Formation of Carbon Grains in Red-supergiant Winds of Very Massive Population III Stars

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○ Abstract We investigate the formation of dust in a stellar wind during the red-supergiant (RSG) phase of a very massive Population III star with a zero-age main sequence mass of 500 M_{sun}. We show that, in a carbon-rich wind with a constant velocity, carbon grains can form with a lognormal-like size distribution, and that all of the carbon available for dust formation finally condenses into dust for wide ranges of the mass-loss rate ([0.1–3]x10^{-3} M_{sun} yr^{-1}) and wind velocity (1–100 km s^{-1}). We also find that the acceleration of the wind, driven by newly formed dust, suppresses the grain growth but still allows more than half of the gas-phase carbon to finally be locked up in dust grains. These results indicate that, at most, 1.7 M_{sun} of carbon grains can be produced during the RSG phase of 500 M_{sun} Population III stars. Such a high dust yield could place very massive primordial stars as important sources of dust at the very early epoch of the universe if the initial mass function of Population III stars was greatly weighted to a much higher mass than that of the present stellar population.

○ Model of a RSG with M_{ZAMS} = 500 M_{sun} (Yoon et al. 2012)

- L_{star} = $10^{7.2}$ L_{sun}, T_{star} = 4,440 K, R_{star} = 6,750 R_{sun}
- A_C = 3.11x10^{-3}, A_O = 1.75x10^{-3} ➔ C / O = 1.78 (C-rich)

○ Calculations of dust formation

- formula of non-steady-state dust formation (Nozawa & Kozasa 2013)
- Table 1 : chemical reactions considered in this study

(1) Model A	C	$C_{n-1} + C \rightleftharpoons C_n$	$(n \geq 2)$
(2) Model B	C_2H	$2(C_2H + H) \rightleftharpoons C_{2n} + 2H_2$ $C_{2(n-1)} + C_2H + H \rightleftharpoons C_{2n} + H_2$	$(n = 2)$ $(n \geq 3)$

○ Model of circumstellar envelope

- spherically symmetry, constant wind velocity
- density and temperature profile

$$\boxed{\rho(r) = \frac{\dot{M}}{4\pi r^2 v_{\rm w}} = \rho_* \left(\frac{r}{R_*}\right)^{-2}}$$

$$\boxed{T(r) = T_* \left(\frac{r}{R_*}\right)^{-\frac{1}{2}}}$$

M_{dot} and v_W are treated as free parameters

fiducial value
- wind velocity : v_W = 20 km/s
- mass-loss rate : M_{dot} = 3x10^{-3} M_{sun} yr^{-1}

- f_c = 1, which is a fraction of carbon atoms available for dust formation after the formation of CO molecules

○ Results of dust formation calculations (Fig. 1)

- C grains form around r = 7.5 R_{star} (r = 12 R_{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

○ Dependence on M_{dot} and v_W (Fig. 2)

- The average grain radius becomes larger for a higher mass-loss rate ($a_{ave,\infty} \propto M_{dot}^{0.88}$) and/or a lower wind velocity ($a_{ave,\infty} \propto v_W^{-1.75}$)
- The condensation efficiency of dust is unity for the condition:

$$\boxed{\left(\frac{f_{\rm c}\dot{M}}{3\times10^{-3}\ M_\odot\ {\rm yr}^{-1}}\right)\left(\frac{v_{\rm w}}{20\ {\rm km\ s}^{-1}}\right)^{-2} \gtrsim 0.04.}$$

- for the fiducial case (M_{dot} = 3x10^{-3} M_{sun} yr^{-1}, v_W = 20 km s^{-1}, f_c = 1)

➔ 1.7 M_{sun} of C grains can form over the lifetime of the RSG

○ Effects of wind acceleration on dust formation (Figs. 3 and 4)

- Momentum equation of wind acceleration (Ferrarotti & Gail 2006)

$$\boxed{v_{\rm w}\frac{dv_{\rm w}}{dr} = -\frac{GM_*}{r^2}\left[1 - \frac{L_*\langle\kappa_{\rm ext}(T)\rangle}{4\pi cGM_*}D\right]}$$

- The wind is rapidly accelerated to > 100 km s^{-1}, reducing the growth rate of grains and the formation rate of seed clusters
- The formation of small grains at later phases, as well as the gradual growth of large grains, enhances $f_{con,\infty}$ up to >0.5 with very small $a_{ave,\infty}$

○ Discussion : How efficient is dust formation?

