
- grow in spiral arm via agglomeration merging/collision
- dispelled in inter-arm star formation shear

Columbo et al. (2014a)
GMC properties vary with environment

Giant Molecular Cloud (GMC) mass function

**disk clouds**
- Grow in spiral arm via agglomeration, merging/collision
- Dispelled in inter-arm star formation shear

**center clouds**
- Growth limited due to radiation field
- AGN
- Central bar

Columbo et al. (2014a)
GMC properties vary with environment

Giant Molecular Cloud (GMC) mass function: slope & truncation mass

- LMC
- M33
- N628
- M31
- N6946
- M51

Stellar Mass

- Mass Spectrum Slope (TPFL)
- Log(Truncation Mass)

Σ(stars)

- Mass Spectrum Slope (TPFL)
- Log(Truncation Mass)

Σ(gas)

- Mass Spectrum Slope (TPFL)
- Log(Truncation Mass)

Rmol

Hughes et al. (in prep.)
GMC properties vary with environment

Giant Molecular Cloud (GMC) mass function: slope & truncation mass

GMC mass function is not universal: strong trend w/ mass of system
1) associate clouds with SF regions
1) associate clouds with SF regions

2) compare cloud numbers associate with travel time $t_{\text{travel}}$

Meidt et al. (2015)
1) associate clouds with SF regions

2) compare cloud numbers associate with travel time $t_{\text{travel}}$

$T_{\text{GMC}} = t_{\text{travel}}/2 \times N_{I}/(N_{I} - N_{II})$
GMC lifetimes in M51

Meidt et al. (2015)

\[ \tau_{\text{shear}} = (\text{Oort} \tau_{\text{travel}}) \]
GMC lifetimes in M51

\[ \tau_{\text{shear}} = (Oort) \]

\( \tau_{\text{travel}} \)

shear only
GMC lifetimes in M51

\[ \tau_{\text{shear}} = (\text{Oort} \tau_{\text{travel}}) \]

Meidt et al. (2015)
GMC lifetimes in M51

Meidt et al. (2015)

GMC lifetimes $\sim$20-30 Myr set by shear timescale

similar value: LMC (Kawamura et al. 2009), M33 (Miura et al. 2012), MW (e.g. Bash et al. 1977)
Molecular gas and star formation in spiral galaxies

#1: 3D distribution of molecular gas differs from atomic gas one

#2: Giant Molecular Cloud properties are set by environment

#3: Conversion of molecular gas into stars is complex process
No relation between gas density and star formation
No relation between gas density and star formation
No relation between gas density and star formation

coincident star formation
No relation between gas density and star formation
No relation between gas density and star formation
No relation between gas density and star formation

**coincident**  **no**  **offset**  star formation

molecular gas surface density is bad predictor for star formation rate surface density
The gas-SFR relation in M51

@ 800pc: $^{12}$CO(1-0),(2-1),(3-2), $^{13}$CO(1-0), 24μm, TIR, Hα, FUV, 20cm, 6cm, 3.6cm ...

Leroy et al. (in prep.)
The gas-SFR relation in M51

@ 800pc: $^{12}\text{CO}(1-0),(2-1),(3-2),^{13}\text{CO}(1-0), 24\mu\text{m}, \text{TIR}, \text{H} \alpha, \text{FUV, 20cm, 6cm, 3.6cm ...}$

Leroy et al. (in prep.)
The gas-SFR relation in M51

Leroy et al. (in prep.)

