Better understand the IMF of the first stars

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What can we learn from present-day star formation about the first stars?

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thanks to ... 

... people in the group in Heidelberg:


... many collaborators abroad!
stars seem to follow a universal mass function at birth $\rightarrow$ IMF

(Kroupa 2002)

Orion, NGC 3603, 30 Doradus
(Zinnecker & Yorke 2007)
stellar masses

- distribution of stellar masses depends on
  - turbulent initial conditions
    --> mass spectrum of prestellar cloud cores
  - collapse and interaction of prestellar cores
    --> accretion and N-body effects
  - thermodynamic properties of gas
    --> balance between heating and cooling
    --> EOS (determines which cores go into collapse)
  - (proto) stellar feedback terminates star formation
    ionizing radiation, bipolar outflows, winds, SN

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(Kroupa 2002)
nearby molecular clouds

scales to same scale

10 pc

(from A. Goodman)

study more closely
image from Alyssa Goodman: COMPLETE survey
„model“ of Orion cloud:
15,000,000 SPH particles,
$10^4 \, M_{\text{sun}}$ in 10 pc, mass resolution
0.02 $M_{\text{sun}}$, forms $\sim$2,500
„stars“ (sink particles)

isothermal EOS, top bound, bottom unbound

has clustered as well as distributed „star“ formation

efficiency varies from 1% to 20%

develops full IMF
(distribution of sink particle masses)

(Bonnell & Clark 2008)
example: model of Orion cloud

Bonnell & Clark 2008

Example: model of Orion cloud: 15,000,000 SPH particles, $10^4 M_{\odot}$ in 10 pc, mass resolution 0.02 $M_{\odot}$, forms ~2,500 "stars" (sink particles)

MASSIVE STARS
- form early in high-density gas clumps (cluster center)
- high accretion rates, maintained for a long time

LOW-MASS STARS
- form later as gas falls into potential well
- high relative velocities
- little subsequent accretion
Dynamics of nascent star cluster

in dense clusters protostellar interaction may be come important!

Trajectories of protostars in a nascent dense cluster created by gravoturbulent fragmentation
Mass accretion rates vary with time and are strongly influenced by the cluster environment.

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application to first star formation
degree of fragmentation depends on EOS!

polytropic EOS: \( p \propto \rho^\gamma \)
\( \gamma < 1 \): dense cluster of low-mass stars
\( \gamma > 1 \): isolated high-mass stars

(see Li et al. 2003; also Kawachi & Hanawa 1998, Larson 2003)
dependency on EOS

\[ \gamma = 0.2 \]

\[ \gamma = 1.0 \]

\[ \gamma = 1.2 \]

for \( \gamma < 1 \) fragmentation is enhanced \( \rightarrow \) cluster of low-mass stars

for \( \gamma > 1 \) it is suppressed \( \rightarrow \) formation of isolated massive stars

(from Li, Klessen, & Mac Low 2003, ApJ, 592, 975)
how does that work?

(1) \( p \propto \rho^{\gamma} \rightarrow \rho \propto p^{1/\gamma} \)

(2) \( M_{\text{jeans}} \propto \gamma^{3/2} \rho^{(3\gamma-4)/2} \)

• \( \gamma < 1 \) → large density excursion for given pressure
  → \( \langle M_{\text{jeans}} \rangle \) becomes small
  → number of fluctuations with \( M > M_{\text{jeans}} \) is large

• \( \gamma > 1 \) → small density excursion for given pressure
  → \( \langle M_{\text{jeans}} \rangle \) is large
  → only few and massive clumps exceed \( M_{\text{jeans}} \)
EOS as function of metallicity

(Omukai et al. 2005)
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present-day star formation

present-day star formation

\[ \frac{\tau}{\gamma} = 1 \]  
(Larson 1985, Larson 2005)

\[ \gamma = 0.7 \]

\[ \gamma = 1.1 \]

\( \log n(H_2) \) (cm\(^{-3}\))

\( \log T \) (°K)

\( \log \rho \) (gm/cm\(^3\))
This kink in EOS is very insensitive to environmental conditions such as ambient radiation field --> reason for universal form of the IMF?  (Elmegreen et al. 2008)

(Larson 1985, Larson 2005)

\[ \gamma = 0.7 \]

\[ \gamma = 1.1 \]
IMF in nearby molecular clouds


\[ \rho_{\text{crit}} \approx 2.5 \times 10^5 \text{ cm}^{-3} \text{ at SFE } \approx 50\% \]

need appropriate EOS in order to get low mass IMF right
transition: Pop III to Pop II.5

(Omukai et al. 2005)
The dashed lines show constant Jeans mass values. Dust temperature for the turbulent and rotating cloud is our primary concern. The opacity varies with dust temperature following the relationship $\kappa \propto T^{-5/2}$, while at much higher grain temperatures, it is necessary to account for the opacity of hydrogen nuclei. At other temperatures, where $[\text{He}]$ is the helium abundance, $\kappa \propto T^{-3}$.

