

Presolar Grains Condensed in Wolf-Rayet Stars (#1797)

A. Gupta¹, S. Sahijpal¹

¹Department of Physics, Panjab University, Chandigarh (India)

Introduction

The dust grains can condense only in stellar environments which have sufficiently high density at low enough temperatures to overcome the vapor pressure. The grains which were produced in the stellar outflows, found their way to solar nebula and survived the solar system formation are called the presolar grains. These dust grains are recorded in the meteorites in our solar system with a wide range of chemical composition that are later separated and analyzed in the laboratory. Isotopic measurements on meteorites show the isotopic heterogeneity of the solar nebula that is caused by pre-solar grains.

It is widely seen that AGB stars and SNe are the potential sources of these anomalies (see e.g. [1,2]). However, the possible candidature of Wolf-Rayet (WR) stars for introducing their dust particles in the solar system cannot be ruled out [3,4]. We present a theoretical framework of thermodynamics associated with the condensation of presolar grains produced in the WR stellar winds. We have developed a novel thermodynamical code [5] in Python to perform the equilibrium as well as non-equilibrium condensation calculations for the WN and WC phases in rotating stellar models.

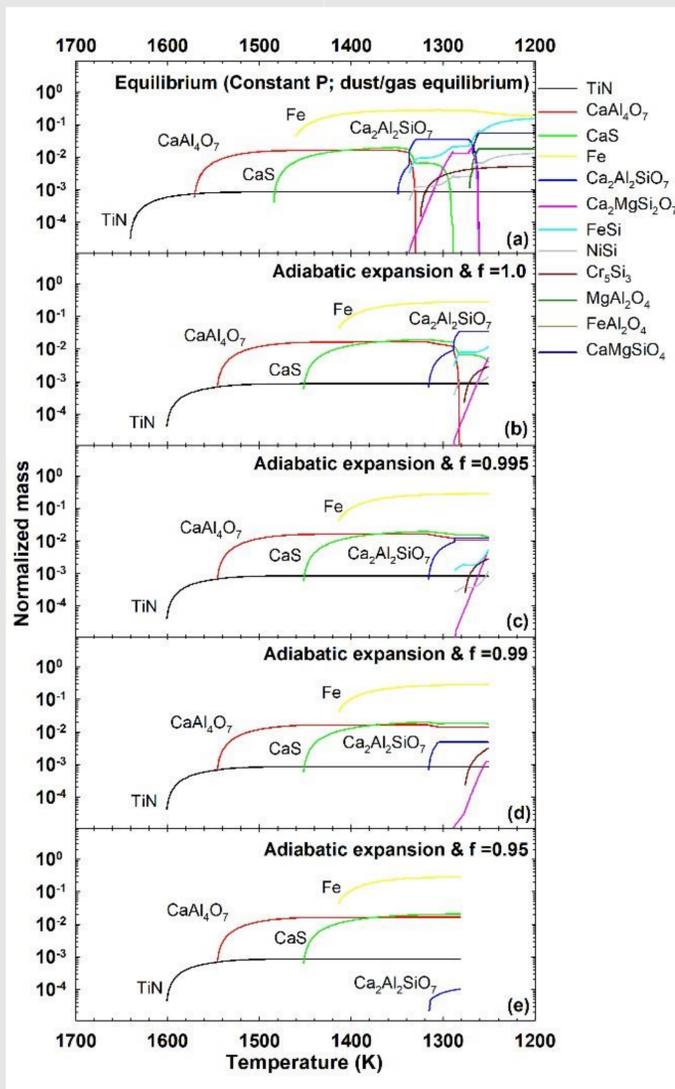


Figure 1. The normalized mass distribution of the condensed phases as a function of temperature for a WN composition in a rotating stellar model at a pressure of 10^{-3} bar for, a) the scenario corresponding to complete dust-gas equilibrium with constant pressure. b) the scenario with dust-gas equilibrium with dynamic pressure variation in an adiabatic manner, c-e) the scenarios with the varied dust-gas non-equilibrium parameter, f , ranging from 0.995-0.95. Few major species have been labelled.