$^{12}\text{CO(1-0),(2-1),(3-2)}$

$^{13}\text{CO(1-0)}$

$\text{HCN(1-0)}$

$\text{HCO+ (1-0)}$

dust

$\Sigma_{TIR}$

$\Sigma_{SFR}$

normalized line intensity

$\Sigma_{\text{SFR}}$
The gas-SFR relation in M51

$\Sigma_{\text{TIR}}$ vs. $\Sigma_{\text{SFR}}$

$\Sigma_{\text{TIR}}$ vs. normalized line intensity

$\Sigma_{\text{SFR}}$

- $^{12}\text{CO}(1-0, 2-1, 3-2)$
- $^{13}\text{CO}(1-0)$
- HCN(1-0)
- HCO+(1-0)
- dust

$Leroy et al. (in prep.)$
The gas-SFR relation in M51

Leroy et al. (in prep.)

\[ \Sigma_{\text{TIR}} \]

\[ \Sigma_{\text{SFR}} \]

normalized line intensity

\[ \sum_{\text{disk}} \]

\[ \sum_{\text{center}} \]

\[ ^{12}\text{CO}(1-0),(2-1),(3-2) \]

\[ ^{13}\text{CO}(1-0) \]

\[ \text{HCN}(1-0) \]

\[ \text{HCO}^+(1-0) \]

dust

Dust

CO 1–0

CO 2–1

CO 3–2

\[ ^{18}\text{CO} \]

\[ \text{HCO}^+ \]

\[ \text{HCN} \]
The gas-SFR relation in M51

Leroy et al. (in prep.)

\[ \Sigma_{\text{TIR}} \]

\[ \Sigma_{\text{SFR}} \]

\[ \sum \text{SFR} \]

\[ \sum \text{TIR} \]

normalized line intensity

disk

center

\[ ^{12}\text{CO}(1-0), (2-1), (3-2) \]

\[ ^{13}\text{CO}(1-0) \]

\[ \text{HCN}(1-0) \]

\[ \text{HCO}^+(1-0) \]

dust

scatter persists

in center:

slope flattens

(excitation effects?)
What if not all gas clouds form stars equally?
Impact of dynamical pressure

Meidt et al. (2013)

disk structures drive gas flows

gas flows increase cloud stability

lower SFR (star formation rate)
increase in depletion time
1,500 clouds identified in M51  
Colombo et al. (2014)

clouds in arm are:

- brighter
- more massive
- higher gas surface density
1,500 clouds identified in M51
Colombo et al. (2014)

clouds in arm are:

- brighter
- more massive
- higher gas surface density

Requirements for dynamical pressure
Hughes et al. (2013b, in prep.)
1,500 clouds identified in M51
Colombo et al. (2014)

clouds in arm are:

- brighter
- more massive
- higher gas surface density

clouds must “know” about environment

Requirements for dynamical pressure
Hughes et al. (2013b, in prep.)
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 $T_{\text{dep}}$

Meidt et al. (2013)
A Quantitative approach

Meidt et al. (2013)

dynamical pressure

cloud mass spectrum

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

log \( N_{cl} \) [(m>M)/kpc^2] vs. log \( M_{lum} \) [M\(_{\odot}\)]
A Quantitative approach

Meidt et al. (2013)

dynamical pressure

cloud mass spectrum

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

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

stable \quad unstable

power-law with

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

cloud mass spectrum

A Quantitative approach

Meidt et al. (2013)

dN/dM \propto M^\gamma

power-law with
dynamical pressure

A Quantitative approach

Meidt et al. (2013)

cloud mass spectrum

power-law with

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

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

pressure decreased, stable mass raised

stable

unstable

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

\[
\log M_{\text{lum}} \left[\text{M}_{\text{sun}}\right]
\]
A Quantitative approach

Meidt et al. (2013)

- **cloud mass spectrum**
  - stable
  - unstable

- **power-law with**
  - $dN/dM \propto M^\gamma$

- With $v_{\text{stream}}$
  - pressure decreased,
  - stable mass raised

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

Meidt et al. (2013)

dynamical pressure

cloud mass spectrum

$\log N_{cl} \quad [(m>M)/kpc^2]$ vs $\log M_{\text{lum}} \quad [M_{\text{sun}}]$ graph with stable and unstable regions.

