Conversion of gas into stars in the Galactic Centre

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Conversion of gas into stars in the GC

• Is SF in the GC different from that in disk?

• If SF is different, what is causing this?

• How similar is the SF in the GC compared to other SF regions across cosmological timescales?

• What can detailed studies of gas in the inner 100pc of the Galaxy tell us about SF in extreme environments?
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- Is SF in the GC different from that in disk?
  How well does gas fit on ‘universal’ SF relations?

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Does the gas in the GC obey ‘universal’ SF relations?
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• Un-controversially, all observations shows CMZ contains roughly
  – ~5-10% of total molecular gas in the Galaxy
  – ~5-10% of total star formation rate

• If star formation relation depends only on total amount of gas
  – CMZ fits with rest of Galaxy

• But gas in CMZ is on average two orders of magnitude more dense than gas in the disk…

• If SF relation depends on gas density in any way:
  – CMZ and MW disk can not fit on same relations
    • $\Sigma_{SFR} = A_{SK} \Sigma_{gas}^{1.4}$
    • $\Sigma_{SFR} = A_{SE} \Sigma_{gas} \Omega$
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Crucial we understand why the physics of star formation is so different!
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Potential suppression mechanisms

- Global gas stability
  - Stars dominate potential at $R_{GC} > 100\text{pc}$
  - Time for gas to become self-gravitating: $t_{\text{grav}} \sim t_{\text{Q}} \sim 20\text{Myr}$
  - Definitely slows down star formation
  - Gas at $R_{GC} \sim 100\text{pc}$ close to self-gravitating

- Another mechanism required to suppress SF

- Local ($R < h$) suppression mechanisms
  - Galactic tides
  - Turbulence
  - IMF
  - Atomic-molecular phase transition
  - Radiation pressure
  - Cosmic rays
Potential suppression mechanisms

Kruijssen, Longmore, Elmegreen, Murray, Bally, Testi & Kennicutt submitted MNRAS
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See also poster of Florent Renaud [P4] for very nice numerical simulation approach tackling this problem
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How does turbulence affect properties of gas in star forming regions?
Simulations of turbulent gas cloud by Kritsuk+11

\[ \log_{10}\langle \text{PDF} \rangle = \begin{cases} 
-2 & \text{for } t=0 \\
-4 & \text{for } t=0.26t_{ff} \\
-6 & \text{for } t=0.42t_{ff} \\
-1.695(2) & \text{lognormal} \\
-0.999(5) & \text{normal}
\end{cases} \]
Density probability distribution function (PDF) of gas in log space
Theories in which turbulence sets initial gas substructure predict density PDF is log-normal before onset of star formation.
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Once sub-regions become self-gravitating, they will experience runaway collapse.
Once sub-regions become self-gravitating, get runaway collapse.

Densest regions collapse first.
Median and dispersion set by Mach number

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Slope gets shallower with time.
Kritsuk+11

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\[ x_{\text{turb}} \equiv n/n_0 = A_x \alpha_{\text{vir}} \mathcal{M}^2 \]

Krumholz & McKee 05, Padoan & Nordlund 11
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Inputting values for CMZ:
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Critical density for star formation in CMZ
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Critical density for star formation in CMZ:

Same threshold in the disk is \(~10^4 \, \text{cm}^{-3}\)
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• Local ($R < h$) suppression mechanisms
  – Turbulence dominant source of pressure
    • High critical density for star formation potentially explains lack of star formation in extreme clouds (e.g. Brick: Longmore+ 2012, Kauffmann+ 2013)
  – But, can’t be full picture
    • Turbulence dissipates on vertical disc-crossing time
      – $t_{diss} \sim 2h/\alpha$ crossing time $\sim 0.5$Myr
    • Something must be driving turbulence
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What is driving the turbulence?
What is driving the turbulence?