Methodology

The computation of the chemical equilibria requires the minimization of the chemical potential of the system assemblage of a given composition. The formulation developed by previous work [6] was used to develop the numerical code for the mineral equilibria for multiphase system. However, a new formalism has been developed to explore the non-equilibrium scenarios [5]. We numerically simulated three distinct chemical non-equilibrium scenarios by introducing a *numerical non-equilibrium parameter, f* , which characterizes the fraction of already condensed dust that will remain in equilibrium with the gas for further chemical reactions at every drop in temperature by 1 K. Remaining fraction of the condensed dust is removed from equilibrium at every drop in temperature by 1 K.

Discussion

We have run the simulations for the calculation of the normalized mass and the condensation temperatures of the various condensates for the rotating WN and WC stellar models. The numerical simulations have been performed at various dust to gas equilibrium fractions with the system pressure static as well as dynamic in an adiabatic manner. In the non-equilibrium condensation scenarios, the normalized mass includes both the equilibrium as well as non-equilibrium dust components that have been removed from the chemical interaction with the residual gas. The grains condensed in the non-equilibrium scenario does not show any major distinction from the equilibrium calculations.

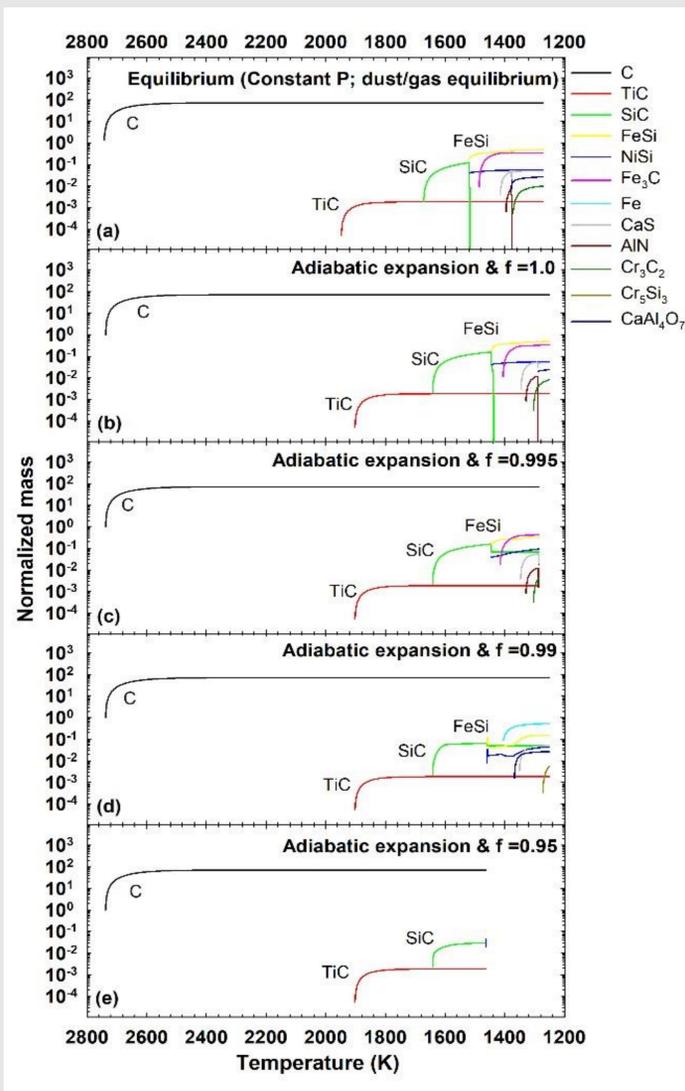


Figure 2. As Fig. 1, but for a WC composition in a rotating stellar model. The major part of the dust mass is in the carbon (graphite) form.

The normalized masses of various stable condensates at 10^{-3} bar pressure are presented in Figures 1-2 and Tables 1-2 with the condensates presented by their formulae.

Table 1. The maximum value of normalized mass of stable condensates in simulated temperature range for the WN phase in the rotating case at 10^{-3} bar pressure (WNR).

