The lifecycle of clouds and star-forming regions

Introduction

CMZ

Extragalactic

Outlook

J. M. Diederik Kruijssen
Heidelberg University

The evolutionary lifecycle of molecular clouds and star-forming regions across cosmic time
Uncertainties in SF & FB dominate in galaxy formation modelling

varying SF model
all else identical

varying FB model
all else identical

Gas surface density:
blue – red – yellow

Many of these choices make sense
We do not know which gives the right answer
What are the “physics of star formation & feedback”?

✦ How do the gas clouds in galaxies collapse to form stars? 
  free-fall vs. magnetic support

✦ Which feedback mechanism(s) halt(s) star formation? 
  supernovae, photoionisation, stellar winds, radiation pressure

✦ What is the resulting rate and efficiency of star formation?

\[
SFR = \frac{\epsilon}{t_{SF}} M_{\text{gas}}
\]

Common denominator: time-evolution
The lifecycle of clouds and star-forming regions

Cosmic SFR peaked at redshift $z = 2–3$

✧ A priori no way of knowing if Local Group constraints are universal

"extreme" star formation is *normal*
"normal" star formation is *unusual*
Star formation in the Galactic centre

- 600 pc from the Galactic centre
- 10 pc from the Galactic centre

The lifecycle of clouds and star-forming regions

J. M. Diederik Kruijssen – Heidelberg University
The nearest ‘extreme’ environment is the Central Molecular Zone (CMZ)

Gas conditions are similar to those in high-redshift galaxies

Kruijssen & Longmore 13


**Suppressed star formation in the CMZ**

✧ Despite high pressures gas under-produces stars by factor of 10–100

*Longmore+13a; Kruijssen+14b*

---

**Diagram:**

- **Gas surface density** vs. **Star formation rate**
- **Black filled symbols** = dense gas in clouds and galaxies
- **Galactic Centre dense gas** (Longmore+13a)
Suppressed star formation in the CMZ

✧ Despite high pressures gas under-produces stars by factor of 10–100; The same is observed in other galaxy bulges and the most massive galaxies

Longmore+13a; Kruijssen+14b; Davis+14
WHY IS THE SFR LOW?
A self-consistent cycle of star formation?

Various mechanisms combine into a single cycle

- Turbulence driving
- Acoustic instability of in-flowing gas
- High, environmentally-dependent density threshold for star formation
- Gas mass builds up to threshold for gravitational instability
- Gravitational instability drives gas to density threshold for star formation
- Starburst and gas consumption

Theoretical models:
- Krumholz & McKee 05
- Padoan & Nordlund 11
- Montenegro+99
- Elmegreen 94
- Kruijssen+14b

Outlook: CMZ

Empirical input: Kruijssen+14b

Extragalactic
The lifecycle of clouds and star-forming regions

Dynamical model for episodic star formation in CMZs

Aim to quantify key elements of cycle prior to “normal” star formation

- high, environmentally-dependent density threshold for star formation
  - turbulence driving
  - acoustic instability of in-flowing gas
  - galactic-scale gas inflow

- gas mass builds up to threshold for gravitational instability
  - gravitational instability drives gas to density threshold for star formation

- starburst and gas consumption

Theoretical references:
- Montenegro+99
- Padoan & Nordlund 11
- Krumholz & McKee 05
- Elmegreen 94
- Krumholz & Kruijssen 15
- Kruijssen+14b
Dynamical model for episodic star formation in CMZs

Krumholz & Kruijssen 15

- 1-D hydrodynamical disc model, outer boundary condition is gas inflow rate
- Radial gas inflow caused by shear-driven acoustic instabilities
- Transport drives turbulence, dissipates on crossing time
- Use observed CMZ rotation curve
  
  Launhardt+02
Evolution of gas within the inner Lindblad resonance

Krumholz & Kruijssen 15

- At large radii: inflowing, low density, large linewidth, gravitationally stable
The lifecycle of clouds and star-forming regions

J. M. Diederik Kruijssen – Heidelberg University

Evolution of gas within the inner Lindblad resonance

Krumholz & Kruijssen 15

🔹 At large radii: inflowing, low density, large linewidth, gravitationally stable

![Graphs showing evolution of gas within the inner Lindblad resonance.](image)

Σ [M⊙ pc⁻²] vs. R [pc] for different time points (t=0 Myr, t=10 Myr, t=25 Myr, t=50 Myr).

