The multi-scale physics of galactic star formation and a solution for the GMC lifetime ‘problem’

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with Steve Longmore (LJMU), Andreas Schruba (MPE)
How do galaxies turn their gas into stars?

\[ \Sigma_{\text{SFR}} \propto \Sigma_{\text{gas}}^{1.4} \]

Schmidt 59
Kennicutt 98

\[ \Sigma_{\text{SFR}} \propto \frac{\Sigma_{\text{gas}}}{\tau_{\text{dyn}}} \propto \Sigma_{\text{gas}} \Omega_{\text{gas}} \]

Elmegreen 97
Silk 97
Star formation occurs in localised events

NGC 300, GALEX
Decomposition of the star formation relation

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

\[ \text{SFR} = \sum_{\text{clouds}} \frac{\epsilon_{\text{cloud}}}{t_{\text{SF,cloud}}} M_{\text{cloud}} \]

Problem #1: need to resolve clouds

Problem #2: how to measure time-scales?
Spatially resolved star formation relations

Recent observations find increasing scatter on smaller scales...

Kennicutt+07, Bigiel+08, Onodera+10, Liu+11, Leroy+13
Spatially resolved star formation relations

◊ ...or bias when focussing apertures on gas or stellar peaks

![Graph showing log t_{depl} vs. Aperture size [pc]](image)

Centre on:
- gas
- stars

**Physics and scale dependence of galactic SF relations**

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Physics and scale dependence of galactic SF relations

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Spatially resolved star formation relations

✧ …or bias when focussing apertures on gas or stellar peaks

![Graph showing aperture size vs. log of depletion time](image)

Centre on:
- gas
- stars

Clouds

Aperture size [pc]

Schruba+10

Introduction

Principle

Simulations

Observations
The breakdown of galactic SF relations on small scales is fundamental.

If a macroscopic correlation is caused by a time-evolution, then it must break down on small scales because the subsequent phases are resolved.
The breakdown of galactic SF relations on small scales is useful.

The way in which galactic star formation relations depend on the spatial scale is a direct probe of the physics of star formation on the cloud scale.
Decomposition of the star formation relation

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

\[ SFR = \sum_{\text{clouds}} \frac{\epsilon_{\text{cloud}}}{t_{\text{SF,cloud}}} M_{\text{cloud}} \]

The multi-scale nature of SF relations provides a way to measure these quantities.
Physics and scale dependence of galactic SF relations

1. a toy model

Kruijssen & Longmore 2014, MNRAS 439, 3239
A statistical toy model (1)

- Galactic SF relation results from homogeneous sampling of time sequence
- Time-integration of single region gives galactic SF relation
What does this mean in practice?

To retrieve galactic SF relation from observations: need (at least) one region in aperture that contains the “shortest” tracer

Example for $t_{\text{gas}} = 9 \times t_{\text{star}}$
A statistical toy model (2)

What does this mean in practice?

To retrieve galactic SF relation from observations: need (at least) one region in aperture that contains the “shortest” tracer

Example for $t_{\text{gas}} = 2 \times t_{\text{star}}$
An uncertainty principle for star formation
Kruijssen & Longmore 14

\[ \Delta x \Delta t^{1/2} \geq \lambda \tau^{1/2} \]

Size-scale over which SF relation is spatially averaged
Duration of shortest SF phase
Separation of independent regions
Total duration of the SF process

If this condition is satisfied, the “shortest” tracer should be well-sampled within the aperture

→ Galactic SF relation is retrieved
Physics and scale dependence of galactic SF relations

An uncertainty principle for star formation
Kruijssen & Longmore 14

\[ \Delta x \Delta t^{1/2} \geq \lambda \tau^{1/2} \]

If this condition is not satisfied:

- Scatter is large
- Time-line may only partially be covered
- Depletion time shorter by a factor \( t_{\text{gas}} / t_{\overline{\text{over}}} \sim 10-20 \)

(hence Heiderman/Lada vs. Kennicutt/Bigiel)

see talks by Alves, André
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Effect when randomly placing an aperture

Simulations

Observations

Introduction

Principle

Gas

Stars
Scatter versus (randomly placed) aperture size

**Graphical Representation**

- **Scatter in log $t_{\text{depl}}$**
- **Aperture size [kpc]**
- **Observations**:
  - Schruba+10 (M33)
  - Blanc+09 (M51)
  - Leroy+13 (HERACLES)
- **Simulations**:
- **Principle**
- **Introduction**
- **Leroy+13 (HERACLES)**
- **Schruba+10 (M33)**
Effect when placing an aperture on peaks of gas or star formation
Gas depletion time bias versus (specifically placed) aperture size

Centre on:

gas

stars

Principle

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Kruĳssen & Longmore 14

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Physics and scale dependence of galactic SF relations
An uncertainty principle for star formation

- Simple interpretative framework describing multi-scale SF

- Potentially very powerful tool to obtain:
  - time-scales involved in SF process (duration, “cloud” lifetimes, etc.)
  - time spent by gas at different densities (by combining different tracers)

