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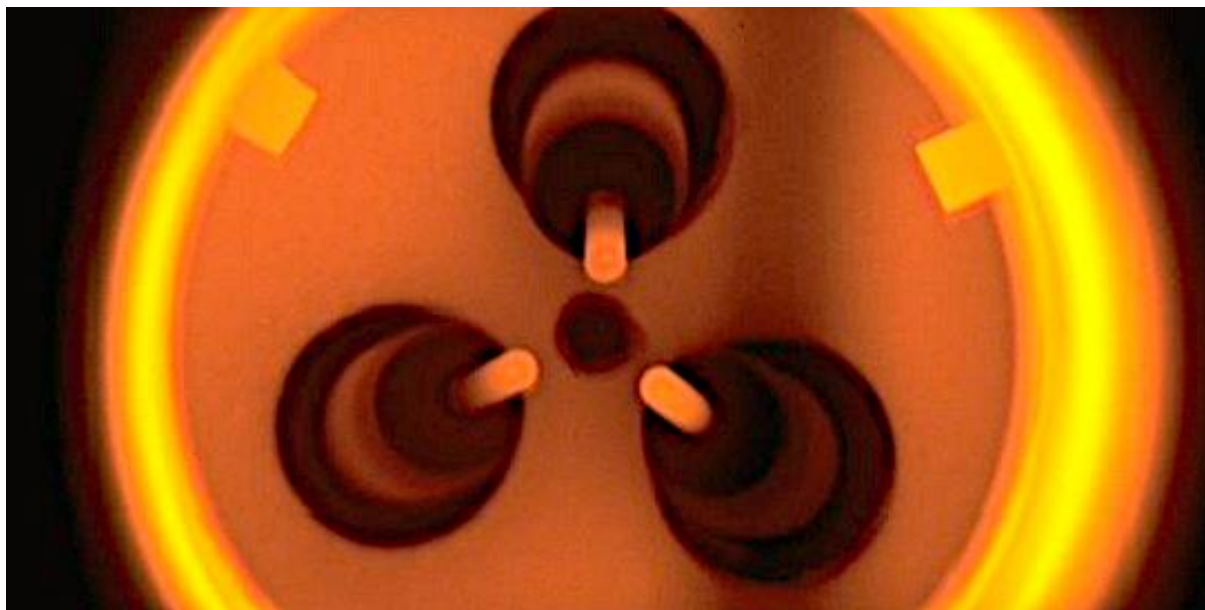
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## High-temperature dust formation in carbon-rich astrophysical environments

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+ Extended Data

## 1 Abstract

2  
3 Condensation processes, responsible for the main chemical differences between gas and solids  
4 in the galaxy, are the major mechanisms that control the cycle of dust from evolved stars to  
5 planetary systems. However, they are still poorly understood, mainly because thermodynamics  
6 and kinetic models of nucleation or grain growth are lacking experimental data. To bridge this  
7 gap, we used a large volume three-phase AC plasma torch to obtain a full high temperature  
8 condensation sequence at elevated C/O ratio from a fluxed chondritic gas composition. We  
9 show that the crystallized suites of carbides, silicides, nitrides, sulfides, oxides and silicates and  
10 the bulk composition of the condensates are properly modelled by a kinetically inhibited  
11 condensation scenario controlled by the gas flow. This validates for the first-time  
12 thermodynamic predictions of condensation sequence at high C/O ratio. On this basis and using  
13 appropriate optical properties, we also demonstrate the influence of pressure on the dust  
14 chemistry as well as the low probability of forming and detecting iron silicides in asymptotic  
15 giant branch (AGB) circumstellar environments as well as in our chondritic meteorites.  
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18