Toomre Q vs. R [pc] for different time points (t=0 Myr, t=25 Myr).

l = 1 deg
The lifecycle of clouds and star-forming regions

J. M. Diederik Kruijssen – Heidelberg University

Evolution of gas within the inner Lindblad resonance

Krumholz & Kruijssen 15

✦ At ~100 pc: stalling, high density, small linewidth, gravitationally unstable

![Graphs showing the evolution of gas within the inner Lindblad resonance.](image)
Dynamical model for episodic star formation in CMZs

Krumholz & Kruijssen 15

- Model reproduces a wide array of observed gas properties in the CMZ

**THEORY**

1. **Galactic-scale gas inflow**
   - *Krumholz & McKee 05*
   - *Montenegro+99*

2. **Acoustic instability of in-flowing gas**
   - *Padoan & Nordlund 11*

3. **Turbulence driving**

4. **Gas mass builds up to threshold for gravitational instability**
   - *Elmegreen 94*

5. **Gravitational instability drives gas to density threshold for star formation**

6. **Starburst and gas consumption**

**Extragalactic**

**Empirical input**

**CMZ**

**Outlook**
Dynamical model for episodic star formation and feedback in CMZs

Krumholz, Kruijssen & Crocker 17

✧ Aim to quantify full star formation cycle in galactic centres

- high, environmentally-dependent density threshold for star formation
  - turbulence driving
  - acoustic instability of in-flowing gas
  - galactic-scale gas inflow

- gas mass builds up to threshold for gravitational instability
  - gravitational instability drives gas to density threshold for star formation
  - starburst and gas consumption

**THEORY**

- Krumholz & McKee 05
- Padoan & Nordlund 11
- Montenegro+99
- Elmegreen 94
- Krumholz, Kruijssen & Crocker 17
The lifecycle of clouds and star-forming regions

Dynamical model for episodic star formation and feedback in CMZs

Krumholz, Kruijssen & Crocker 17

- Model of Krumholz & Kruijssen 15 + star formation + feedback
- Allows the modelling of multiple cycles and galactic winds
- Episodic star formation, duty cycle matches CMZ and extragalactic nuclei

Extragalactic

Empirical input

CMZ

Outlook

SFR $[M_\odot \text{ yr}^{-1}]$ vs. time $t$ [Myr]

Observed SFR in CMZ
Dynamical model for episodic star formation and feedback in CMZs

Kruijssen+14b; Krumholz & Kruijssen 15; Krumholz, Kruijssen & Crocker 17

- Qualitative scenario has matured to a first quantitative model

- Galactic Centre-specific physics - “it’s just shear” is a major oversimplification

The lifecycle of clouds and star-forming regions

J. M. Diederik Kruijssen – Heidelberg University
The cloud lifecycle in extragalactic environments
Molecular cloud lifecycle (e.g. lifetime) is a long-standing problem

 Presence of inter-arm molecular clouds suggested >100 Myr lifetimes
  Scoville & Hersh 79, Scoville & Wilson 04, Koda+09

 Classification of cloud ‘types’ based on stellar content gives 10-30 Myr
  Elmegreen 00, Hartmann+01, Engargiola+03, Kawamura+09, Meidt+15

 Central Molecular Zone streamline along known gas orbit gives 1-2 Myr
  Kruijssen+15, Henshaw+16b, Barnes+17
A multi-scale theory of cloud evolution and star formation in galaxies: Small-scale variations of gas-to-SFR ratio reflect underlying timeline

Kruijssen & Longmore 14

Gas-to-SFR ratio as a function of spatial scale

**focus on gas**
- long timescale
- common
- small bias

**focus on young stars**
- short timescale
- rare
- large bias

Gas-to-stellar flux ratio

- ~5x cloud size
- Aperture size
- galaxy scale
Gas-to-SFR ratio as a function of spatial scale

- ‘Uncertainty principle’ is a non-degenerate probe of cloud-scale physics
- Does not require resolving individual clouds, but only their separation

- Cloud lifetime, feedback timescale, cloud separation length provide e.g.: FB velocity, SF efficiency, mass loading factor, FB-ISM coupling efficiency
Method has been tested with 300 experiments on simulated disc galaxies

- Retrieved cloud lifetimes are accurate to within < 30%
- The behaviour, dependences, and biases are understood & under control

**Example**

![Graph showing gas-to-stellar flux ratio vs. aperture size](image)

- Gas peaks
- Galactic average
- Stellar peaks

![Graph showing retrieved 'cloud lifetime' vs. true 'cloud lifetime'](image)

- HR, extended emission
  - $\sigma_{\log_{10}(y/x)}^{\text{errors}} = 0.08$
  - $\sigma_{\log_{10}(y/x)}^{\text{true}} = 0.15$
  - $\sigma_{\log_{10}(y/x)}^{\text{sys}} = 0.12$

Kruijssen+ in prep.
The lifecycle of clouds and star-forming regions

J. M. Diederik Kruijssen – Heidelberg University

Method fundamentally constrains *relative* timescales

✦ Applications require *absolute* ‘reference timescale’ from SF to obtain *absolute* timeline

![Diagram showing relationship between region mass, SFR surface density, Hα lifetime, SF tracer lifetime, and [Fe/H].]

**Model**: $1.0 \times 8.14 \, M_\odot$

**Well-Sampled IMF Value**: 5.4 Myr

**Well-Sampled IMF Value Uncertainty**: $\pm 0.8 \pm 0.5$ Myr

**Region mass ~ SFR surface density** $[M_\odot]$

**Hα lifetime [Myr]**

**SF tracer lifetime [Myr]**

**[Fe/H]**

*Haydon+ in prep.*
Application to NGC 300

- Using far-UV and CO(1-0)

Many quantities, e.g.

