Issues in understanding the spatial distributions of stars and gas

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Motivation

• See talks by Sarah, Nick, Simon & Michael

• We want to understand conversion of gas to stars (is it a direct mapping?)

• We want to quantify the initial conditions of star formation (and subsequent planet formation)

• My question to me (and us): are measures for quantifying spatial distributions robust enough?
Quantifying structure and morphology

- Divides mean MST length by mean separation length

\[ Q = \frac{\bar{m}}{\bar{s}} \]

Centrally concentrated Plummer sphere (Q = 1.1)
Quantifying structure and morphology

- Divides mean MST length by mean separation length

\[ Q = \frac{\bar{m}}{\bar{s}} \]

Hierarchical fractal distribution (Q = 0.4)

Divides mean MST length by mean separation length:

\[ Q = \frac{\bar{m}}{\bar{s}} \]

- \( Q > 0.9 \) = radially concentrated
- \( Q < 0.7 \) = substructured
- Many young star-forming regions substructured (e.g. Cartwright & Whitworth 2004; Schmeja et al 2008; Sanchez & Alfaro 2009)
Gas structure

Control Run I from Dale et al 2014

Q \sim 0.72 \text{ for sink particles, i.e. border between substructured and smooth }
Q \sim 1.01 \text{ for the gas, i.e. smooth }

(Parker & Dale 2015, using method from Lomax et al 2011)
Gas structure

Dual-feedback Run I from Dale et al 2014

Q ~ 0.49 for sink particles, i.e. substructured
Q ~ 0.88 for the gas, i.e. smooth

(Parker & Dale 2015, using method from Lomax et al 2011)
Why does the Q-parameter not tell me what I want to hear?

- Let’s assume the structure in the gas resembles a ring, constructed from making a hole in a centrally concentrated distribution:

\[ (a) \ Q = 1.1 \]

\[ (b) \ Q = 0.75 \]

\[ (c) \ Q = 0.60 \]

(Parker & Dale 2015)
Now something more complicated:

- Broken ring; 2000 points, $Q = 0.3$
- Uniform background; 1000 points, $Q = 0.7$
- Central clump, 3000 points, $Q = 1.7$
- Combined: $Q = 0.9!$

(Parker & Dale 2015)
Gas structure

Big clump of gas dominates the distribution (Parker & Dale 2015)
But is this something we should just accept?
Mass segregation: $\Lambda_{\text{MSR}}$

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

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

(M. McCaughrean/ESO 2001)

$$\Lambda_{\text{MSR}} = \frac{\langle l_{\text{norm}} \rangle}{l_{\text{massive}}} \pm \frac{\sigma_{\text{norm}}}{l_{\text{massive}}}$$

Allison et al 2009
In hydro simulations


Maschberger & Clarke 2011
Primordial mass segregation?

Simulations from Dale et al 2012/2014 WITHOUT feedback:

1 Myr
Primordial mass segregation?

Simulations from Dale et al 2012/2014 WITHOUT feedback:

1 Myr

Full evolution
Primordial mass segregation?

Simulations from Dale et al 2012/2014 WITH feedback:
Local surface density \( \Sigma_{\text{LDR}} \)

- Determine the local density of every star.
- Compare to the local density of the massive stars:
  \[ \Sigma_{\text{LDR}} = \frac{\Sigma_{\text{massive}}}{\Sigma_{\text{cluster}}} \]

Maschberger & Clarke 2011
Local surface density $\Sigma_{LDR}$

- Massive stars in areas of higher than average surface density


Maschberger & Clarke 2011
Local surface density $\Sigma_{LDR}$

Control Run I from Dale et al 2014

- $\Sigma_{LDR} \gg 1$ with NO FEEDBACK (Parker, Dale & Ercolano 2015)
Local surface density $\Sigma_{\text{LDR}}$

Dual-feedback Run I from Dale et al 2014

- $\Sigma_{\text{LDR}} \sim 1$ WITH FEEDBACK (Parker, Dale & Ercolano 2015)
Myers et al (2014) find that magnetic fields lead to $\Sigma_{LDR} \gg 1$ compared to control run.
The density degeneracy problem

(Parker 2014)
The density degeneracy problem

(Parker 2014)
Dynamical evolution

Cool-collapse model from Allison et al 2010; Parker et al 2014a,b
Quantifying 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. Cartwright & Whitworth 2004; Schmeja et al 2008; Sanchez & Alfaro 2009)
Evolution of structure and morphology

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

![Graphs showing evolution of structure and morphology](image)

- Dynamics rapidly erases substructure (Scally & Clarke 2002; Goodwin & Whitworth 2004; Parker & Meyer 2012; Parker, Wright, Goodwin & Meyer 2014)
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 2014)
We can constrain the initial density of nearby star-forming regions by using their structure (Parker 2014).
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Warm expansion model from Parker et al 2014a,b
Evolution of structure and morphology

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

(Parker & Meyer 2012; Parker, Wright, Goodwin & Meyer 2014)
Evolution of structure and morphology

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

(Parker & Meyer 2012; Parker, Wright, Goodwin & Meyer 2014)
Morphological stochasticity
Local surface density $\Sigma_{LDR}$

- Determine the local density of every star.
- Compare to the local density of the massive stars:
  \[ \Sigma_{LDR} = \frac{\Sigma_{\text{massive}}}{\Sigma_{\text{cluster}}} \]

Maschberger & Clarke 2011

\[ \Sigma = \frac{N - 1}{\pi r^2} \]
Using surface density to probe evolution

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

$$\Sigma_{\text{LDR}} = \frac{\Sigma_{\text{massive}}}{\Sigma_{\text{cluster}}}$$

(Küpper et al 2011, Parker, Wright, Goodwin & Meyer 2014)
Dynamical histories of star clusters

(Parker, Wright, Goodwin & Meyer 2014; Parker 2014; Wright et al 2014; Parker & Alves de Oliveira 2017; Sacco et al, 2017)
Dynamical histories of star clusters

Very dense

\((10^4 \text{ stars/pc}^3)\)

Less dense

\((100 \text{ stars/pc}^3)\)

(Parker, Wright, Goodwin & Meyer 2014; Parker 2014; Wright et al 2014; Parker & Alves de Oliveira 2017; Sacco et al, 2017)
Radial velocities

NGC1333 – Foster et al 2015

\[ \sigma_{\text{vir}} = \sqrt{\frac{2GM}{\eta R}} \]
Radial velocities

\[ \sigma_{\text{vir}} = \sqrt{\frac{2GM}{\eta R}} \]

Parker & Wright 2016
Virial ratio

Parker & Wright 2016
Conclusions/provocations

• No direct mapping of spatial distribution of gas to stars
• No convincing evidence for primordial mass segregation in hydrodynamical simulations

• BUT: spatial distributions can/might be a clock for dynamical evolution
• NO observed SF regions supervirial
• Initial density typically 100 – 1000 stars pc$^{-3}$

• Kinematics even more confusing…?