Results of our low-resolution simulations show the dependence extremely rapidly due to the melting of the grains. We adopted initial conditions similar to those in the gas would fragment, we employed $0.3$ million SPH particles. We modelled two different amounts of compressional heat, and the mass resolution was $5.33$ times the typical stellar mass. We can follow the collapse down to scales of the order of an AU, but at this point we reach the limit of our computational resources. We see that its internal structure is also filamentary. If we zoom in on one of the overdense clumps in the center, we see that its internal structure is also filamentary. Overdense clumps in the center of the high-density region fragment into several objects. Figure 3 shows the evolution of the gas is close to adiabatic. The gas also cools the gas down to $411 \text{ K}$, for the same metallicity, the agreement is better with their one-dimensional plus 2D hydrodynamical calculations. We can fully resolve compressional heating rates couple for densities higher than $21 \times 10^3 \text{ cm}^{-3}$, the typical stellar mass is similar to what is observed for Pop III to Pop II.5

Fig. 2.— Number density maps for a slice through the high density region. The image shows a sequence of zooms in the density structure in the gas immediately before the formation of the first protostar.

Fig. 3.— Number density map showing a slice in the densest clump, and the sink formation time evolution, for the $50$ million particles simulation, and $Z = 10^{-4} Z_\odot$. The box is $100 \text{ AU} \times 100 \text{ AU}$ and the time is measured from the formation of the first sink particle.

transition: Pop III to Pop II.5

Fig. 4.— Sink particle mass function at the end of the simulations. High and low resolution results and corresponding resolution limits are shown. To resolve the fragmentation, the mass resolution should be smaller than the Jeans mass at the point in the temperature-density diagram where dust and gas couple and the compressional heating starts to dominate over the dust cooling. At the time shown, around $5\ M_\odot$ of gas had been accreted by the sink particles in each simulation.

dense cluster of low-mass protostars builds up:

- mass spectrum peaks below $1 \ M_\text{sun}$
- cluster VERY dense
  $n_{\text{stars}} = 2.5 \times 10^9 \ pc^{-3}$
- fragmentation at density
  $n_{\text{gas}} = 10^{12} - 10^{13} \ cm^{-3}$

dense cluster of low-mass protostars builds up:

- mass spectrum peaks below 1 M\(_{\text{sun}}\)
- cluster VERY dense
  \[ n_{\text{stars}} = 2.5 \times 10^9 \text{ pc}^{-3} \]

- *predictions:*
  * low-mass stars with \([\text{Fe/H}] \sim 10^{-5}\)
  * high binary fraction

\(Z = 10^{-5} Z_{\odot}\)

(Clark et al. 2008)
dust induced fragmentation at $Z=10^{-5}$

2 extremely metal deficient stars with masses below 1 Msun.

dense cluster of low-mass protostars builds up:

- mass spectrum peaks below $1\, M_{\text{sun}}$
- cluster VERY dense $n_{\text{stars}} = 2.5 \times 10^9 \, \text{pc}^{-3}$

- predictions:
  * low-mass stars with $[\text{Fe}/\text{H}] \sim 10^{-5}$
  * high binary fraction

(plot from Salvadori et al. 2006, data from Frebel et al. 2005)
metal-free star formation

- slope of EOS in the density range $5 \text{ cm}^{-3} \leq n \leq 16 \text{ cm}^{-3}$ is $\gamma \approx 1.06$.
- with non-zero angular momentum, disk forms.
- disk is unstable against fragmentation at high density

(Omukai et al. 2005)
metal-free star formation

- most current numerical simulations of Pop III star formation predict very massive objects (e.g. Abel et al. 2002, Yoshida et al. 2008, Bromm et al. 2009)

- similar for theoretical models (e.g. Tan & McKee 2004)

- there are some first hints of fragmentation, however (Turk et al. 2009, Stacy et al. 2010)
• star formation will depend on *degree of turbulence* in protogalactic halo

• speculation: *differences in stellar mass function*, just like in present-day star formation

(Greif et al. 2008)
multiple Pop III stars in halo

- parameter study with different strength of turbulence using SPH: study Pop III.1 and Pop III.2 case (Clark et al., 2011a, ApJ, 727, 110)

- 2 very high resolution studies of Pop III star formation in cosmological context
  - SPH: Clark et al. 2011b, Science, 311, 1040

- complementary approaches with interesting similarities and differences....
Pop III.1

(Clark et al, 2011a, 727, 110)
Pop III.2

(Clark et al, 2011a)
once again: thermodynamics

also Pop III.2 gas heats up above the CMB

--> weaker fragmentation!

