Competitive accretion and the formation of high-mass stars in stellar clusters

Zinnecker & Yorke 2007, ARA&A

Ian Bonnell
University of St Andrews
High-mass star formation: Observations confront Theory, 2007

Responsibility for setting the characteristic stellar mass. Low-mass stars and brown dwarfs can form through the fragmentation of dense filaments and disks, possibly followed by early ejection from these dense environments, which truncates their growth in mass. Higher-mass stars and the Salpeter-like slope of the IMF are most likely formed through continued accretion in a clustered environment. The effects of feedback and magnetic fields on the origin of the IMF are still largely unclear. Finally, we discuss a number of outstanding problems that need to be addressed in order to develop a complete theory for the origin of the IMF.

Protostars and Planets V, 2007

HansFest: Wonders of Star Formation
PRE-MAIN SEQUENCE BINARIES

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ABSTRACT

The astrophysics of pre-Main Sequence (PMS) binaries is discussed. Recent observational results on visual, speckle, lunar occultation and spectroscopic PMS binaries are summarized. An outlook into the near future is given. Several suggestions for new observations are made: to image the known visual PMS binaries with NIR arrays (to separate the NIR excess of the components); to measure the 10 µm excess of each component (to probe for separate circumstellar disks); to detect UV boundary layer emission from the individual components (as a tracer of the mass accretion rates); to search for aligned double jets from the components (to probe for coplanar disks). The latter observation might be a means to discriminate between a fragmentation and a capture origin of wide binaries. On the theory side, numerical calculations of the collapse of an elongated filament, rotating end over end, are proposed as a promising mechanism for the formation of wide binaries. The origin of close binaries remains a more daunting challenge. Any formation process must be capable of creating pairs of roughly equal mass and high orbital eccentricity.

1 Introduction

If we look at stars from a sociological point of view, pre-Main Sequence binaries would be the analogs of couples that just got married. Of course, there is a certain percentage of stars and people that remain single. That percentage may depend on (and vary with) the detailed conditions in the respective birthplaces and communities. Normally the percentage of singles is small (10-30%); obviously life is more interesting in pairs. It is also obvious that studying young pairs (when the constituents are settling) is more rewarding than mature pairs (when both have settled on the Main Sequence). Young pairs allow us to gain insight into the dating process, i.e. how the two bodies initially got physically attracted to each other.

At this point I will quit the comparative sociology of stars and people, in the hope that it will have done the trick to remind the reader of the fundamental fact that most young stellar objects must be expected to be physical pairs - a fact well known, yet still too often ignored.

Zinnecker, 1989
Rotating filaments as binary formation

Fig. 1. Schematic evolution of a prolate subcondensation in a filament into a protobinary system. Here the angular momentum vector is perpendicular to the plane of the sky. The velocity gradient along the filament is $\sim 1 \text{ km s}^{-1} \text{ pc}^{-1}$. Arrows indicate the direction of motion. The initial length of the subcondensations is $\sim 0.2 \text{ pc}$, the final major axis of the binary system is between 100 and 1000 AU.
Fig. 1. Schematic evolution of a prolate subcondensation in a filament into a protobir system. Here the angular momentum vector is perpendicular to the plane of the sky, and the velocity gradient along the filament is $\sim 1 \text{ km s}^{-1} \text{ pc}^{-1}$. Arrows indicate the direction of motion. The initial length of the subcondensations is $\sim 0.2 \text{ pc}$, the final major axis of binary system is between 100 and 1000 AU.
Abstract

A simple analytical accretion model is developed for the protostellar mass spectrum in the infrared cluster in Orion (OMC1/KL region) in which protostellar cores compete for the accretion of the gas of their parent cloud. Unlike coagulation models, this model is a linear model which includes the conservation of the number of accretion nuclei, with no collisional mergers occurring. Gas exhaustion effects are not included, since less than 50 percent of the cloud gas will be accreted before the most massive star powers the formation of a hot H II region or the formation of an energetic stellar wind, thereby freezing the mass spectrum. A mass spectrum is predicted to be of the form \( \frac{dN}{d \log M} \) approximately equal to \( \frac{1}{M} \) for \( M \) greater than or approximately equal to 1 solar mass, independent of the form of the mass spectrum at the beginning of the accretion process. In particular, a runaway growth of the most massive star, with a big gap in mass to the next massive star, is predicted.
Competitive accretion

- Fragmentation down to (thermal) Jeans Mass
  - Form as lower mass stars ($\sim 0.5 \, M_{\odot}$)
  - Subsequent accretion forms high-mass stars

- Accretion limited by
  - Tidal effects
  - Gas velocities: Bondi-Hoyle

**Stars do not have to move!**

- Gas inflow due to cluster potential
  - Fragmentation inefficient: common gas reservoir
  - Higher gas densities and accretion rates:

- Requirements:
  - $N > 2$ fragments, gravitationally bound
  - Common gas reservoir

Bonnell & Bate 2006

Bonnell, Larson & Zinnecker 2007

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Accretion reservoirs

Accretion onto high-mass stars comes from cluster scale, lower density gas. Yellow = mass which will be accreted by the most massive sink within 0.25 $t_{\text{dyn}}$.

