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

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The origin of cosmic dust in the early universe has been hotly debated since the discoveries of huge amounts of dust grains in high-redshift ($z \geq 5$) quasars.Although the characteristic mass of the early generation of stars remains to be clarified, recent calculations of stellar evolution found that non-rotating Population III stars with the zero-age main sequence mass of $M_{\rm ZAMS} > 250\,M_\odot$ undergo convective dredge-up of a large amount of carbon and oxygen from the helium-burning core to the hydrogen-rich envelope during the red-supergiant (RSG) phase [1]. This may lead to enrichment of the surrounding medium with CNO elements via RSG winds, which can serve as formation sites of dust in the early universe.

We investigate the formation of carbon dust in a stellar wind during the RSG phase of a very massive Population III star with $M_{\rm ZAMS} = 500\,M_\odot$ [2].The calculations are performed by applying the formulation of non-steady-state dust formation [3]. The formula enables us to evaluate the size distribution of newly formed grains and their condensation efficiency defined as the fraction of free carbon atoms that are locked up in grains.

The results of the calculations 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 condense into dust for wide ranges of the mass-loss rate ($\geq 8 \times 10^{-5}\,M_\odot\,{\rm yr}^{-1}$) and wind velocity (1–100 km s^{-1}) (see Figs. 1 and 2). These results indicate that, at most, 1.7 $M_\odot$ of carbon grains can form in total during the RSG phase of 500 $M_\odot$ Population III stars. We note that these newly formed grains could not be destroyed by the blast wave arising from a supernova explosion because such a very massive star would finally collapse into a black hole. Thus, the derived 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 top-heavy.

We also propose a new formation scenario of carbon-rich ultra-metal-poor stars; such primitive low-mass stars were born in the gas clouds that were enriched with carbon grains and CNO elements from Population III RSGs.

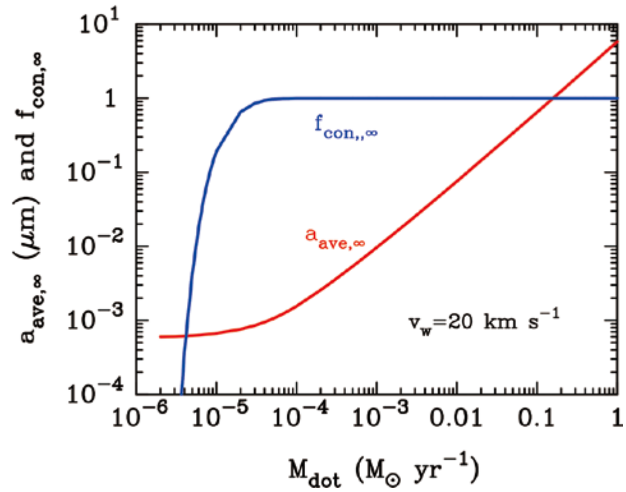

Figure 1: Final average radius ($a_{\rm ave,\infty}$) and final condensation efficiency ($f_{\rm con,\infty}$) of carbon grains formed in mass-loss winds of a 500 $M_\odot$ Popularion III RSG as a function of mass-loss rate $\dot{M}$ for a fixed wind velocity of $v_{\rm w} = 20$ km s^{-1}.

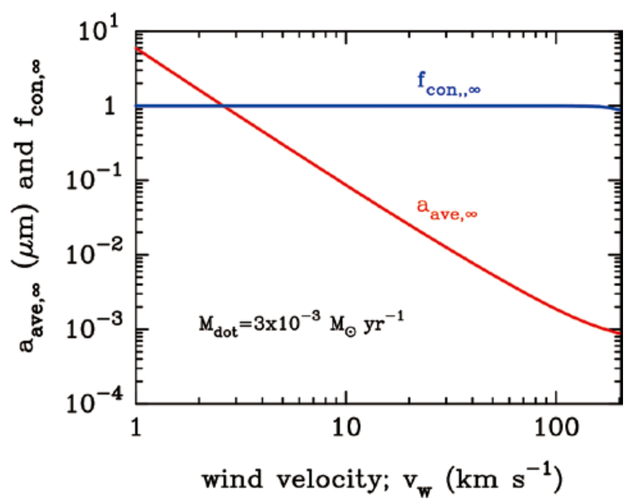

Figure 2: Same as Figure 1, but as a function of wind velocity $v_{\rm w}$ for a fixed mass-loss rate of $\dot{M} = 3 \times 10^{-3}\,M_\odot\,{\rm yr}^{-1}$.

References

[1] Yoon, S.-C., Dierks, A., Langer, N.: 2012, *A&A*, **542**, A113.
[2] Nozawa, T., et al.: 2014, *ApJ*, **787**, L17.
[3] Nozawa, T., Kozasa, T.: 2013, *ApJ*, **776**, 24.