Fig. 6.— Temperature as a function of number density for the Pop. III.1 (dark blue) and Pop. III.2 (light blue) $\Delta v_{\text{turb}} = 0.1 c_s$ simulations. In both cases, the curves denote the state of the cloud at the point just before the formation of the sink particle.
once again: thermodynamics

comparison of accretion rates...

Fig. 8.— Accretion rates as a function of enclosed gas mass in the Pop. III.1 (upper lines; blue) and Pop. III.2 (lower lines; magenta) simulations, estimated as described in Section 4.1. Note that the sharp decline in the accretion rates for enclosed masses close to the initial cloud mass is an artifact of our problem setup; we would not expect to see this in a realistic Pop. III halo.
Figure 1: Density evolution in a 120 AU region around the first protostar, showing the build-up of the protostellar disk and its eventual fragmentation. We also see ‘wakes’ in the low-density regions, produced by the previous passage of the spiral arms.
Figure 2: Radial profiles of the disk’s physical properties, centered on the first protostellar core to form. The quantities are mass-weighted and taken from a slice through the midplane of the disk. In the lower right-hand plot we show the radial distribution of the disk’s Toomre parameter, $Q = \frac{c_s \kappa}{\pi G \Sigma}$, where $c_s$ is the sound speed and $\kappa$ is the epicyclic frequency. Because our disk is Keplerian, we adopted the standard simplification, and replaced $\kappa$ with the orbital frequency. The molecular fraction is defined as the number density of hydrogen molecules ($n_{\text{H}_2}$), divided by the number density of hydrogen nuclei ($n$), such that fully molecular gas has a value of 0.5

(Clark et al. 2011b, Science, 331, 1040)
Figure 3: The mass transfer rate through the disk is denoted by the solid black line, while the mass infall rate through spherical shells with the specified radius is shown by the dark blue dashed line. The latter represents the total amount of material flowing through a given radius, and is thus a measure of the material flowing through and onto the disk at each radius. Both are shown at the onset of disk fragmentation. In the case of the disk accretion we have denoted annuli that are moving towards the protostar with blue dots, and those moving away in pink (further details can be found in Section 6 of the online material). The light blue dashed lines show the accretion rates expected from an ‘alpha’ (thin) disk model, where \( \dot{M}(r) = 3 \pi \alpha c_s(r) \Sigma(r) H(r) \), with two global values of alpha and where \( c_s(r) \), \( \Sigma(r) \), and \( H(r) \) are (respectively) the sound speed, surface density and disk thickness at radius \( r \).

(Clarke et al. 2011b, Science, 331, 1040)
Figure 7: (a) Dominant heating and cooling processes in the gas that forms the second sink particle. (b) Upper line: \( t_{\text{thermal}} \) to the free-fall timescale, \( t_{\text{ff}} \), for the gas that forms the second sink particle. Periods when the gas is cooling are indicated in blue, while periods when the gas is heating are indicated in red. Lower line: ratio of \( t_{\text{thermal}} \) to the orbital timescale, \( t_{\text{orbital}} \), for the same set of SPH particles (c) Temperature evolution of the gas that forms the second sink (d) Density evolution of the gas that forms the second sink

(Clarke et al. 2011b, Science, 331, 1040)
Arepo study: surface density at different times

5 kpc (comoving)  10 pc  200 AU

First star forms ($t_{\text{SF}}$)  $t_{\text{SF}} + 30 \text{ yr}$  $t_{\text{SF}} + 100 \text{ yr}$

one out of five halos

Arepo study: mass spectrum of fragments

primordial star formation

just like in present-day SF, we expect
  turbulence
  thermodynamics
  feedback
  magnetic fields
to influence Pop III/II star formation.

masses of Pop III stars still uncertain (surprises from new generation of high-resolution calculations that go beyond first collapse)

disks unstable: Pop III stars should be binaries or part of small clusters

effects of feedback less important than in present-day SF
questions

• is claim of Pop III stars with \( M \sim 0.5 \, M_\odot \) really justified?
  - stellar collisions
  - magnetic fields
  - radiative feedback

• how would we find them?
  - spectral features

• where should we look?

