The First Stellar Cluster?

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Metal-free gas

Inefficient cooling ↓ Stiff equation of state ↓ Limited fragmentation

Metal-enriched gas

More efficient cooling ↓ Softer equation of state ↓ More fragmentation

- Omukai, 2000:
 - one-zone models with detailed chemical model and cooling function
 - predicts sharp drop in temperature at
 n > 10¹⁰ cm⁻³ in Z < 10⁻⁴ Z_{sol} gas,
 resulting from onset of efficient dust cooling
- Schneider et al, 2002:
 - this should lead to fragmentation, with a mass scale M \sim 0.01 $\rm M_{sol}$

 Subsequent work (Omukai et al, 2005; Schneider et al, 2006) has lowered Z_{crit}:

$$Z_{crit} \sim 10^{-5} - 10^{-6} Z_{sol}$$



Omukai et al, 2005

- Tsuribe & Omukai 2006:
 - SPH simulations of dust cooling in dense, low metallicity cores
 - use tabulated equation of state (EOS) based on results from Omukai et al, 2005
 - simulations begin at n = 10^{10} cm⁻³, use N ~ 2 x 10⁶ particles
 - consider only cores with zero angular momentum!



Tsuribe & Omukai, 2006

- TO06 results:
 - Oblate cores do not fragment
 - Prolate cores fragment if they have initial axis ratios > 2
 - Fragmentation becomes much more effective with increasing Z
- BUT: because angular momentum is zero, fragments do not survive

- Clark, Glover & Klessen 2008:
 - Basic approach similar to TO06
 - Larger particle number: $N = 2.5 \times 10^7$
 - Lower initial density ($n = 5 \times 10^5 \text{ cm}^{-3}$)
 - Rotation!
 - Sink particles
 - Simulate clouds with Z=0, 10⁻⁶, 10⁻⁵ Z_{sol}



Clark, Glover & Klessen, 2008 (CGK08)









- Single star forms first, near center of dense, disc-like structure
- Rapid cooling of the disc leads to violent gravitational instability
- Many protostars form within ~ 400 years
- Without sink particles, most of this fragmentation would have been missed



CGK08

- Resulting IMF broad, peaks below 1 M_{sol}
- Natural consequence of competitive accretion
- Ejection ⇒ some low mass stars survive



Caveats

- Single EOS not really appropriate
- Amount of heating prior to dust cooling quite uncertain (dynamics, chemistry)
- No protostellar feedback
- No mergers
- Dust model uncertain
- No magnetic fields

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Conclusions

- Dust cooling leads to highly efficient fragmentation at $Z_{dust} \sim 10^{-5} Z_{sol}$
- These stars form in very dense, clustered environments
- We predict that stars with total metallicities < 10⁻⁴ solar will be found