

STELLAR ATMOSPHERE THERMAL HISTORY FOR PRESOLAR CORE/RIM CARBON SPHERES.

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Introduction: The subset of pre-solar grains extracted from meteorites, and made up of s-process isotopes, likely formed around thermally-pulsing asymptotic giant branch (AGB) stars “after third dredge-up” of newly made carbon atoms [1]. In particular the core/rim subset of micron-size carbon spheres in pre-solar collections e.g. from the meteorite Murchison contain unlayered graphene sheets in their core [2,3], whose size and abundance likely provide information on the thermal history during formation. Laboratory evidence for supercooled droplet formation during carbon vapor condensation, the spherical nature of the cores with their atomically-abrupt transition from core to rim, and TEM evidence for unlayered graphene structures (some in the form of faceted penta-cones), have for example prompted construction of models for nucleation and growth of these sheets from a super-cooled carbon melt for various cooling rates [4].

Here we examine simple models of AGB star temperature as a function of the distance from the star’s center ($T(R)$), and radiation pressure ejection, to put constraints on the radius of carbon condensation, and the rate of cooling during possible supercooled droplet solidification of these cores. In particular, we show that the literature on container-less supercooling of metallic liquids moves the likely radius of condensation and solidification inward, and that the cooling rates during solidification were likely between 0.2 and 0.002 Kelvin/second, with the lower rates corresponding to maximum-luminosity (minimum-temperature) phases of a given star.

Stellar radii of formation: A 2018 review article on mass loss from AGB stars [5] describes a generic model for temperature as function of radius in units of a star’s effective temperature T^* and radius R^* . They also argue that amorphous carbon is likely to condense at around 1500K, although this can be pushed higher for lower O/C ratios [6].

On the other hand, the literature on containerless solidification of metallic liquids predicts droplet supercooling temperatures closer to 30% below the effective melting temperature [7] (for elemental carbon closer to 4600K although of course at low pressure sublimation occurs near 3900K). However the 2D nature of sp^2 carbon, and our models, suggest that 50% below the melting temperature (say 2350K) is plausible for solidification.

The plot below of the Höfner $T^*[R^*]$ curve thus illustrates how increasing the solidification temperature suggests that condensation of the core/rim subset of carbon particles likely occurs at even higher tempera-

ture, deeper into the circumstellar atmosphere, and perhaps in settings with lower O/C ratios as well.

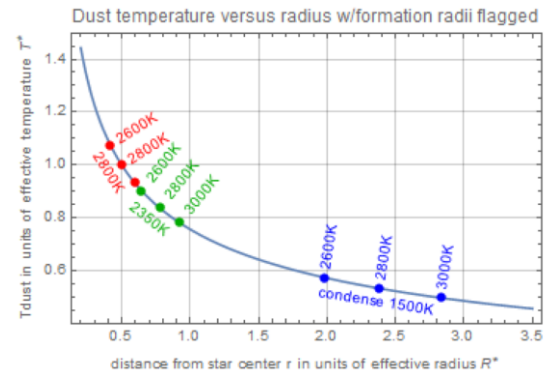


Figure 1: Blue dots assume the 1500K a-carbon condensation temperature used by Hofner [5]. The green dots use a 2350K solidification temperature of liquid carbon, which we’ve chosen as a plausible maximum supercooling level based on literature experience with other metallic liquids. The red dot may be a more typical condensation temperature for those core/rim particles.

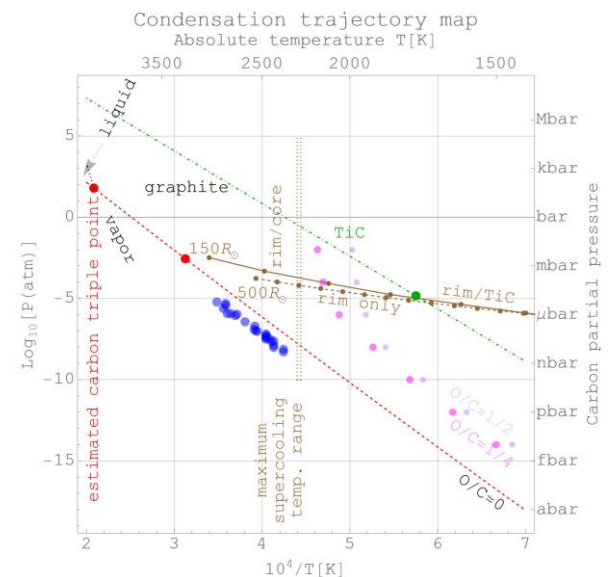


Figure 2: Sample maximum-temperature phase (solid brown) and min-temperature phase (dashed brown) trajectories for a parcel of gas being ejected adiabatically from a spherical three solar-mass carbon-star described by Lodders & Fegley [6].

Cooling rates: The temperature as a function of radius in cool giant stellar photospheres and circumstellar envelopes is often modeled as a power law, be-

ginning with an exponent of 1 for the virial theorem, through exponents of C_p/C_v between say 0.84 and 2 for adiabatic models [6], through (for carbon) an exponent of 0.4 for carbon particles in the more recent Hofner model discussed above. The derivative of $T[R]$ with respect to radial distance R from star center i.e. dT/dR , times the ejection velocity at any given radius i.e. dR/dt , gives us an estimate for grain cooling rate dT/dt .

Consider the model star at max-L/min-T and min-L/max-T phases from [6], whose model P vs. T trajectory is depicted in Fig. 2 here. For the temperature gradient dT/dR at the effective radius R^* and temperature T^* , the Hofner model -3.6×10^{-9} K/m and -13×10^{-9} K/m, respectively. Somewhat higher values arise, because of the larger exponent, if we use the adiabatic model of [7].

In both cases the gradient is about a factor of 3 lower in the max-L/min-T phase because of the much larger distances involved. If we multiply by an ejection velocity dR/dt of about 10 km/s [5] or about 50 km/s (escape velocity), we similarly get cooling rates of around 0.0007 K/s in the max-L/min-T phase, and a factor of 3 higher in the min-L/max-T phase.

Discussion: These cooling rates are more than 7 orders of magnitude lower than the ones we've so far been able to achieve in "evaporating carbon ovens" in the laboratory [7]. They are also consistent with our observation in the presolar cores of graphene sheet number density and size [4], which suggest that graphene sheet growth is well into the saturation phase i.e. where growing sheets by and large have few carbon atoms in position to add to their size.

Further work on these individual particle cooling rate models, for AGB stars likely to have contributed to our presolar collections, is clearly needed as is further work on slow-cooled carbon vapor in the laboratory. This, as well as the modeling work [4] also discussed in a separate abstract to the meeting, are relevant to our ability to interpret the story told by future presolar core/rim carbon particles in the kind of collections made available e.g. by researchers at U. Chicago. It is also relevant to the materials science community, in understanding metastable liquid carbon at low pressures as well as in exploring the possible diffusion-barrier properties of unlayered-graphene composite materials.

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