• what about magnetic fields?
• magnetic field amplification in primordial collapse (see also talk by Dominik Schleicher)

• influence of streaming motions on collapse in primordial halos (see also talk by Thomas Greif)

• fragmentation-induced starvation as key to understand final stellar masses (Peters et al. 2010abc, 2011)
B fields in the early universe?

• we know the universe is magnetized (now)

• knowledge about B-fields in the high-redshift universe is extremely uncertain
  - inflation / QCD phase transition / Biermann battery / Weibel instability

• they are thought to be extremely small

• however, THIS MAY BE WRONG!
small-scale turbulent dynamo

- **idea**: the small-scale turbulent dynamo can generate strong magnetic fields from very small seed fields

- **approach**: model collapse of primordial gas ---\(\to\) formation of the first stars in low-mass halo at redshift \(z \sim 20\)

- **method**: solve ideal MHD equations with very high resolution
  - grid-based AMR code FLASH
    (effective resolution \(65536^3\))
magnetic field structure

density structure

Field amplification during first collapse seems unavoidable.

QUESTIONS:
• Is it really the small scale dynamo?
• What is the saturation value?
  Can the field reach dynamically important strength?
analysis of magnetic field spectra

Slope $+3/2$ of Kazantsev theory

(e.g. Brandenburg & Subramanian, 2005, Phys. Rep., 417, 1)

analysis of magnetic field spectra

first attempts to calculate the saturation level.

We seem to get a saturation level of $\sim 10\%$

**QUESTIONS:**
- Is this true in a proper cosmological context?
- What does it mean for the formation of the first stars?

(see, e.g., Subramanian 1997, or Brandenburg & Subramanian 2005)
• small-scale turbulent dynamo is expected to operate during Pop III star formation

• process is fast \( (10^4 \times t_{ff}) \), so primordial halos may collapse with B-field at saturation level!

• simple models indicate saturation levels of \( \sim 10\% \)
  --> larger values via \( \alpha \Omega \) dynamo?

• QUESTIONS:
  - does this hold for “proper” halo calculations (with chemistry and cosmological context)?
  - what is the strength of the seed magnetic field?
effects of streaming velocities

- relative velocity of gas and DM of a few km/s
  (Tseliakhovich & Hirata 2010)

- how does that influence formation and evolution of minihalos?
Figure 1. Comparison of the statistical binning in halos with no streaming velocity (top panels), and with an initial streaming velocity of 3 km s$^{-1}$ applied at $z=99$ from left to right (middle and bottom panels). We show the density-squared weighted gas temperature projected along the line of sight when the hydrogen density is just exceeded $n_\text{H}=10^{9}$ cm$^{-3}$ (top and bottom panels), and when the streaming case has evolved to the same redshift as the no-streaming case (middle panels). In the presence of streaming velocities, the effective Jeans mass of the gas is increased. The underlying DM halo therefore becomes more massive before the gas can cool, which delays the onset of collapse. We also find that virial shocks are more pronounced in the direction of the incoming streaming flow than in other directions. Non-linear effects of this sort may result in a higher velocity dispersion of the gas (see also Figure 4).
The initial fluctuation power spectrum is that of a cold dark matter (CDM) cosmology at a starting redshift of 19.9, respectively. According to this simple argument, the Jeans mass of the gas is captured with a primordial chemistry network (Glover & Jappsen 2007; Greif et al. 2011). The gas fractions and central densities of the minihalos are as an additional source of pressure, which increases the Jeans mass of the gas.

In Figure 1, we show the temperature of the gas as a function of redshift. The different linearly extrapolated present-day Jeans masses lead to a reduction of the number of star-forming minihalos. Simulations without an additional streaming velocity of 1 km s\(^{-1}\) are indicated by the arrows, the virial mass required for delayed collapse is shifted from 19.9 to 6, 19.9, respectively. This is equivalent to altering the redshift of reionisation, we employ 256 different linearly extrapolated present-day Jeans masses.

