Formation of Carbon Dust in Red-supergiant 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; TN+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 Msun (Hosokawa+2011; Susa 2013)
  - >300 Msun (Omukai+2003; Ohkubo+2009)
  - 10-1000 Msun (Hirano+2014)
1-2. Very massive Population III stars

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

- **Evolution of massive Pop III stars**
  - non-rotating stars with \(M_{\text{ZAMS}} > 250\text{M}_{\odot}\) undergo convective dredge-up of C and O during the RSG phase \((\text{Yoon}+2012)\)
  - enriching the surrounding medium with CNO through the RSG winds ➔ serving as formation sites of dust

Dust grains formed in the winds are not likely to be destroyed by the SN shocks
3-1. Model of Pop III red-supergiant winds

- **RSG model: m500vk00** (Yoon+2012)
  - $M_{\text{ZAMS}} = 500 \, M_{\odot}$ (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: $\rho(r) = \frac{\dot{M}}{4\pi r^2 v_w} = \rho_\star \left(\frac{r}{R_\star}\right)^{-2}$
  - temperature profile: $T(r) = T_\star \left(\frac{r}{R_\star}\right)^{-1/2}$

- **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 $7 \times 10^4 \, \text{yr}$
3-2. Chemical equilibrium calculations

major carbon-bearing gas species other than CO:
- atomic carbon at $T > \sim 1800K$
- $C_2H$ molecules at $T = 1400-1700$ K

## Formation of PAHs would not ## be expected

chemical reactions considered in this study

\[
\begin{align*}
(1) \text{Model A} & \quad C & \quad C_{n-1} + C \rightleftharpoons C_n \quad (n \geq 2) \\
(2) \text{Model B} & \quad C_2H & \quad 2(C_2H + H) \rightleftharpoons C_{2n} + 2H_2 \quad (n = 2) \\
& & \quad C_{2(n-1)} + C_2H + H \rightleftharpoons C_{2n} + H_2 \quad (n \geq 3)
\end{align*}
\]

- Dust formation calculations (TN & Kozasa 2013)
formulation of non-steady-state dust formation
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 $M_{\text{dot}}$ and $v_w$

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

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

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

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

- **Dust ejection efficiency by very massive Pop III RSGs**
  - $X_{\text{VMS}} = \frac{M_{\text{dust}}}{M_{\text{ZAMS}}} < 3.4 \times 10^{-3} = \sim 0.3 \%$
  - $M_{\text{dust}} / M_{\text{metal}} < 0.24$

- **Dust ejection efficiency by CCSNe**
  - $X_{\text{CCSN}} = (0.1-30) \times 10^{-3} = 0.1-3.0 \%$
  - $M_{\text{dust}} / M_{\text{metal}} = 0.01-0.25 \ (M_{\text{dust}} / M_{\text{metal}} < 0.15)$

  ## The ranges above reflects 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

$(X_{\text{VMS}} N_{\text{VMS}}) / (X_{\text{CCSN}} N_{\text{CCSN}}) > \sim 1$
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.

→ The derived 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 (UMP) stars with [Fe/H] < -4 would record chemical imprints 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+2014)

**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 CNO-rich low-mass stars

- We do not predict the presence of heavier elements (Mg, Si, Fe)
  → Further observations and more quantitative theoretical studies are needed to show whether UMP stars formed through our scenario

## SMSS J0313-6708: [C/H] = -2.6, [Fe/H] < -7 (Keller+2014)
6. Summary

We have examined the possibility of dust formation 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:

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

$\Rightarrow$ the first dust grains in the universe ??

- 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.

# The extinction curves expected from ejected C grains are different from any known ones.

# The chemical feedback by PopIII VMSs predicts a new type of UMP stars.