- Feedback and classical drivers of turbulence (e.g. Mac Low & Klessen 2004) are not effective
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  – Turbulent energy diss. rate = $10^{-20}$ erg cm$^{-3}$ s$^{-1}$
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    • Acoustic instability of inflowing gas may provide solution
Turbulence driven by acoustic gas instabilities
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\[ R_{GC} > ILR \rightarrow \text{spiral waves driven by grav instabilities} \]

\[ R_{GC} < ILR \rightarrow \text{spiral waves driven by pressure waves} \]
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\( R_{GC} > ILR \rightarrow \) spiral waves driven by grav instabilities

\( R_{GC} < ILR \rightarrow \) spiral waves driven by pressure waves

• Montenegro+ 1999 model:
  – Non self-gravitating gas falls into stellar mass-dominated potential
  – Geometric gas convergence (cram more gas into smaller volume)
  – Gas compressed to high \( \rho \) despite no self-gravity
  – Acoustic instability drives spiral wave in which turbulent pressure increases (Dobbs, Burkert & Pringle 2011)
  – If compression reaches \( \rho_{gas} > \rho^* \)
    • Gravitational collapse
    • Energy dissipation
    • Star formation
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Can we put all this in to a self-consistent picture to explain star formation in the GC?
Self-consistent star formation cycle

I. Outline

Kruijssen, Longmore, Elmegreen, Murray, Bally, Testi & Kennicutt submitted MNRAS
Self-consistent star formation cycle

II. Implications

- Multiscale: different size scales affect each other
  - Overall gas supply regulated on global scale
  - Gas consumption time set locally

- Rate-limiting factor is long evolution of gas towards gravitational collapse

- Whether system observed in starburst/quiescent phase determined by relative timescales of stages
  - Inflow $\rightarrow$ dynamical time $\approx 100$ to $5\times10^5$ Myr
  - Time to become grav. unstable $\approx Q/\kappa$ $\approx 20$ to $10^5$ Myr
  - Gas consumption time short ($t_{ff} \approx 10^5$ yr)

- Star formation happens in specific locations
  - 100 pc ring may be unstable phase of proposed cycle
Self-consistent star formation cycle
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In quiescent phase, gas not self gravitating so can proceed to BH without forming stars

→ Low SF activity = efficient BH growth?
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$\rightarrow$ Low SF activity = efficient BH growth?

Direct predictions for relative number of external galaxies fitting on/off SF relations
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    • Turbulent pressure $\rightarrow$ high $\rho_{\text{crit}}$
    • Rate-limiting factor is time for clouds to become self-gravitating

• How important is understanding SF in the GC in a cosmological context?
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  Depends how similar the properties of gas in the CMZ are to other environments across the Universe…
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Kruijssen & Longmore accepted MNRAS
Aim = compare gas properties in a representative, but not exhaustive, sample of SF regions across full range of observed environments
Local clouds

- CMZ regions
- CMZ clouds
- Perseus clouds and cores
- Solar neighbourhood clouds
- Solar neighbourhood cloud centres
- Nearby galaxy clouds
- Antennae clouds
- Nearby spirals
- Arp 220 regions
- High-z clouds
- High-z galaxies, $t_{\text{depl}} > 100$ Myr
- High-z galaxies, $t_{\text{depl}} < 100$ Myr

$V \ [\text{km s}^{-1}]$ vs. $R \ [\text{pc}]$
Nearby galaxies
High-z clouds, high-z galaxies, local starburst nuclei

$V$ [km s$^{-1}$]

$R$ [pc]
characteristic uncertainty = factor 2
CMZ, high-z clouds and rapidly star forming high-z galaxies
- larger V for same size than local clouds and nearby galaxies
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To avoid clear scale dependence, need to compare normalised properties
Local clouds
Nearby galaxies
High-z clouds/galaxies
CMZ clouds/regions

$V/R^{0.5}$ [km s$^{-1}$ pc$^{-0.5}$]

$\Sigma_{\text{gas}}$ [$M_\odot$ pc$^{-2}$]

Kruijssen & Longmore, submitted
Local clouds
Nearby galaxies
High-z clouds/galaxies
CMZ clouds/regions

Normalisation of linewidth-size relation

Cumulative distribution

Kruijssen & Longmore, submitted
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Nearby galaxies
High-z clouds/galaxies
CMZ clouds/regions

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$V/R^{0.5}$ vs $\Sigma_{gas}$

CMZ & high-z $\Rightarrow$ similar gas/dynamical surface densities

Local clouds
Nearby galaxies
High-z clouds/galaxies
CMZ clouds/regions
Local clouds
Nearby galaxies
High-z clouds/galaxies
CMZ clouds/regions

Kruijssen & Longmore, submitted
Stellar mass surface density

Local clouds
Nearby galaxies
High-z clouds/galaxies
CMZ clouds/regions

CMZ & high-z \textarrow{\Rightarrow} similar gas/stellar surface densities

Kruijssen & Longmore, submitted
Local clouds
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CMZ clouds/regions