- Dust ejection efficiency by very massive Population III RSGs

➔ X_{VMS} = M_{dust} / M_{ZAMS} < 3.4x10^{-3}

- Dust ejection efficiency by core-collapse supernovae (CCSNe)

➔ X_{CCSN} = (0.1-30)x10^{-3}

Dust production efficiency of Population III RSGs is comparable with, or slightly less than that of CCSNe

➔ very massive Population III RSGs could be important sources of dust if the IMF of Population III star was highly top-heavy

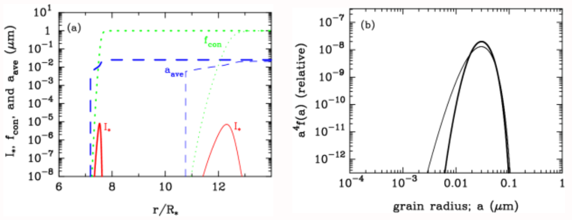

Fig. 1 – (a) Formation rate of seed clusters with n* = 100, divided by the nominal concentration of the key molecules (I*, solid), condensation efficiency (f_{con}, dotted), and average grain radius (a_{ave}, dashed) as a function of distance from the center of the star (r/R_{star}), and (b) final size distribution spectrum by mass of newly formed C grains for a mass-loss rate M_{dot} = 3x10^{-3} M_{sun} yr^{-1}, a wind velocity v_W = 20 km s^{-1}, and f_c = 1. The thick lines represent the results for Model A where the chemical reaction (1) in Table 1 is considered for the formation of clusters, while the thin lines represent those for Model B with the chemical reaction (2).

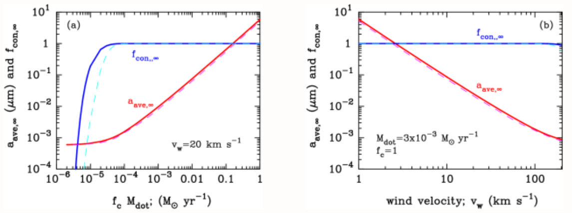

Fig. 2 – Final average radius $a_{ave,\infty}$, and final condensation efficiency $f_{con,\infty}$, of C grains formed in the outflowing gas; (a) as a function of product f_c M_{dot} for v_W = 20 km s^{-1}, and (b) as a function of v_W for f_c M_{dot} = 3x10^{-3} M_{sun} yr^{-1}. The thick solid lines represent the results for Model A, while the thin dashed lines represent those for Model B.

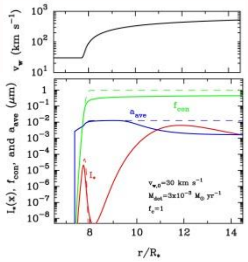

Fig. 3 – Wind velocity v_W (upper panel), formation rate of seed clusters I*, condensation efficiency f_{con}, and average radius a_{ave} (lower panel) as a function of r/R_{star} for model A with the wind acceleration. The initial wind velocity and mass-loss rate are set to be $v_{W,0}$ = 30 km s^{-1} and M_{dot}= 3x10^{-3} M_{sun} yr^{-1}, respectively. The dashed lines in the lower panel are the results without wind acceleration.

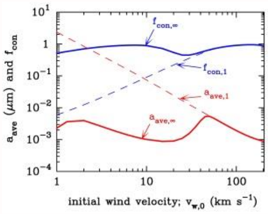

Fig. 4 – Solid lines show the dependence of $a_{ave,}$, and f_{con} on $v_{W,0}$ in the case with wind acceleration for Model A with $f_c M_{dot}$ = 3x10^{-3} M_{sun} yr^{-1}. The dashed lines show the average radius $a_{ave,1}$ and condensation efficiency $f_{con,1}$ just before the grain growth is depressed by wind acceleration.