Dust Formation in Stellar Winds of Very Massive Population III Stars

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1-1. Sources of dust in the early universe

- **Origin of massive dust at high redshifts (z > 5)**
  - core-collapse supernovae (CCSNe) may be promising sources of dust grains (e.g., Todini & Ferrara 2001; Nozawa+2003; Dwek+2007)
  - the contribution from **AGB stars** is also invoked to explain the observed dust mass (e.g., Valiante+2009; Dwek & Cherchneff 2011)

  ➔ what stellar mass range can mainly contribute dust budget in the early universe depends on the stellar IMF

- **Typical mass of Pop III stars**
  - Pop III stars may be much more massive than Pop I/II stars
  - ~40 M$_\odot$ (Hosokawa+2011; Susa 2013)
  - >300 M$_\odot$ (Omukai+2003; Ohkubo+2009)
  - 10-1000 M$_\odot$ (Hirano+2013)
1-2. Very massive Population III stars

- **Role of very massive stars (M\textsubscript{ZAMS} > \sim 250 M\textsubscript{sun})**
  - emitting numerous ionizing photons
    \rightarrow reionization of the universe
  - finally collapsing into black holes
    \rightarrow serving as seeds of SMBHs

- **Evolution of massive Pop III stars**
  - non-rotating stars with M\textsubscript{ZAMS} > 250M\textsubscript{sun}
    undergo convective dredge-up of C and O during the RSG phase \cite{Yoon+2012}
  - enriching the surrounding medium with CNO through the RSG winds
    \rightarrow serving as formation sites of dust

Dust grains formed in the winds are not likely to be destroyed by the SN shocks
2-1. Dust formation calculations

Formula of non-steady-state dust formation *(Nozawa & Kozasa 2013)*

- **Master equations of cluster formation**

\[
\frac{dc_n}{dt} = J_n(t) - J_{n+1}(t) \quad \text{for} \quad 2 \leq n \leq n_*,
\]

where

\[
J_n(t) = \alpha_{n-1} c_1 \left[ c_{n-1} - c_n \exp(\gamma_n) \right].
\]

\[
\alpha_n = \frac{s_n}{1 + \delta_{1n}} \cdot 4\pi a_0^2 n_\infty^2 \left( \frac{kT}{2\pi m_n} \right)^{1/2}, \quad \gamma_n = \mu \left[ \left( n - \frac{1}{\omega} \right)^{2/3} - \left( n - 1 - \frac{1}{\omega} \right)^{2/3} \right] - \ln S
\]

- **Equation of grain growth**

\[
\frac{da}{dt} = s\Omega_0 \left( \frac{kT}{2\pi m_1} \right)^{1/2} c_1 \left( 1 - \frac{1}{S} \right),
\]
2-2. Scaling relation of average grain radius

\[ \Lambda_{\text{on}} \equiv \frac{\tau_{\text{sat}}(t_{\text{on}})}{\tau_{\text{coll}}(t_{\text{on}})} \]

\[ \Lambda_{\text{on}} > 30 \]

\[ f_{\text{con},\infty}, a_{\text{ave},\infty} \]

- \( f_{\text{con},\infty} \) and \( a_{\text{ave},\infty} \) are uniquely determined by \( \Lambda_{\text{on}} \)
- steady-state nucleation rate is applicable for \( \Lambda_{\text{on}} > 30 \)

\( \Lambda_{\text{on}} = T_{\text{sat}}/T_{\text{coll}} \propto T_{\text{cool}} \eta_{\text{gas}} \)
3-1. Model of Pop III red-supergiant winds

- **RSG model: m500vk00** (Yoon+2012)
  - $M_{ZAMS} = 500 \, M_{\odot}$ (no rotation)
  - $L = 10^{7.2} \, L_{\odot}$, $T_{\text{star}} = 4440 \, K$, $R_{\text{star}} = 6750 \, R_{\odot}$
  - $A_C = 3.11 \times 10^{-3}$, $A_O = 1.75 \times 10^{-3} \Rightarrow C/O = 1.78$, $Z = 0.034$

- **Model of circumstellar envelope**
  - spherically symmetry, constant wind velocity
  - density profile: $\rho(r) = \frac{M}{4\pi r^2 v_w} = \rho_\ast \left(\frac{r}{R_\ast}\right)^{-2}$
  - temperature profile: $T(r) = T_\ast \left(\frac{r}{R_\ast}\right)^{-\frac{1}{2}}$

- **Fiducial values of $M_{\dot{\text{m}}}$ and $V_w$**
  - wind velocity: $v_w = 20 \, \text{km/s}$
  - mass-loss rate: $M_{\dot{\text{m}}} = 0.003 \, M_{\odot}/\text{yr}$
    $\Rightarrow$ losing 90% (208 $M_{\odot}$) of envelope during $7 \times 10^4$ yr
3-2. Chemical equilibrium calculations

major carbon-bearing gas species other than CO:
- atomic carbon at T > ~1800K
- C2H molecules at T = 1400-1700 K

chemical reactions considered in this study

(1) Model A  
C

C_{n-1} + C \rightleftharpoons C_n \quad (n \geq 2)

