From Cluster-Forming Region Properties to Galaxy Evolution with Star Clusters

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Image Credit

- **Elliptical galaxy M87** (APOD 16.06.2004):
  - Canada-France Hawaii Telescope, J.-C. Cuillandre

- **Globular Cluster M10** (APOD 30.06.2001):
  - Till Credner, Sven Kohle (Bonn University), Hoher List Observatory

- **Orion Nebula Mosaic** (HST – WFPC2):
  - O’Dell and S.K. Wong (Rice University), NASA

- **Open Cluster Pleiades M45** (APOD 01.12.2002):
  - Anglo-Australian Observatory/Royal Observatory, Edinburgh

- **Open Cluster Hyades**:

- **Spiral galaxy NGC3370** (APOD 14.05.2005):
  - Hubble Heritage Team, A. Riess (STScI) NASA
Star Clusters: at the crossroad between star formation and galaxy evolution

10pc:
individual
gas-free
star clusters

1-pc:
star formation
in embedded
star clusters

a few kpc - 100kpc:
systems of
star clusters
and galaxies
Setting the Scene: Star Clusters (SC) as Powerful Tracers of Galaxy Evolution

Star Clusters (SC):
- Compact groups of coeval stars bound together by gravity
- Identified on a one-by-one basis against the background of their host galaxy

Multi-band imaging of SC systems
- → cluster magnitudes, colours
- feasible out to Virgo Galaxy Cluster distances ($\approx 20$ Mpc)
- combined to Simple Stellar Population models → estimates of cluster age, mass, metallicity

Comprehensive view of galaxy-:
- chemical enrichment history,
- interaction history,
- star formation history over the past Hubble-Time

Star clusters are at the very heart of many astrophysical topics

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The Big Issue: SCs versus field stars

Most stars in our Galaxy:

- are born in SCs → young SCs tell us about star formation
- but are observed as field stars
- SCs start losing stars as soon as they are born ...

Star clusters have the potential of tracing

- galaxy star formation histories

provided we get a firm handle on the ratio of star formation still residing in (observed) star clusters as a function of age

Violent relaxation = Most traumatizing phase

- Very short (10-50 Myr)
- SC Dynamical response to residual star-forming gas expulsion
Intra-Cluster Gas-Expulsion and Violent Relaxation

Effects of gas expulsion - VIOLENT RELAXATION

- Cluster expansion
- Star loss (infant weight-loss), or
- Cluster dissolution (infant mortality)
Violent Relaxation (VR): Observable Signatures And Prime Parameters

Effects of gas expulsion - VIOLENT RELAXATION
- Cluster expansion
- Cluster infant weight-loss and infant mortality

Observable Imprints upon Star Cluster Systems:
- Cluster mass distribution,
- Cluster age distribution,
- Cluster radius distribution

Prime parameters: (e.g. Baumgardt & Kroupa 2007)
- SFE in cluster-forming region (CFRg)
- Gas expulsion time-scale: $\tau_{\text{GExp}} / \tau_{\text{cross}}$
- Impact of external tidal field (environment)

See also Adams (2000), Vesperini et al (2009), …

Geyer & Burkert (2001)
Violent Relaxation (VR): SC Mass Functions

Time-Evolution of SC Mass Functions: What observers tell us …
No evolution of the MF shape over the first few 10Myr

\[
\frac{dN}{dm} \propto m^{-2} \\
\equiv \frac{dN}{d \log m} \propto m^{-1}
\]

\[F_{\text{bound}} = m_{\text{cluster}} \text{ (end of VR)} \]
\[= F_{\text{bound}} \times m_{\text{ecl}} \text{ (at Gas Exp)}\]

Fig 7, Chandar+2010

F_{\text{bound}} \text{ is mass-independent}

Note: what happens after 100Myr remains disputed …
SFE and SC Mass Functions

\[ m_{\text{cluster}}(\text{end of VR}) = F_{\text{bound}}(SFE) \times SFE \times m_{\text{CFRg}} \]

\[ F_{\text{bound}}(SFE \, \varepsilon) \]

**SFE**
- fraction of gas ending up in stars

**\( F_{\text{bound}} \)**
- fraction of stars remaining bound to the cluster at the end of VR

\( F_{\text{bound}} \) is mass-independent
\( \rightarrow \) **SFE is mass-independent**