\( t_{\text{GMC}} = \)  
\( t_{\text{FB}} = \)  
\( \lambda = \)  
\( \varepsilon \sim t_{\text{gas}} / f_{\text{GMC}} \)  
\( t_{\text{depl}} \sim \)  
\( V_{\text{fb}} = \)  
\( \eta_{\text{fb}} \sim \)
Application to NGC 300

- As a function of radius (i.e. environment)

- Direct tests of theories of molecular cloud evolution
Other galaxies yield similar results (but with interesting differences)

\[ t_{\text{gas}} = t_{\overline{\text{over}}} = \lambda = \varepsilon \sim \]

- Kruijssen+ NGC300
- Hygate+ M33
- Schruba+ M31

Alex Hygate
The lifecycle of clouds and star-forming regions

ALMA gallery

Physics at High Angular resolution in Nearby Galaxies

www.phangs.org
Systematic application to a representative galaxy sample

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>Distance (Mpc)</th>
<th>$t_{\text{gas}}$ (Myr)</th>
<th>$t_{\text{over}}$ (Myr)</th>
<th>$\lambda$ (pc)</th>
<th>Spatial resolution (pc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC0628</td>
<td>7.2</td>
<td></td>
<td></td>
<td></td>
<td>60</td>
</tr>
<tr>
<td>NGC3351</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td>111</td>
</tr>
<tr>
<td>NGC3627</td>
<td>9.0</td>
<td></td>
<td></td>
<td></td>
<td>83</td>
</tr>
<tr>
<td>NGC4321</td>
<td>14</td>
<td></td>
<td></td>
<td></td>
<td>150</td>
</tr>
<tr>
<td>NGC5068</td>
<td>5.5</td>
<td></td>
<td></td>
<td></td>
<td>37</td>
</tr>
</tbody>
</table>

‘Short’ molecular cloud lifetimes, but with a strong environmental variation
Comparison to theoretical models for different evolutionary mechanisms

Radial variation of cloud lifetime agrees with theoretical predictions

<table>
<thead>
<tr>
<th>Radius [kpc]</th>
<th>Timescale [Myr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
</tr>
<tr>
<td>4</td>
<td>100</td>
</tr>
<tr>
<td>6</td>
<td>1000</td>
</tr>
<tr>
<td>8</td>
<td>10000</td>
</tr>
</tbody>
</table>

- Observations
- Radial perturbations
- Free-fall
- Cloud-cloud collisions
- Shear
- Lifetime

Mélanie Chevance
Poster S9-2
Theoretical interpretation of molecular cloud lifetimes

To first order, lifetime \( \sim \frac{1}{\Omega} \); factor \(~20\) variation on top of that probes physics of individual mechanisms

\[
\tau = \left( \tau_k^{-1} + \tau_{\Omega_p}^{-1} + \tau_{\text{ff,g}}^{-1} + \tau_{\text{cc}}^{-1} - \tau_{\beta}^{-1} \right)^{-1}
\]
The lifecycle of clouds and star-forming regions

Introduction

CMZ

Extragalactic

Outlook

Theoretical interpretation of molecular cloud lifetimes

Parameter space divided into regions dominated by different mechanisms

\[ \tau = \left( \frac{1}{\tau_K} + \frac{1}{\Omega_p} + \frac{1}{\omega_f, g} + \frac{1}{\tau_c} - \frac{1}{\Omega_p} \right)^{-1} \]
The lifecycle of clouds and star-forming regions

J. M. Diederik Kruijssen – Heidelberg University

Outlook

Introduction

CMZ

Extragalactic

Sarah Jeffreson
Poster S3-2

Predict relevant mechanisms as a function of radius, e.g. in the Milky Way

✦ Shear and free-fall/feedback important everywhere in MW, cloud-cloud collisions only matter at solar radius
Summary of results

- CMZ is best local analogue for high-redshift star formation

- Current SFR in CMZ is low due to episodic cycle of gas pile-up and bursty star formation at R~100 pc — shear-driven, but requires R < R_{ILR}

- Accurate method for measuring lifecycle of clouds & star-forming regions

- SFR tracer lifetime sets absolute scale: measured for Hα, FUV, NUV

- Molecular cloud lifetime is environmentally dependent

- Mix of evolutionary mechanisms is responsible, often competition between shear and free-fall/feedback
Applications will be extended out to high redshift

![Graph showing resolution vs. redshift](image)
Applications will be extended out to high redshift
Outlook

✧ ‘Uncertainty principle’ method enables constraining cloud-scale ISM physics of star formation & feedback under broad range of conditions

✧ Talk focused on cloud lifetime — future work will address other quantities:
  - star formation efficiency
  - region separation length
  - feedback timescale, velocity, mass loading, coupling efficiency

✧ Method applications will be extended to cover galaxies across cosmic time

✧ *Extreme* is the new normal