## 19 Introduction

20  
21 Cosmic dust is of crucial importance for the evolution of our galaxy since it actively participates  
22 in the cycle of matter (gas and dust) from the interstellar medium (ISM) to stars and back from  
23 stars to the ISM<sup>1</sup>. Dust grains form principally in the gas outflowing from evolved stars and in  
24 the ejecta resulting from supernova (SN) explosions. Amongst progenitors, AGB stars are  
25 assumed to be the major contributor to the global cosmic dust budget<sup>2</sup>. During their late  
26 evolutionary stages, low- and intermediate-mass stars ( $< 8 M_{\odot}$ ) become red giants, increasing  
27 their radius by 2-3 orders of magnitude, and decreasing their surface temperature to 2000-3000  
28 K. Further evolution of these stars (AGB phase) lead to significant mass loss of gaseous  
29 molecules and dust grains giving rise to circumstellar envelopes (CSE). Mass-loss rates of AGB  
30 stars, determined with various observational methods, are typically in the range of  $10^{-8}$ – $10^{-5}$   
31  $M_{\odot} \cdot \text{year}^{-1}$  but values as high as  $10^{-4} M_{\odot} \cdot \text{year}^{-1}$  have been found for more extreme objects<sup>3</sup>.  
32 Around cool stars, dust is formed in dense shells created by stellar pulsations or large-scale  
33 convective motions which propagate gas beyond the stellar surface<sup>4</sup> where gas cooling yields  
34 dust condensation. These dust grains are then accelerated away from the star by radiation  
35 pressure, dragging the gas away through friction, creating outflows with typical velocities of  
36 5–30 km/s and eventually feeding the ISM<sup>5</sup> contributing thus to the material out of which our  
37 solar system formed.  
38

39 Dust forms from the matter already present when the stars formed and from the elements  
40 produced by the stars themselves. The dust composition changes as the star evolves and notably  
41 when the carbon to oxygen ratio changes during the episodic third dredge-up process<sup>6</sup>.  
42 Thermodynamic equilibrium calculations have provided convincing explanations of the marked  
43 chemical differentiation between oxygen-rich and carbon-rich AGB stars based on the high  
44 bond energy of carbon (i.e.,  $1077 \text{ kJ} \cdot \text{mol}^{-1} \approx 11.1 \text{ eV}$ )<sup>7</sup> and that CO is a very stable gaseous  
45 molecule at relatively high temperatures. Consequently, the dust chemistry in the inner CSE of  
46 AGB stars,  $R=1-10R_{*}$  where  $R_{*}$  is the stellar radius, is primarily controlled by the carbon-to-  
47 oxygen ratio. When  $C/O \leq 1$  (O-rich stars), all carbon is bound in the CO molecule and the  
48 oxygen in excess participates to oxygen-rich dust formation<sup>8</sup>. In contrast, when  $C/O \geq 1$  (C-rich  
49 stars) carbon is in excess while all the oxygen is bound in CO and hydrocarbons molecules and  
50 carbon-rich grains are formed<sup>9,10</sup>. While the C/O ratio likely explains the fundamental

51 difference between C-rich and O-rich stars, temperature and pressure within their inner  
52 circumstellar envelopes (CSEs) play obviously a significant role (see below).