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$F_{\text{bound}} \left( \text{SFE} \varepsilon, \frac{\tau_{\text{GExp}}}{\tau_{\text{cross}}} \right)$

Constant radius:
more massive star cluster progenitors have
- a deeper potential well
- a slower gas-expulsion t-s
- can survive despite a low SFE of, say, 20%

$F_{\text{bound}}$ is mass-independent
→ $\tau_{\text{GExp}}/\tau_{\text{cross}}$ is mass-independent

but looser constrain
Tidal Field Impact

\[ F_{\text{bound}} \left( \frac{\text{SFE} \, \varepsilon}{\tau_{\text{cross}}}, \frac{\tau_{\text{GExp}}}{\tau_{\text{cross}}}, \frac{r_{\text{half-mass}}}{r_{\text{tidal}}} \right) \]

Half-mass radius \( r_{\text{half-mass}} \approx r_{\text{CFRg}} \)

Limiting tidal radius:

\[ r_{\text{tidal}} = \left( m_{\text{ecl}} \right)^{1/3} \left( \frac{G \, D_{\text{gal}}^2}{2 \, V_c^2} \right)^{1/3} \propto \left( \text{SFE} \cdot m_{\text{CFRg}} \right)^{1/3} \]

Strong t.f. impact

Weak t.f. impact

Embedded cluster mass

SC environment
Half-Mass Radius—to—Tidal Radius Ratio

\[
\left( \frac{r_{\text{CFRg}}}{1\text{pc}} \right) = 0.01 \left( \frac{m_{\text{CFRg}}}{1\text{M}_\odot} \right)^{1/2}
\]

\[
\Sigma_{\text{CFRg}} = 0.5\text{g.cm}^{-2}
\]

\[
r_{\text{CFRg}} \propto r_{\text{half-mass}} \propto m_{\text{CFRg}}^{\delta}
\]

\[
r_{\text{tidal}} \propto m_{\text{ecl}}^{1/3} \propto m_{\text{CFRg}}^{1/3}
\]

\[
\frac{r_{\text{half-mass}}}{r_{\text{tidal}}} = m_{\text{CFRg}}^{\delta - 1/3}
\]

\[
s_{\text{ecl}} = 0.33
\]

\[
V_c = 220 \text{ km.s}^{-1}
\]

\[
D_{\text{gal}} = 4 \text{ kpc}
\]

\[
\kappa = 0.5
\]

\[
n_{\text{H}_2} = 6.10^4 \text{ cm}^{-3}
\]

\[
\rho_{\text{CFRg}} = 4000 \text{ M}_\odot\text{pc}^{-3}
\]
**Bound Fractions at the End of Violent Relaxation**

\[
\left( \frac{r_{\text{CFRg}}}{1\,\text{pc}} \right) = 0.01 \left( \frac{m_{\text{CFRg}}}{1\,M_\odot} \right)^{1/2}
\]

\[
\rho_{\text{CFRg}} = 4000\,M_\odot\,\text{pc}^{-3}
\]

\[
\Sigma_{\text{CFRg}} = 0.5\,\text{g}\,\text{cm}^{-2}
\]

Parmentier & Kroupa (2011)
Young SC Mass Functions

\[ \frac{dN}{d \log m} = \frac{\rho_{\text{CFRg}}}{m_{\text{CFRg}}} \]

\[ \frac{r_{\text{CFRg}}}{1 \text{pc}} = 0.01 \left( \frac{m_{\text{CFRg}}}{1 M_\odot} \right)^{1/2} \]

\[ \Sigma_{\text{CFRg}} = 0.5 \text{g.cm}^{-2} \]

\[ \rho_{\text{CFRg}} = 4000 M_\odot \cdot \text{pc}^{-3} \]

SFE = 0.33

\[ \frac{V_c}{1 \text{km.s}^{-1}} = 220 \]

\[ D_{\text{gal}} = 4 \text{kpc} \]

\[ \kappa = 0.50 \]

Fig7, Chandar+2010
Young SC Mass Functions

Constant Mean Surface Density CFRgs:
When more massive means more vulnerable ...