Stellar mass surface density

CMZ & high-z \(\Rightarrow\) similar gas/stellar surface densities

Local clouds/galaxies very different

Kruijssen & Longmore, submitted
Stellar mass surface density

\[ \Sigma_{\text{star}} \left[ M_\odot \text{ pc}^{-2} \right] \]

\[ M_{\text{vir}}/r^2 = v^2/r \]

Kruijssen & Longmore, submitted
Stellar mass surface density

\[
\Sigma_{\text{star}} \left[ M_\odot \text{ pc}^{-2} \right] = \frac{M_{\text{vir}}}{r^2} = \frac{v^2}{r}
\]

CMZ and high-z overlap

Local clouds
Nearby galaxies
High-z clouds/galaxies
CMZ clouds/regions

Kruijssen & Longmore, submitted
Conversion of gas into stars in the GC

• Is SF in the GC different from that in disk?
  – Yes.
  – Factor >10x lower SFR than expected given universal SF relation

• If SF is different, what is causing this?
  – Self-consistent multi-scale cycle
    • Turbulent pressure \( \rightarrow \) high \( \rho_{\text{crit}} \)
    • Rate-limiting factor is time for clouds to become self-gravitating

• How important is understanding SF in the GC in a cosmological context?
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Does the CMZ represent the initial conditions of a high-z starburst?
Self-consistent star formation cycle

I. Outline

- high, environmentally-dependent density threshold for star formation
  - Krumholz & McKee 05
  - Padoan & Nordlund 11
- turbulent cascade
- acoustic instability of in-flowing gas
  - Montenegro+99
- gas mass builds up to threshold for gravitational instability
  - Kritsuk+11
- gravitational instability drives gas to density threshold for star formation
- starburst and gas consumption

THEORY

Dashed line: indicates progression of time only as starburst and gas consumption don’t affect Galactic scale inflow
Self-consistent star formation cycle

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- turbulent cascade
- galactic-scale gas inflow
- 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
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If mass inflow rate is sufficiently large, these steps happen so quickly to be unnoticeable.

THEORY

- Krumholz & McKee 05
- Montenegro+99
- Padoan & Nordlund 11
- Kritsuk+11
- Kruijssen, Longmore, Elmegreen, Murray, Bally, Testi & Kennicutt submitted MNRAS

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Does the CMZ represent the initial conditions of a high-z starburst?
Worth further investigation!
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• What can detailed studies of gas in the inner 100pc of the Galaxy tell us about SF in extreme environments?
Schematic diagram: as viewed from Earth

Arches

Quintuplet
Schematic diagram: as viewed from Earth

- Clouds "e" and "f"
- Cloud "d" "The Brick"
- Sgr B2
- Quintuplet
- 50km/s cloud
- 20km/s cloud
- Sgr A*
- Sgr C
- Arches
Schematic diagram: as viewed from Earth

Solid line = near side of ring
Dashed line = far side of ring

3D geometry interpreted from gas kinematics ➔ “Twisted Ring”
- Orbiting GC at 80km/s
- 2 vertical oscillations per orbit
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3D geometry interpreted from gas kinematics ➔ “Twisted Ring”
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Intriguing point of the 3D geometry of gas in the ring is that Sgr A*, the centre of the Galactic gravitational potential, is not at the ring centre…
As viewed from Earth

Sgr A* not at centre of ring

Top-down view

Sgr B2
Clouds "e/f"
Cloud "d"
G0.253+0.016
50 km/s cloud
20 km/s cloud
to Earth

x_1?
100pc
60pc
x_1?
Sgr A* not at centre of ring

Near side of the ring (as viewed from Earth) passes closer to bottom of Galactic gravitational potential.
As viewed from Earth

Sgr A* not at centre of ring

Near side of the ring (as viewed from Earth) passes closer to bottom of Galactic gravitational potential

Is the gas affected by this close passage?
Column density map of inner 250 pc of Galaxy (Greybody fit to Hershel data)

Longmore et al 2013c, MNRAS, 433, 15 → used HiGAL data to map the distribution of gas density along the ring
1. Dense gas lies close to, and downstream from, Sgr A*
2. Diffuse gas lies far from Sgr A*
3. 20 and 50 km/s clouds potentially interacting with Sgr A* and surrounding nuclear cluster (Herrnstein & Ho 2005)
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Seems plausible that gas in the ring may be affected close passage to Sgr A*
Hypothetical Scenario

• Gas gets compressed by close passage to bottom of global gravitational potential

• Energy injected into gas through compression

• Gas dissipative so gets rid of this energy through shocks

• After pericentre passage clouds are at higher density but have lost energy so will begin collapsing to form stars
Follow up – testing this scenario…
Follow up – testing this scenario…

Work in progress!
Follow up – testing this scenario…

Approach

Work in progress!