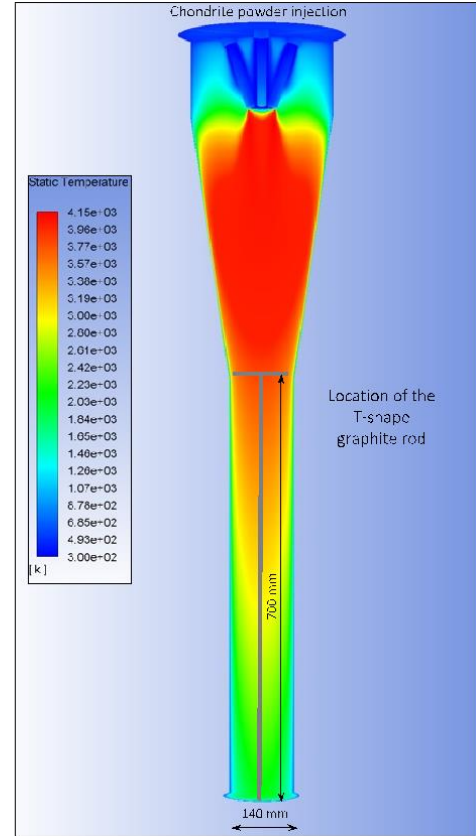
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54 Complex dynamical effect in stellar outflows<sup>3</sup> and highly diverse circumstellar O-rich and C-  
55 rich grains inventory in chondrite meteorites<sup>11,12</sup> highlight, however, the need to consider  
56 beyond simple thermodynamic equilibrium in order to understand dust formation around AGB  
57 stars, including kinetics, nucleation/seeding processes and models like chaotic solid  
58 formation<sup>8,13, 14,15</sup>. This issue has been already the subject of extensive theoretical works<sup>13</sup>. Ref<sup>16</sup>  
59 recently re-emphasized the importance of kinetics for dust formation in astrophysical  
60 environments, and the need for laboratory condensation experiments to provide insights into  
61 the formation of dust and the reactions that allow their growth. While nucleation and growth of  
62 simple metal or H<sub>2</sub>O grains from a gas have been extensively studied for applications in  
63 atmospheric or material science<sup>17,18,19,20,21</sup>, condensation of more complex gas, such as those of  
64 stellar outflows, is less well studied. The difficulty resides in simulating astrophysical  
65 conditions in the lab: (1) producing a multi-elemental refractory gas of controlled composition  
66 and (2) condensing it in equilibrium/disequilibrium conditions at very high temperature<sup>22,23,24,25</sup>.  
67 Several conditions need indeed to be met for dust/condensed matter formation, such as densities  
68 above a certain threshold to ensure sufficient collisions between the constituent particles,  
69 moderate temperatures below the stability threshold of the dust component, and sufficient time  
70 for the nucleation and growth of molecular clusters into larger grains.

71

72 Here 600 g of a 20 μm-sized powder of NWA869 ordinary chondrite have been processed for  
73 an hour inside a large volume 250 kW three-phase alternating current (AC) plasma torch with  
74 hot graphite electrodes operating at PERSEE, Mines-Paris-Tech, Sophia-Antipolis, France (Fig.  
75 1). Chondritic dust particles were injected using argon gas for propulsion into a 5000 K H<sub>2</sub>-Ar  
76 admixture gas plasma formed between three graphite electrodes (see Methods). The vapor  
77 formed in the plasma flew downwards in a cylindrical meter-sized graphite-coated chamber in  
78 which condensation occurred according to the thermal gradient at a pressure  $\approx 10^5$  Pa. Nitrogen  
79 was injected during the run to avoid hydrogen flammability. The experiment was terminated by  
80 shutting down both the electrical power and the powder supply.