In Figure 2, we show the velocity dispersion of the gas as a function of redshift. The different linearly extrapolated present-day Jeans masses lead to a reduction of the number of star-forming minihalos. Simulations without an additional streaming velocity of 1 km s\(^{-1}\) are indicated by the arrows, the virial mass required for delayed collapse is shifted from 19.9 to 6, 19.9, respectively. This is equivalent to altering the redshift of reionisation, we employ 256 different linearly extrapolated present-day Jeans masses.
A streaming velocity of 1 km s\(^{-1}\) is particularly important in minihalos, since a qualitative description of their simulation results. The increased amount of turbulence might later affect the fragmentation of the gas and alter the mass function of the halos. Stacy et al. (2010) showed that this picture corresponds to factors of 2 \(\times 10^3\) increase in minimum halo mass required for collapse. The Jeans mass of the gas: 

\[ M_{\text{ff}} = \frac{c_s^2}{G} \]

where \(c_s\) is the sound speed of virialized gas in halos with a streaming velocity. The increased virial mass leads to a reduction of the number of star-forming minihalos by up to an order of magnitude. The influence of Pop III stars on observables such as the 21 cm background or the reionization of the universe might therefore be substantially reduced.

**Result:**

- **number of star forming minihalos** at any redshift decreases by roughly **factor of 10**
- **stronger turbulence** should lead to **higher degree of fragmentation**


**Figure 5.** The comoving number density of minihalos that are expected to cool and form Pop III stars for no streaming velocity (solid line), and for an initial streaming velocity of 3 km s\(^{-1}\) at \(z = 99\) (dotted line). The factor of \(\approx 3\) increase in minimum virial mass leads to a reduction of the number of star-forming minihalos by up to an order of magnitude. The influence of Pop III stars on observables such as the 21 cm background or the reionization of the universe might therefore be substantially reduced.
Effects of feedback: high-mass star formation at present day

- what is the role of feedback?
  - can non-ionizing radiation heat the gas and prevent fragmentation?
    → **ANSWER:** to some degree yes, but not strong effect!
  - can ionizing radiation stop mass accretion?
    → **ANSWER:** probably no, as indicated by simulations

- what determines the final mass of a star?
  - dynamical processes! (fragmentation-induced starvation, see Peters et al. 2010abc, 2011)
We want to address the following questions:
• how do massive stars (and their associated clusters) form?
• what determines the upper stellar mass limit?
• what is the physics behind observed HII regions?
our (numerical) approach

- focus on collapse of individual high-mass cores...
  - massive core with 1,000 M\(_\odot\)
  - Bonnor-Ebert type density profile (flat inner core with 0.5 pc and rho \(\sim r^{-3/2}\) further out)
  - initial m=2 perturbation, rotation with \(\beta = 0.05\)
  - sink particle with radius 600 AU and threshold density of \(7 \times 10^{-16}\) g cm\(^{-3}\)
  - cell size 100 AU

our (numerical) approach

- method:
  - FLASH with ionizing and non-ionizing radiation using ray tracing based on hybrid characteristics
  - protostellar model from Hosokawa & Omukai
  - rate equation for ionization fraction
  - relevant heating and cooling processes
  - some models include magnetic fields
  - first 3D MHD calculations that consistently treat both ionizing and non-ionizing radiation in the context of high-mass star formation

Peters et al. (2010a,b,c)
- all protostars accrete from common gas reservoir
- accretion flow suppresses expansion of ionized bubble
- cluster shows “fragmentation-induced starvation”
- halting of accretion flow allows bubble to expand

Peters et al. (2010a,b,c)
ray tracing method
(hybird characteristics)

Monte Carlo: full RT
(with scattered radiation)
mass load onto the disk exceeds inward transport
--> becomes gravitationally unstable (see also Kratter & Matzner 2006, Kratter et al. 2010)

fragments to form multiple stars --> explains why high-mass stars are seen in clusters

younger protostars form at larger radii

“burst” of star formation

mass load onto the disk exceeds inward transport
---> becomes gravitationally unstable (see also Kratter & Matzner 2006, Kratter et al. 2010)

fragments to form multiple stars ---> explains why high-mass stars are seen in clusters

- compare with control run without radiation feedback
- total accretion rate does not change with accretion heating
- expansion of ionized bubble causes turn-off
- no triggered star formation by expanding bubble

- magnetic fields lead to weaker fragmentation
- central star becomes more massive (magnetic breaking

Fragmentation-induced starvation in a complex cluster

Gas density as function of radius at different times

Mass flow towards the center as function of radius at different times

Girichidis et al. (2011a,b)
questions

• stellar masses strongly influenced by dynamics: *fragmentation-induced starvation*

• process depends on initial conditions: *what are those for primordial halos? not only look at first halo but at 10th, 20th, etc.*

• at present days, feedback cannot stop accretion: *what about Pop III stars?* (Hosokawa et al. 2011)
conclusions

primordial star formation exhibits the *same complexity* as stellar birth at present days

- turbulence
- thermodynamics
- feedback
- magnetic fields

all influence Pop III and Pop II.5 star formation.