Infalling fragments (cores) need to be dense, tidally bound to form low-mass stars.

Smith et al 2009
Accretion in clusters and the IMF

- Higher mass stars formed through accretion

\[ \dot{M} \propto M^{2/3} \]

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Maschberger et al 2014
SPH: nested simulations
Self-gravity included in final set and star formation is resolved

Molecular cloud evolution viewed from within disc

T=350 Myr
T=352 Myr
T=354 Myr

2 kpc
500 pc
20 pc
The Galactic plane

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Mass growth by accretion and mergers

Smilgys & Bonnell 2017

Cluster growth through mergers

Gas accretion significant in higher-mass clusters

Mass fraction entering the cluster as gas
Cluster properties

Clusters have significant age spreads

Cluster sizes \( R \sim M \)

Similar, smaller scaling to pre-cluster clumps
Failed cluster formation

Tidal forces impede merger, Formation of OB association?

Smilgys & Bonnell 2018
Merging clusters and isolated high-mass stars

Later, dry mergers in cluster formation
High-mass stars dispersed due to tidal fields of secondary cluster
On the formation of massive stars

Ian A. Bonnell, Matthew R. Bate and Hans Zinnecker

Abstract

We present a model for the formation of massive ($M \gtrsim 10 \, M_\odot$) stars through accretion-induced collisions in the cores of embedded dense stellar clusters. This model circumvents the problem of accreting on to a star whose luminosity is sufficient to reverse the infall of gas. Instead, the central core of the cluster accretes from the surrounding gas, thereby decreasing its radius until collisions between individual components become sufficient. These components are, in general, intermediate-mass stars that have formed through accretion on to low-mass protostars. Once a sufficiently massive star has formed to expel the remaining gas, the cluster expands in accordance with this loss of mass, halting further collisions. This process implies a critical stellar density for the formation of massive stars, and a high rate of binaries formed by tidal capture.

$$E_{\text{tot}} = \frac{p^2}{2M_{\text{stars}}} - \frac{GM_{\text{core}}M_{\text{stars}}}{R_{\text{core}}}.$$
Accretion can force core to contract

$$R_{\text{core}} \propto M_{\text{stars}}^{-3}.$$ 

But if core is decoupled from cluster, it will dissolve

Requires large N clusters (> 30,000)

Collisional formation of very high-mass stars in rich stellar clusters possible

Clarke & Bonnell 2008
Moeckel & Clarke 2011

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Bonnell, Bate & Zinnecker 1998
Cluster dynamics cannot explain high-mass close binaries

Most high-mass stars in close binaries

Expected binary separations from dynamical hardening

Limit: $E_{\text{bin}} \sim E_{\text{cluster}}$

Requires $> \cdot$
Problem: most high-mass stars are in close binary systems. Separation $<< R_{\text{Jeans}}$

Need to accrete mass without angular momentum. Solution: magnetic braking during accretion phase.
Formation of close binaries by magnetic braking

M = 500 Mo
R = 0.5 pc
Ω = 3 \times 10^{-14} \text{ rad/s}

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Lund & Bonnell 2018
Close binaries from core properties

Example:

<table>
<thead>
<tr>
<th>Cloud mass ($M_\odot$)</th>
<th>Cloud radius (pc)</th>
<th>Binary mass ($M_\odot$)</th>
<th>Binary separation (au)</th>
<th>Magnetic field ($\mu$G)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1145</td>
<td>0.58</td>
<td>5.9</td>
<td>3.842</td>
<td>0</td>
</tr>
<tr>
<td>1145</td>
<td>0.58</td>
<td>26.5</td>
<td>0.046</td>
<td>100</td>
</tr>
</tbody>
</table>


Accretion-induced binary mergers to form highest mass stars?
Ionisation and stellar winds

Dale, Ercolano & Bonnell 2012, 2014

Lower density clouds affected

But none are destroyed outright

Radiation leaks out through cloud

Can unbind gas in clouds with

\[ v_{\text{esc}} < c_s \text{ (HII)} \]
Ionisation and stellar winds

Dale, Ercolano & Bonnell 2012, 2014

Lower density

Fraction gas unbound

Fraction stars unbound

Unbound stellar mass

$V_{\text{esc}} \ll c_s \ (\text{HII})$

Dale, Ercolano & Bonnell 205
Summary

- Star clusters form due to large-scale compressive flows
  - Self gravity dominates locally,
  - Hierarchical fragmentation, gas accretion and mergers

- Accretion in clusters can explain (most) high-mass star formation
  - Simultaneous to cluster formation

- Close high-mass binaries from accretion and magnetic braking
  - Stellar mergers?

- Feedback predominately affects lower density gas
  - Has moderate ~2 reduction on ongoing star formation

- If Hans has an idea: it is worthwhile listening!

HansFest: Wonders of Star Formation