the transition from Population III to Population II stars

Raffaella Schneider
INAF/Osservatorio Astronomico di Roma
DAVID

http://www.arcetri.astro.it/david

Dark Ages Virtual Department

A collaboration network for the study of Cosmology and the high redshift Universe

Simone Bianchi
INAF/OAArcetri

Benedetta Ciardi
MPA

Pratika Dayal
ROE-Edinburgh

Carmelo Evoli
Hamburg/DESY

Andrea Ferrara
SNS

Simona Gallerani
SNS

Fabio Iocco
IAP

Francisco Shu-Kitaura
MPA

Antonella Maselli
SNS

Stefania Salvadori
Kapteyn Institute

Ruben Salvaterra
INAF/IAFS

Raffaella Schneider
INAF/OARoma

Sunghye Baek
SNS

Marcos Valdes
SNS

Rosa Valiante
INAF/OARoma

Livia Vallini
SNS

Andrei Meisinger
SNS

Stefania Pandolfi
DARK
Outline

• is there a transition in mass-scale?

• what drives the transition: metals or dust?

• do we need to know the exact value of $Z_{cr}$?

• how can we make real progress?
is there a transition in mass-scale?

Ambiguous results from theory and simulations:

- **thermal physics and fragmentation:**

  Larson (2005)
  
  “The thermal properties of star-forming clouds have an important influence on how they fragment into stars, and it is suggested in this paper that the low-mass stellar initial mass function (IMF), which appears to be almost universal, is determined largely by the thermal physics of these clouds. In particular, it is suggested that the characteristic stellar mass, a little below one solar mass, is determined by the transition from an initial cooling phase of collapse to a later phase of slowly rising temperature that occurs when the gas becomes thermally coupled to the dust. Numerical simulations support the hypothesis that the Jeans mass at this transition point plays an important role in determining the peak of the mass of the IMF....”

3D simulations: fragmentation depends on the EOS: $T \propto \rho^{\gamma-1}$

FIRST STARS IV - The Pop III/II transition

Li, Klessen & Mac Low (2003)
Jappsen et al. (2005)
is there a transition in mass-scale?

Ambiguous results from theory and simulations:

- 3D simulations of primordial star formation

\[ M_{ch} = M_{\text{Jeans}}(n_{\text{frag}}, T_{\text{frag}}) \sim 10^3 M_{\odot} \]

Accretion disk instability: fragmentation \( M_{ch} = ? \)

\[ \text{Minihalo 300pc} \]
\[ \text{Molecular cloud} \]
\[ \text{New-born protostar} \]
\[ \text{25 solar-radii} \]

Yoshida et al. (2008)

Abel et al. (2002); Bromm et al. (2002)

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Turk et al. (2009); Stacy et al. (2010); Clark et al. (2008-2011); Greif et al. (2011)
is there a transition in mass-scale?

Ambiguous results from theory and simulations:

- late accretion phase and radiative feedback

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Hosokawa et al. 2011
is there a transition in mass-scale?

Observational evidence:

- no metal-free stars observed
  
  \[ Z_* \approx 10^{-2} Z_{\text{sun}} \]

  HE 0107-5240  
  [Fe/H] = -5.2  
  Christlieb et al 02,04,08

  HE 1327-2326.  
  [Fe/H] = -5.4  
  Frebel et al 05

  HE 0557-4840  
  [Fe/H] = -4.75  
  Norris et al. 08

  SDSS J102915  
  [Fe/H] = -4.99  
  Caffau et al 11

- could we observe a \( Z_* \approx 0 \) low-mass star?
  
  accretion of interstellar gas as the star orbits the Galaxy for \( \sim 10 \) Gyr might set a minimum pollution limit:
  
  \[ [\text{Fe/H}] \approx -5.7 \]  
  (Iben 1983)

  fast space velocities from kinematic analysis: little accreted mass (Frebel et al 2009)

  if weak stellar winds are present: no material is accreted (Johnson et al 2011)
is there a transition in mass-scale?

Observational evidence:

- shape of the metallicity distribution function and statistics of observed samples of very metal poor stars

\[ F_o = \frac{\# \text{metal-free stars}}{\# \text{observed stars}} \text{ [Fe/H] < -2.5} \quad < F_{obs} = 8.7 \times 10^{-4} \]  

(Oey 2003; Tumlinson 2006)

\[ \begin{array}{|c|c|} 
\hline 
Z_{crit}/Z_{sun} & F_o \\
10^{-4} & << F_{obs} \\
10^{-6} & << F_{obs} \\
0 & 7.5 \times 10^{-3} \\
\hline 
\end{array} \]
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• is there a transition in mass-scale? probably yes

• what drive the transition: metals or dust?

• do we need to know the exact Zcr?

• how can we make real progress?
what drives the transition: metals or dust?

**metal-cooling**

- depends on gas metallicity:
  \[ Z_{cr} = 10^{-3.5} Z_{sun} \]  
  (Bromm+2001)

- OI, CII, SII, Fell are the most important coolants:
  
  \[ [O/H]_{cr} = -3.05 \pm 0.2 \, \quad [C/H]_{cr} = -3.5 \pm 0.1 \]  
  (Bromm & Loeb 2003)

  \[ [Si/H]_{cr} = -4.08 \, \quad [Fe/H]_{cr} = -3.8 \]  
  (Santoro & Shull 2006)

- is effective at \( n \leq [10^3 - 10^6] \, \text{cm}^{-3} \)

**dust-cooling**

- depends on gas metallicity and on dust depletion factor \( f_{dep} = M_{dust}/(M_{dust} + M_{met}) \):
  \[ Z_{cr} = 10^{-6} Z_{sun} \text{ for } f_{dep} \geq 0.2 \]  
  (Schneider+2002-2011; Omukai+2005)