- Improvements with respect to previous work:
  - self-consistently accounts for statistics ➔ direct translation to time-scales
  - no need to resolve individual clouds ➔ works out to $z \sim 4$
An uncertainty principle for star formation

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This is what ALMA was made to do
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Physics and scale dependence of galactic SF relations

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Introduction

Simulations

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Principle
2. practical application

Kruijssen, Schruba & Longmore, in prep.
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Pipeline to characterise cloud-scale physics

✧ Step 1: select tracers

CO(1-0) ←→ Hα ~ 6 Myr
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Pipeline to characterise cloud-scale physics

✧ Step 2: select emission peaks

CO(1-0)

Hα
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Pipeline to characterise cloud-scale physics

✧ Step 3: cut peak sample

CO(1-0)

Hα
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Pipeline to characterise cloud-scale physics

✧ Step 4: convolve maps with top-hat kernels of varying size

50 pc 100 pc 200 pc 400 pc 800 pc
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Pipeline to characterise cloud-scale physics

✧ Step 5: depletion time bias (= CO-to-Hα flux ratio w.r.t. galactic average)

![Graph showing depletion time bias vs. aperture size]
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Pipeline to characterise cloud-scale physics

✧ Step 6: fit depletion time bias with KL14++ model and obtain $t_{\text{gas}}$, $t_{\text{over}}$, $\lambda$, $\epsilon$, $v_{\text{fb}}$

Observations

Centre on:
- gas
- stars

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Aperture size [pc]

$\frac{t_{\text{depl}}}{t_{\text{depl, galaxy}}}$

$10^2$ $10^3$

Kruijssen, Schruba & Longmore, in prep.
3. numerical testing

Kruijssen, White, Schruba, Hu & Longmore, in prep.
How well does it work?

- Test using numerical simulations
- ‘New SPH’ version of Gadget3 – see Chia-Yu Hu et al. (2014)
  - pressure-entropy SPH
  - Wendland smoothing kernel
  - improved artificial viscosity
  - artificial thermal energy conduction
- M33-like disc, resolution in clouds is < 20 pc
- Age-bin the stars and use maps for tests

(Kruijssen, White, Schruba, Hu, Longmore)
Current pipeline is accurate to within a factor of 2
Current pipeline yields even more accurate “durations” of SF & FB

**Point sources**

$\frac{t_{\text{over}}}{t_{\text{star}}}$ vs $\frac{t_{\text{gas}}}{t_{\text{star}}}$

Kruijssen+, in prep.
Numerical simulations show that the method can be used to reliably measure tracer lifetimes
4. application
Second test: application to M33

- Using Hα and CO(1-0) (Rosolowsky+07)
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Application to the arms (!) of M51

- Using H\(\alpha\) and CO(1-0) (PAWS; Schinnerer+13)

![Graph showing the ratio of depl / depl,galaxy vs. aperture size [pc] for M51.]
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Interpretation – physics of cloud-scale star formation?
see talks by Padoan, Chabrier, Fukui, Onishi

✧ Tempting to draw physical conclusions

✧ Compare \( t_{\text{gas}} \sim 30 \text{ Myr} \) to \( t_{\text{dyn,gal}} = R/V \sim 35 \text{ Myr} \) and \( t_{\text{dyn,GMC}} \sim 10 \text{ Myr} \)

⇒ large fraction of supervirial, transient clouds, hence low \( \varepsilon \sim 0.03 \)?

 cf. Dobbs+11

✧ \( t_{\text{over}} \sim 3 \text{ Myr} \) suggests HII regions/winds/radiation end star formation

✧ \( \lambda \sim 100 – 300 \text{ pc} \) similar to the Toomre length \( \pi G \Sigma / \Omega^2 \sim 200 \text{ pc} \)

✧ Tentative interpretation – only a handful of galaxies so far
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Future application at ~15 pc resolution & few $10^3 \, M_\odot$ sensitivity

NGC 300: 8 + 20 hours (ext’d + compact) ALMA Cycle 2 time

(Schruba & Kruijssen + Longmore, Tacconi, van Dishoeck, Dalcanton)
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Method opens up entire observable Universe for cloud-scale SF studies

see lots of talks on Thursday and Friday

Low-resolution simulation
\[ t_{\text{gas}} = 30 \text{ Myr} \]
\[ t_{\text{gas,fit}} = 32^{+27}_{-12} \text{ Myr} \]

Observed sub-mm galaxy CO(2–1)
\[ z = 4.05 \]
Conclusions

✧ Simple framework explains scale dependence of galactic SF relations

✧ Powerful method to constrain cloud-scale SF physics out to $z \sim 4$

✧ Numerical simulations show measured time-scales are accurate

✧ “The GMC Lifetime” does not exist – it is environmentally dependent

✧ *Method applies to any correlation that connects subsequent phases*