Constant Mean Volume Density CFRgs:
mass-independent
Infant weight-loss

Fig7, Chandar+2010
A Volume Density Threshold for the Star-Forming Gas

- Gao & Solomon (2004), Wu+2005
  → HCN mapping of entire galaxies + Galactic individual molec clumps
- the SFR scales as the mass of dense molecular gas: $n_{H_2} > 3.10^4 \text{cm}^{-3}$
  → comparison of IR extinction maps of molecular clouds with their census of Young Stellar Objects
- the SFR scales as the mass of dense molecular gas: $n_{H_2} > 10^4 \text{cm}^{-3}$

- CFRgs of about constant mean volume density ($n_{H_2} = \text{few } n_{th}$)
- Conclusion identical as for the tidal field impact analysis (Parmentier & Kroupa 2011)

Dense star-forming gas vs diffuse quiescent molecular gas
- Slopes of the cloud and cluster mass functions
- Slope of the Kennicutt-Schmidt law
CFRgs - Molecular Clump Mapping: Do Not Mix!

Star-forming region: W43S

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<th>log(n [cm⁻³])</th>
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To identify a mass-radius diagram of molecular clumps as the mass-radius diagram of the star clusters they are forming is not as straightforward as sometimes quoted in the literature.

≠ tracers probe ≠ molecular clump regions, with higher densities corresponding to inner, smaller regions.
### Star-forming region: W43S

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To identify a mass-radius diagram of molecular clumps as the mass-radius diagram of the star clusters they are forming is not as straightforward as sometimes quoted in the literature.

**BEWARE!!**

Molecular clump densities vary over smaller regions.
From the mass function of GMCs/clumps to that of gas-free star clusters ...

\[ \frac{dN}{dm} \propto m^{-\alpha} \]

- \( \alpha = 1.7 \), molecular clumps and Giant Molecular Clouds
- \( \alpha = 2 \), young star clusters
- Steeper than \( \alpha = 2 \)

Mass-varying SFE: lower SFE at higher cloud/clump mass ??

But then mass-varying \( F_{\text{bound}} \) too ??

\( F_{\text{bound}} \)

Gas-free star clusters

Embedded -clusters
From the mass function of GMCs/clumps to that of gas-free star clusters ... with a volume density threshold for star formation

➢ Cluster-forming regions: constant mean volume density (tidal field impact analysis)

➢ GMCs and

➢ Molecular clumps with signs of SF activity: constant mean surface density
  • Larson 1981
  • Blitz+ 2006
  • Heyer+ 2009

GMCs in
- LMC
- MW

Fig8 in Blitz+06

Galactic C$^{18}$O Molec. clumps with SF activity

Fig10b, Parmentier (2011)
From the Mass Function of Molecular Clumps to that of Embedded Star Clusters

- Constant mean surface density clumps
→ a clump of higher mass has a lower fraction of its mass above a given volume density threshold

\[ \rho_{\text{low}} \propto \log(m) \]

\[ \rho_{\text{high}} \propto \frac{1}{r} \]

\[ m_{\text{clump}} \propto r_{\text{clump}}^{1/2} \]

\[ r \propto m^{1/3} \]
From the Mass Function of Molecular Clumps to that of Embedded Star Clusters

Molecular clumps: 2-zone model

- Low-density outer envelope: $n_{\text{H}_2} < n_{\text{th}}$
- High-density cluster-forming region (CFRg): $n_{\text{H}_2} > n_{\text{th}}$

The local SFE must be measured over the CFRg, not over the whole molecular clump

$\rho_{\text{clump}}(r) \propto r^{-1.9}$

$\begin{align*}
\frac{m_{\text{CFRg}}}{m_{\text{clump}}} & \propto m_{\text{clump}}^{-0.3} \\
\end{align*}$

Mueller+02: density index $\approx 1.8$
Massive Star Formation (MSF) Limit

Non-MSF clumps: \( m_{\text{max}} < 10M_\odot \)

MSF clumps: \( m_{\text{max}} > 10M_\odot \)

Fig2 and Eq1, Kauffmann & Pillai (2010)

\[ m_{\text{clump}} = 870M_\odot \left( \frac{r_{\text{clump}}}{\text{pc}} \right)^{1.33} \]

Tool to define ALMA targets for MSF studies

Intercept and slope?
What do we need to form a 10M_{\odot} star?