- depends on dust grain cross-section per unit dust mass: smaller grains, larger S, smaller \( Z_{cr} \) for fixed \( f_{dep} \)
  (Schneider+2006, 2011; Hirashita & Omukai 2009)

- is effective at \( n \geq 10^{12} \, \text{cm}^{-3} \)
H$_2$, metal and dust-driven fragmentation:
3 different mass-scales

**H$_2$-line cooling:**

$M_{jeans} \sim 10^3 \ M_{sun}$

Abel+ (2002),
Bromm+ (2002),
Yoshida+ (2008)

**metal-line cooling:**

$M_{jeans} > 10s \ M_{sun}$

Bromm+ (2001),
Bromm & Loeb (2003),
Santoro & Shull (2006)

**dust cooling:**

$M_{jeans} < 1 \ M_{sun}$

Omukai+ (2005)
simulations of metal-driven fragmentation

multiple clump formation when $10^{-4} Z_{\text{sun}} < Z_{\text{cr}} \leq 10^{-3} Z_{\text{sun}}$

Smith & Sigurdsson (2007)

Bromm et al. (2001); Smith et al. (2009); Aykutalp & Spaans (2011)
simulations of dust-driven fragmentation

dust-cooling is effective already at $Z = 10^{-5} Z_{\text{sun}}$

Dopcke et al. (2011)

Tsuribe & Omukai (2006), Clark et al. (2008), Omukai et al. (2010)

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critical metallicity or dust-to-gas ratio?

dust cooling depends on the absolute metallicity AND dust depletion factor $f_{dep} = M_{dust}/(M_{met} + M_{dust})$.

$Z = 10^{-4} Z_{sun}$

$Z = 10^{-4} Z_{sun}$

$20\%$ $3\%$ $8\%$

$f_{dep} = 90\%$

$RS, \text{ Omukai, Bianchi, Valiante (2011)}$

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thermal evolution with different $f_{\text{dep}}$

$Z = 10^{-7} Z_{\odot}$

$Z = 10^{-6} Z_{\odot}$

$Z = 10^{-5} Z_{\odot}$

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RS, Omukai, Bianchi, Valiante (2011)
low mass star formation: critical dust-to-gas ratio

Energy transfer rate between gas and dust > Compressional heating rate

\[ S \mathcal{D}_{cr} > 1.4 \times 10^{-3} \text{cm}^2/\text{gr} \left[ \frac{T}{10^3 \text{K}} \right]^{-1/2} \left[ \frac{n_H}{10^{12} \text{cm}^{-3}} \right]^{-1/2} \]

FIRST STARS IV - The Pop III/II transition

RS, Omukai, Bianchi, Valiante (2011)
what drives the transition: metals or dust?

Observational evidence from stellar archaeology

transition discriminant for metal-cooling $D_{\text{trans}} = \log(10^{[\text{C/H}]} + 0.3 \times 10^{[\text{O/H}]} \geq -3.5$

Frebel et al. (2009)

SDSS 102915 is a strong candidate for dust-driven transition
the formation of the primitive star SDSS 102915 relies on dust?

RS, Omukai, Limongi, Ferrara, Salvaterra, Chieffi, Bianchi (2012)

Reconstruct the birth environment of SDSS 102915:

1. Fit the observed elemental abundances with SN models

2. Use these SN models to compute the associated dust yields

3. Follow the thermal evolution during the collapse of the parent cloud of SDSS 102915 to check for fragmentation conditions
the formation of the primitive star SDSS 102915 relies on dust?

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SDSS J102915 provides a strong evidence in support of the dust-driven transition

the observed properties of SDSS J102915 constrain the SN progenitors to have masses ≈ [20 – 40] Mₜₚₜ and to release ≈ [0.01 – 0.4] Mₜₚₜ of dust in the surrounding medium

RAPID DUST ENRICHMENT AT HIGH REDSHIFT
Outline

• is there a transition in mass-scale? probably yes

• what drive the transition: metals or dust? dust but more data is needed

• do we need to know the exact $Z_{cr}$?

• how can we make real progress?
the inhomogeneous nature of metal enrichment


Tornatore et al. (2007)
do we need to know the exact value of $Z_{cr}$?

metallicity distribution in the first protogalaxies

Ricotti et al. (2002, 2008); Tornatore et al. (2007); Whalen et al. (2008); Greif et al. (2008, 2010); Maio et al. (2010)

Wise et al. (2012)

large spread in $Z$

$Z \sim 10^{-3} Z_{\odot}$ floor
do we need to know the exact value of $Z_{\text{cr}}$?

metallicity distribution of star forming regions in the first protogalaxies

Ricotti et al. (2002, 2008); Whalen et al. (2008); Wise et al. (2008, 2012); Greif et al. (2008, 2010), Maio et al. (2010)

data from Tornatore et al. (2007) simulation
do we need to know the exact value of $Z_{cr}$?

metallicity distribution of star forming regions in the first protogalaxies

Ricotti et al (2002, 2008); Tornatore et al. (2007); Wise et al. (2008, 2012); Whalen et al. (2008); Maio et al. (2010)
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how can we make real progress?

**numerical simulations →** metal diffusion/mixing, dust enrichment

- how do metal enriched ejecta propagate into star forming regions?
- is there enough dust to activate fragmentation at $Z \sim Z_{cr}$?

**theory →** origin of carbon-enhanced stars

- dependence on the environment?
- hint of peculiar IMF or binarity?

**observations →** larger samples of metal-poor stars with $Z < 10^{-3} Z_{\text{sun}}$

- physics behind the transition?
- constraints on the properties of the stellar populations in the first galaxies?