Condensate	Static	Adiabatic with the non-equilibrium parameter, f			
	$f=1$	$f=1$	0.995	0.99	0.95
WNR					
TiN	8.5×10^{-4}	8.5×10^{-4}	8.5×10^{-4}	8.5×10^{-4}	8.5×10^{-4}
CaAl ₄ O ₇	1.6×10^{-2}	1.6×10^{-2}	1.6×10^{-2}	1.6×10^{-2}	1.6×10^{-2}
CaS	1.9×10^{-2}	1.9×10^{-2}	1.9×10^{-2}	1.9×10^{-2}	2.0×10^{-2}
Fe-Metal	2.7×10^{-1}	2.7×10^{-1}	2.8×10^{-1}	2.8×10^{-1}	2.8×10^{-1}
Ca ₂ Al ₂ SiO ₇	3.4×10^{-2}	3.4×10^{-2}	1.2×10^{-2}	4.9×10^{-3}	1.0×10^{-4}
Ca ₂ MgSi ₂ O ₇	1.9×10^{-2}	5.3×10^{-3}	5.3×10^{-3}	1.2×10^{-3}	1.0×10^{-6}
FeSi	1.5×10^{-1}	1.1×10^{-2}	5.3×10^{-3}	-	-
NiSi	1.2×10^{-2}	1.3×10^{-3}	1.1×10^{-3}	-	-
Cr ₅ Si ₃	5.2×10^{-3}	2.8×10^{-3}	2.8×10^{-3}	3.1×10^{-3}	-
MgAl ₂ O ₄	1.8×10^{-2}	-	-	-	-
FeAl ₂ O ₄	5.2×10^{-7}	-	-	-	-
CaMgSiO ₄	5.4×10^{-2}	-	-	-	-

Table 2. Same as Table 1 but for the WC phase in rotating case.

Condensate	Static	Adiabatic with the non-equilibrium parameter, f			
	$f=1$	$f=1$	0.995	0.99	0.95
WCR					
C	6.9×10^1	6.9×10^1	6.9×10^1	6.9×10^1	7.0×10^1
TiC	1.8×10^{-3}	1.8×10^{-3}	1.8×10^{-3}	1.8×10^{-3}	1.8×10^{-3}
SiC	1.1×10^{-1}	1.5×10^{-1}	1.5×10^{-1}	7.0×10^{-2}	2.8×10^{-2}
FeSi	4.7×10^{-1}	4.8×10^{-1}	3.4×10^{-1}	1.5×10^{-1}	1.1×10^{-1}
NiSi	5.4×10^{-2}	5.4×10^{-2}	9.0×10^{-2}	4.4×10^{-2}	4.7×10^{-2}
Fe ₃ C	3.6×10^{-1}	3.3×10^{-1}	4.4×10^{-1}	-	-
Fe-Metal	-	-	-	5.2×10^{-1}	-
CaS	4.8×10^{-2}	5.2×10^{-2}	5.3×10^{-2}	4.8×10^{-2}	-
AlN	7.4×10^{-3}	1.1×10^{-2}	1.2×10^{-2}	-	-
Cr ₃ C ₂	9.7×10^{-3}	8.0×10^{-3}	4.2×10^{-3}	-	-
Cr ₅ Si ₃	-	-	-	5.4×10^{-3}	-
CaAl ₄ O ₇	2.5×10^{-2}	2.3×10^{-2}	1.7×10^{-2}	2.6×10^{-2}	-

Conclusion

From the thermodynamical equilibrium as well as non-equilibrium condensation calculations, we infer that

1. The carbides, nitrides, and sulphides can condense in various N-rich and C-rich evolutionary phases of the massive stellar ejecta.
2. WR stars can be the sources of graphite and carbide grains present in the solar system.
3. WN stars have comparatively high value of ¹³C isotope, whereas, WC stars are almost completely ¹³C depleted.
4. The rotating WN stellar winds can be a source of the oxide grains. However, these grains are depleted in ¹⁶O isotope.
5. Also, the grains extremely depleted in ¹⁸O isotope can be associated with non-rotating WN and WC stars.

Acknowledgments

AG acknowledges the Council of Scientific & Industrial Research (CSIR) for providing doctoral financial assistance, which was used to write the code.

References

- [1] Amari S., Zinner E. and Lewis R.S. (1996) *ApJL* 470, L101-L104.
- [2] Marhas K.K. and Sharda P. (2018) *ApJ*, 853, 12-26.
- [3] Arnould M., Meynet G. and Paulus G. (1997) *AIP Conference Proceedings* 402, 179.
- [4] Nittler L.R. and Ciesla F. (2016) *ARAA* 54, 53-93.
- [5] Gupta A. and Sahijpal S. (2019) *MNRAS*, 492, 2058-2074.
- [6] Ebel D.S., Ghiorso M.S., Sack R.O. and Grossman L. (2000) *J. Computational Chem.* 21, 247-256.