**Molecular clump:** $m_{\text{clump}}$

- $m_{\text{CFRg}}(p, \rho_{th}, m_{\text{clump}}, r_{\text{clump}})$

- $n_{\text{H}_2} > n_{th}$

**Star-forming gas:** $m_{\text{CFRg}} > 150M_{\odot}$

- $\text{SFE} = 0.3$

**Embedded-cluster:** $m_{\text{ecl}} > 50M_{\odot}$

**Most-massive star:** $m_{*,\text{max}} > 10M_{\odot}$

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**Fig3, Weidner+2010**

$\log(m_{*,\text{max}}) = \log(m_{\text{ecl}}) + 4$
Massive Star Formation (MSF) Limit

Volume density threshold for overall star formation:
\[ n_{H_2} > n_{th} \]

\[ m_\ast = 10M_\odot : \frac{m_{CFRg}}{SFE} = \frac{m_{ecl}}{150M_\odot} \]
\[ < n_{CFRg} \geq few \times n_{th} \]

Non-MSF clumps:
\[ m_{\ast,\text{max}} < 10M_\odot \]

MSF clumps:
\[ m_{\ast,\text{max}} > 10M_\odot \]

\[ m_{\text{clump}} = 870M_\odot \left( \frac{r_{\text{clump}}}{\text{pc}} \right)^{1.33} \]
Massive Star Formation Limit

Fig2, Kauffmann & Pillai (2010)

\[
m_{\text{clump}} = \left( m_{\text{CFRg}} \right)^{p/3} \left( \frac{4\pi \rho_{\text{th}}}{3-p} \right)^{(3-p)/3} r_{\text{clump}}^{3-p}
\]

Parmentier (2011), Eq.3

- Non-MSF clumps: \( m^{*,\max} < 10M_\odot \)
- MSF clumps: \( m^{*,\max} > 10M_\odot \)

Clump mass \([M_\odot]\) vs. Clump radius \([\text{pc}]\)

Clump mass \([M_\odot]\) vs. log10 (Clump mass \([M_\odot]\))

Clump mass \([M_\odot]\) vs. log10 (Clump radius \([\text{pc}]\))

\( m_{\text{CFRg}} = 10M_\odot \)

\( m_{\text{CFRg}} = 1E3M_\odot \)

\( n_{\text{th}} = 10^5 \text{cm}^{-3} \)
Massive Star Formation Limit

\[ m_{\text{clump}} = 870M_0 \left( \frac{r_{\text{clump}}}{\text{pc}} \right)^{1.33} = \frac{m_{\text{CFRg}}^p}{3-p} \left( \frac{4\pi \rho_{\text{th}}}{3-p} \right)^{(3-p)/3} r_{\text{clump}}^{3-p} \]

Non-MSF clumps: \( m_{\text{*,max}} < 10M_0 \)

MSF clumps: \( m_{\text{*,max}} > 10M_0 \)

Fig 2, Kauffmann & Pillai (2010)

\[ m_{\text{CFRg}} = 10^3 M_0 \]

\[ m_{\text{CFRg}} = 10^5 M_0 \]

\[ n_{\text{th}} = 10^5 \text{ cm}^{-3} \]
Massive Star Formation Limit

Matching the slopes:

\[ m_{\text{clump}} = 870M_0 \left( \frac{r_{\text{clump}}}{\text{pc}} \right)^{1.33} = m_{\text{CFRg}}^{p/3} \left( \frac{4\pi \rho_{\text{th}}}{3 - p} \right)^{\frac{3 - p}{3}} r_{\text{clump}}^{3 - p} \]

**MSF limit:** \( p=1.7 \) (Parmentier+, subm)

**GMC/SC MFs:** \( p=1.9 \) (Parmentier 2011)

**Dust Cont. mapping:** \( p=1.8 \) (Mueller+ 2002)

Matching the intercepts:

\[ m_{\text{clump}} = 870M_0 \left( \frac{r_{\text{clump}}}{\text{pc}} \right)^{1.33} = m_{\text{CFRg}}^{p/3} \left( \frac{4\pi \rho_{\text{th}}}{3 - p} \right)^{\frac{3 - p}{3}} r_{\text{clump}}^{3 - p} \]

- **Parmentier+, subm**, \( m_{\text{CFRg}} = 150M_0 \)
- **Lada, Lombardi & Alves (2010):** \( n_{\text{th,H2}} = 10^4 \text{ cm}^{-3} \)
Conclusions

Properties of young star cluster systems
→ sharp insights into the clustered mode of star formation
→ star formation conditions determine what mass fraction clusters lose as they age
→ information needed to reconstruct galaxy SFH
→ time-variations? (e.g. metallicity)

“Even a long journey starts with a one single step”
Oriental saying

An exciting era has just started:
HERSCHEL, ALMA, …