(2) Model B  
C_2H

2(C_2H + H) \rightleftharpoons C_{2n} + 2H_2 \quad (n = 2)

C_{2(n-1)} + C_2H + H \rightleftharpoons C_{2n} + H_2 \quad (n \geq 3)

- parameter fc: a fraction of carbon available for dust formation

\rightarrow fc = 1 as the fiducial case
4-1. Results of dust formation calculations

- carbon grains form around $r = 7.5 \, R_{\text{star}}$ ($r = 12 \, R_{\text{star}}$) for Model A (Model B)
- final condensation efficiency is unity for both of the models
- final average radius is similar in both Model A and Model B

→ the results are almost independent of chemical reactions
4-2. Dependence on $M_{\dot{\text{}}}$ and $v_w$

- The condensation efficiency of dust is unity for the condition:

$$\left( \frac{f_c \dot{M}}{3 \times 10^{-3} \, M_\odot \, \text{yr}^{-1}} \right) \left( \frac{v_w}{20 \, \text{km} \, \text{s}^{-1}} \right)^{-2} \gtrsim 0.04.$$

- for the fiducial case ($M_{\dot{\text{}}} = 3 \times 10^{-3} \, M_\odot \, \text{yr}^{-1}$, $v_w=20 \, \text{km/s}$, $f_c=1$)

$\Rightarrow$ producing 1.7 $M_\odot$ of C grains over the lifetime of the RSG
5-1. How efficient is dust formation?

- **Dust ejection efficiency by very massive Pop III RSGs**
  - $X_{\text{VMS}} = \frac{M_{\text{dust}}}{M_{\text{ZAMS}}} < 3.4 \times 10^{-3}$
  - $\frac{M_{\text{dust}}}{M_{\text{metal}}} < 0.24$

- **Dust ejection efficiency by CCSNe (PISNe)**
  - $X_{\text{CCSN}} = (0.1-30) \times 10^{-3}$ ($X_{\text{PISN}} < 0.05$)
  - $\frac{M_{\text{dust}}}{M_{\text{metal}}} = 0.01-0.25$ ($\frac{M_{\text{dust}}}{M_{\text{metal}}} < 0.15$)

### depending on the destruction efficiency
### of dust by the reverse shock

If $N_{\text{VMS}} \sim N_{\text{CCSN}}$ in the Pop III IMF ...

⇒ The contribution of dust from very massive RSGs is comparable with, or even higher than that from CCSNe

$\left( \frac{X_{\text{VMS}} N_{\text{VMS}}}{X_{\text{CCSN}} N_{\text{CCSN}}} \right) > \sim 1$

Hirano+2013
5-2. Expected extinction curves

- Extinction curves derived in this study do not resemble any of the known extinction law such as those in the MW and SMC.

- The extinction curves observed for high-z quasars do not show a bump structure, being inconsistent with those given here.

⇒ These extinction curves can be powerful tools to probe the formation of C grains in very massive Pop III stars.
5-3. Composition of low-mass UMP stars

- The ultra-metal-poor stars with \([\text{Fe}/\text{H}] < -4\) record chemical imprint of Population III stars

- The formation of such low-mass metal-poor stars is triggered through the cooling of gas by dust produced by Pop III SNe
  (e.g., Schneider+2012a, 2012b; Chiaki+2013)

**Possible channel for C-rich UMP star formation**

- Very massive Pop III RSGs are sources of carbon grains as well as CNO elements
  - In the gas clouds enriched by Pop III RSGs, carbon grains enable the formation of low-mass stars whose chemical compositions are highly enriched with CNO

- We do not predict the presence of any heavier elements
  - Further observations and more quantitative theoretical studies are needed to show whether any UMP stars have formed through our scenario
6. Summary

We examine the formation of dust grains in a carbon-rich mass-loss wind of a Pop III RSG with \( M_{\text{ZAMS}} = 500 \, M_{\odot} \).

- For a steady stellar wind, C grains can form with a lognormal-like size distribution whose average radius is sensitive to wind velocity.

- The condensation efficiency is unity for

\[
\left( \frac{f_c \dot{M}}{3 \times 10^{-3} \, M_{\odot} \, \text{yr}^{-1}} \right) \left( \frac{v_w}{20 \, \text{km s}^{-1}} \right)^{-2} \gtrsim 0.04.
\]

- The mass of C grains is \(<1.7 \, M_{\odot} \) (\( M_{\text{dust}}/M_{\text{ZAMS}} < 3.4 \times 10^{-3} \)), which would be high enough to have impacts on dust enrichment history in the early universe, if the IMF of Pop III stars were top-heavy.