$dN/dM \propto M^\gamma$

with $v_{\text{stream}}$

pressure decreased, stable mass raised

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

Depletion time

$T_{\text{dep}} = \frac{\Sigma_{H_2}}{\Sigma_{\text{SFR}}}$
A Quantitative approach

Meidt et al. (2013)

A cloud mass spectrum is shown, with a power-law relationship:

\[
dN/dM \propto M^\gamma
\]

where \( \gamma \) is the slope of the cloud mass spectrum, which is approximately -1.5.

The depletion time is defined as:

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

and is related to the velocity dispersion of the stream and the pressure term as:

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

where \( \sigma \) is the velocity dispersion, and \( v_{\text{stream}} \) is the velocity of the stream.

The dynamical pressure is discussed, with a decrease in pressure causing a raise in the stable mass.
dynamical pressure

A Quantitative approach

Meidt et al. (2013)

cloud mass spectrum

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

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

stable \quad unstable

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

power-law with \( v_{\text{stream}} \)

pressure decreased, stable mass raised

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

deployment time

\[ \tau_{\text{dep}} = \frac{\Sigma_{H_2}}{\Sigma_{\text{SFR}}} \]

measure from observed kinematics

slope of cloud mass spectrum \( \sim -1.5 \)
Gas motion introduces scatter in gas-SFR relation

Meidt et al. (2013)
Gas motion introduces scatter in gas-SFR relation

Gas streaming increases depletion time
Close look at spiral arm segment

CO(1-0)
Off-set star formation = stars form in spurs?

Schinnerer et al. (in prep.)
HII regions are off gas arm along spurs, but varying.

Off-set star formation = stars form in spurs?

Schinnerer et al. (in prep.)
HII regions are off gas arm along spurs, but varying hot dust (24 μm) associated with HII regions

Off-set star formation = stars form in spurs?

Schinnerer et al. (in prep.)
HII regions are off gas arm along spurs, but varying hot dust (24 μm) associated with HII regions

Off-set star formation = stars form in spurs?

Schinnerer et al. (in prep.)

young stellar clusters abundant off arm, along spurs
Onset of star formation delayed/prevented in spiral arm observations

young stars (<10 Myr)
molecular gas
Onset of star formation delayed/prevented in spiral arm

no significant star formation in arms, restricted to gas spurs

collapse of clouds delayed or prevented in spiral arm
Complex relation between clouds and stellar clusters

YSC and GMC properties tracked:

- maximum mass
- number density
- mass surface density

But ...
Complex relation between clouds and stellar clusters

\[ \text{slope}_{\text{GMC}} = \text{slope}_{\text{YSC}} + 0.3 \text{dex} \]

Hughes et al. (2013a)
Hughes et al. (2013a)

Complex relation between clouds and stellar clusters

\[
slope_{\text{GMC}} = slope_{\text{YSC}} + 0.3 \text{dex}
\]

YSC: Young Stellar Cluster
GMC: Giant Molecular Cloud

no feedback
Complex relation between clouds and stellar clusters

\[ \text{slope}_{\text{GMC}} = \text{slope}_{\text{YSC}} + 0.3 \text{dex} \]

YSC: Young Stellar Cluster
GMC: Giant Molecular Cloud

Fall et al. (2010)

Hughes et al. (2013a)
Hughes et al. (2013a)

**Complex relation between clouds and stellar clusters**

- YSC: Young Stellar Cluster
- GMC: Giant Molecular Cloud

\[ \text{slope}_{\text{GMC}} = \text{slope}_{\text{YSC}} \]

- no simple relation
- diverse set of mechanisms at work

Hughes et al. (2013a)
Star formation regulation on molecular cloud scales

#1: 3D distribution of molecular gas differs from atomic gas one

#2: Giant Molecular Cloud properties are set by environment

#3: Conversion of molecular gas into stars is a complex process. Spiral arms have significant impact, and ALMA will open up this research field.