1. Observationally constrain P-P-V space of gas streams as accurately as possible, including associated uncertainties (difficult as in galaxy)

2. Simulate gas particles on trajectories around G.C. Map progression through P-P-V space as would be “observed”

3. Run parameter space study over full range of orbital properties and directly compare to data to derive best-fit orbital solution

4. Run hydro simulations of gas clouds on best-fit orbit

5. Run similar sims on circular orbits as control experiment

6. Directly compare detailed properties of simulated & observed clouds on same parts of the orbit
1. Systematic search for coherent gas streams

(i) Use dense gas tracer data to identify coherent velocity structures in data cubes

(ii) For each coherent structure, step through equally-spaced Galactic longitude increments and select latitude with the highest intensity for coherent velocity structures

(note: sometimes another ignored component may actually be brighter).
2. Simulate gas particles on trajectories around GC

(i) Integration of orbits using Launhardt+ (2002) gravitational potential and vertical flattening

(ii) Trajectory of orbits mapped into observers P-P-V space

(iii) Start with analytical model of Molinari+ (2011)

Come across difficulties
Difficulties in fitting the Molinari model
Difficulties in fitting the Molinari model

Orbits in extended gravitational potential can NOT be closed \( \rightarrow \) they precess
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Constant orbital velocity is not possible
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Proper motion of Sgr B2 doesn’t fit

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Can’t fit “wiggle” in P-V diagram

No way a single orbit could do this

Constant orbital velocity is not possible
3. Orbital parameter space study

6-parameter orbit
- Pericentre
- Apocentre
- Z-vel through pericentre
- Z-pos at pericentre
- Z compression factor
- Projection angle

Fit the orbit with three coherent velocity streams
- circles
- triangles
- squares

Best-fit result has reduced-$\chi^2 = 2$
4. SPH simulations of gas clouds on best-fit orbit

Initial conditions:
- Mass = $2 \times 10^6 \, M_\text{sun}$
- Radius = $20 \, \text{pc}$
- $\sigma = 20 \, \text{km/s}$
- $10^5$ particles

Control run:
- Same cloud properties
- Circular orbit: radius equal to mean of best-fit orbit

Physics:
- No SF feedback, B, turb. driving
- Turbulent energy dissipates
  $\rightarrow$ gas will always form stars

Goal $\rightarrow$ see the effect of pericentre passage in controlled setting
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Dense gas fraction: $\frac{M_{\text{sinks}}}{(M_{\text{sinks}} + M_{\text{gas}})} \sim \text{SFE}$
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Solid line = best-fit orbit
Dashed line = circular orbit
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Pericentre passage induces star formation
Variation in density probability distribution function along the orbit

$d\rho / d\ln(n)$

0.03 Myr
0.30 Myr
$R=R_{peri}$
Brick
d,e,f
Sgr B2

$n \left[ \text{cm}^{-3} \right]$
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Typical density where sinks form

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$n \text{ [cm}^{-3}]$
Variation in density probability distribution function along the orbit

Towards pericentre, PDF widens and shifts to higher $\rho$ due to global collapse and increased linewidth (shear)
Variation in density probability distribution function along the orbit

Solid line = best-fit orbit  
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Typical density where sinks form

Towards pericentre, PDF widens and shifts to higher $\rho$ due to global collapse and increased linewidth (shear)

Given such high $\rho_{\text{crit}}$ this could be enough to push clouds to SF

$R = R_{\text{peri}}$

0.03 Myr

0.30 Myr

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d, e, f

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Typical density where sinks form

Prediction for how density varies as function of position

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Typical density
where sinks form

Prediction for how density varies as function of position

Possible to directly test this prediction through $\text{H}_2\text{CO}$ densitometry project on VLA/GBT

PI Ginsburg
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Directly test claims that ISM conditions lead to IMF variations in the early Universe

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