Dynamical evolution of clusters and the influence of binaries

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Open questions:

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   • What is a cluster?
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Open questions:

1. What fraction of stars form in clusters?
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3. Do star clusters contribute to the Galactic field?
4. Can we determine the initial conditions of star formation?
5. Can Gaia (and surveys) help?
What is a star cluster?

- Define based on a surface density threshold:
  - Lada & Lada (2003): 3 stars pc$^{-2}$
  - Gutermuth et al. (2009): 60 stars pc$^{-2}$
  - Bressert et al. (2010): “dense clusters” – 200 stars pc$^{-2}$
What is a star cluster?

- “Bound” versus “unbound” (e.g. Gieles & Portegies Zwart 2011)
- Define based on crossing time:

\[ T_{cr} \equiv 10 \left( \frac{R_{\text{eff}}^3}{GM} \right)^{1/2} \]
The birthplace of clusters?

- Star-forming cores observed in filaments (e.g. Andre et al 2010, Herschel) – low velocity dispersion
- Filaments intersect at “hubs” (Myers 2012)
Clustered star formation

Trapezium/ONC
(M. McCaughrean/ESO 2001)
Clusters versus associations?

Hot

Cool

Universal initial conditions?
What can we measure?

- Initial mass function
- Binary properties (overall fraction, mass ratio, separation)
- Cluster structure/morphology
- Mass segregation
- Local surface density
- Velocity dispersions
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Clusters: structure and morphology

- Divides mean MST length by mean separation length
  \[ Q = \frac{\bar{m}}{\bar{s}} \]
- \( Q > 0.8 \) = radially concentrated
- \( Q < 0.8 \) = substructured
- Many young star-forming regions substructured (e.g. Sanchez & Alfaro (2009))
Clusters: structure and morphology

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Substructure

(a) Plummer \((Q=1.1)\)       (b) fractal \((Q = 0.4)\)
Mass segregation

Allison et al (2009)
(also Maschberger & Clarke 2011, Olczak et al 2011)

\[ \Lambda_{MSR} = \frac{\langle l_{\text{norm}} \rangle}{l_{\text{massive}}} \pm \frac{\sigma_{\text{norm}}}{l_{\text{massive}}} \]
Mass segregation

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Allison et al (2009)
N-body simulations

- Cool and clumpy (Virial ratio = 0.3, fractal dimension 1.6)
- Hot and clumpy (Virial ratio = 1.5, fractal dimension 1.6)
- Tepid and smooth (Virial ratio = 0.5, fractal dimension 2.6)

- Simulations: 1500 stars in a cluster
- Maschberger (2013) IMF
- Evolved for 10 Myr with **Starlab** (Portegies Zwart et al 1999)
  a) All single stars
Evolution of structure and morphology

- Measuring structure - evolution of the Q-parameter in a collapsing (cool) fractal cluster:

  - Dynamics rapidly erases substructure (Scally & Clarke 2002; Goodwin & Whitworth 2004; Parker & Meyer 2012; Parker, Wright, Goodwin & Meyer, submitted)
Evolution of structure and morphology

• Measuring structure - evolution of the Q-parameter in a collapsing (cool) fractal cluster:

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Supervirial stochasticity
Measuring structure - evolution of the Q-parameter in an unbound (hot) association:

Evolution of structure and morphology (Parker & Meyer 2012; Parker, Wright, Goodwin & Meyer, submitted)
Evolution of structure and morphology

- Measuring structure - evolution of the Q-parameter in an unbound (hot) association:

(Parker & Meyer 2012; Parker, Wright, Goodwin & Meyer, submitted)
Structure versus mass segregation

(Parker, Wright, Goodwin & Meyer, submitted)
Structure versus mass segregation

Different dynamical histories?

Blue: Ber96
Red: Ber94

(Delgado et al 2013)
Using surface density to probe evolution

The Σ – m technique (Maschberger & Clarke 2011):
- Determine the local density of every star.
- Compare to the local density of the massive stars:

\[ \Sigma_{\text{LDR}} = \frac{\Sigma_{\text{massive}}}{\Sigma_{\text{cluster}}} \]

(Parker, Wright, Goodwin & Meyer, submitted)
Structure versus surface density

Dense and cool

Dense and hot

(Parker, Wright, Goodwin & Meyer, submitted)
Structure versus surface density

Evolution of a low-density region

- + 0 Myr
- o 1 Myr
- x 5 Myr
The influence of binaries

- Single stars
- Primordial binaries
Removing outliers

Single stars

primordial binaries
Cool & clumpy; 0Myr

(Allison 2012)
Tepid & smooth; 0Myr

(Allison 2012)
Cool & clumpy; 4Myr

(Allison 2012)
Tepid & smooth; 4Myr

(Allison 2012)
Ejected stars with *Gaia*

- Define an ejection:
  - velocity magnitude > escape velocity
  - radial velocity > tangential velocity
  - position is beyond a cropping distance
(moving fast enough, in right direction, and far enough away)
Ejected velocities; 4Myr

(Allison 2012)
Primordial binaries

Fractional number of ejected stars

Tepid & smooth
Cool & clumpy

Velocity (km/s)
Summary

• Different initial conditions for star formation give very different spatial distributions in clusters/associations

• Strong dynamical evolution betrayed by mass segregation and high local surface densities around massive stars

• More observational data would be very helpful 😊

• What will Gaia (and ground-based surveys) give us?