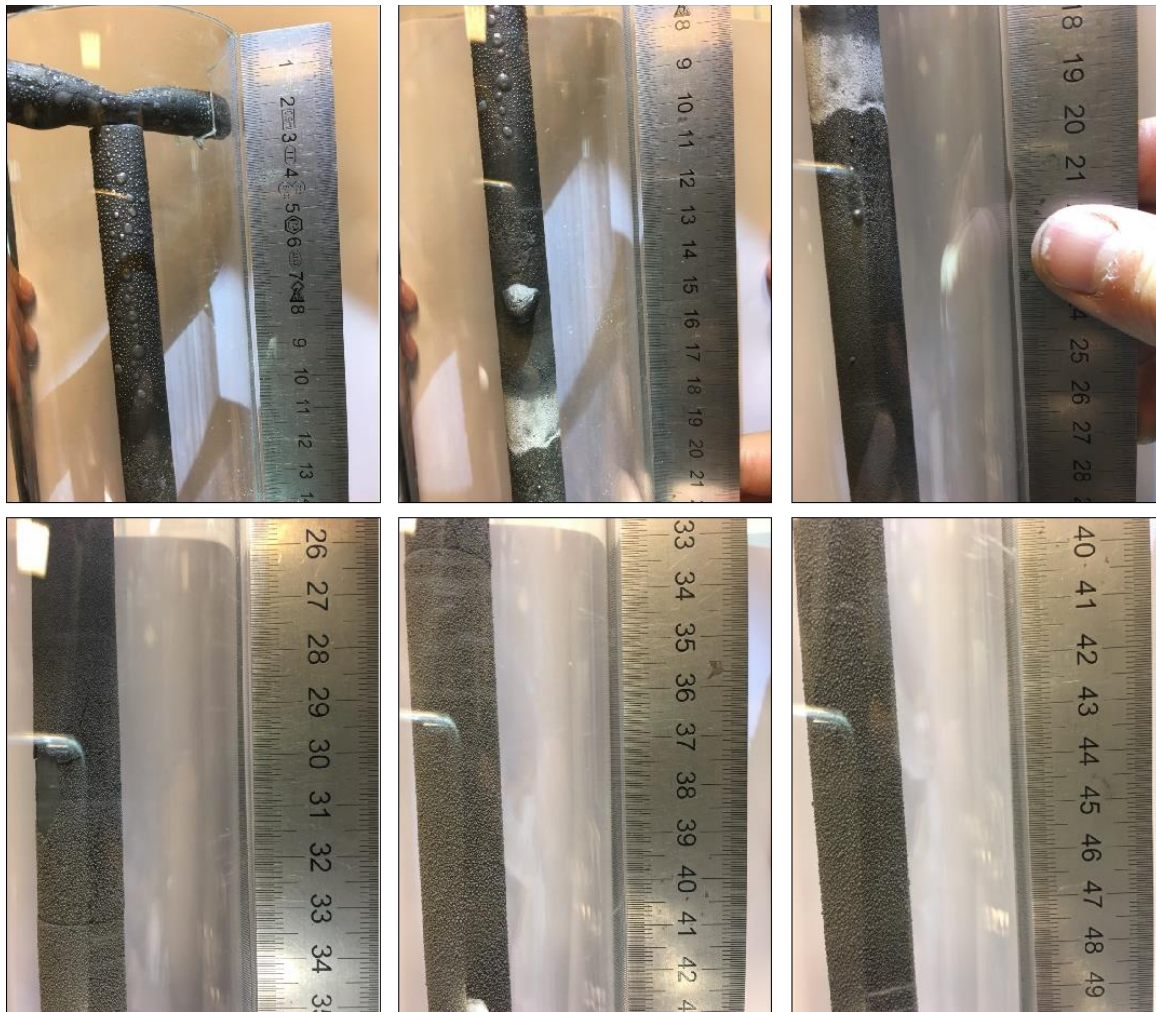
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82 **Fig. 1:** a) 240kW three electrode arc plasma torch (PERSEE, Mines ParisTech, Sofia-  
 83 Antipolis, Nice) in which 600 g of a 20  $\mu\text{m}$ -sized powder of NWA869 ordinary chondrite  
 84 have been processed for an hour. b) Simulated 3D thermal regime inside the condensation  
 85 chamber using the ANSYS Fluent computational fluid dynamic software. A removable T-  
 86 shape graphite rod was placed at the center of the chamber and was recovered after the  
 87 experiment for chemical and mineralogical analyses of the condensates. The 3D simulation  
 88 was performed in a computational domain that does not explicitly incorporate the T-shape  
 89 graphite rod. To account for the rod's presence, the torch power was set to the  
 90 experimentally determined value, maintaining the appropriate source temperature while  
 91 ensuring overall energy balance. To achieve this, losses induced by the rod were  
 92 redistributed onto the walls of the chamber, preserving the global thermal behavior of the  
 93 gas flow. While the thermal distribution may not be locally exact near the rod location, the  
 94 rod temperature can be considered to lie within the thermal boundary layer that forms near  
 95 the walls. Equivalence calculations suggest that the rod temperature is approximately  
 96 between 1/8 and 1/6 of the nozzle diameter away from the walls.  
 97

98  
 99  
 100 A removable T-shape graphite rod was placed at the center of the chamber and was recovered  
 101 after the experiment for chemical and mineralogical analyses of the condensates (Fig. 1 and  
 102 Extended Data Fig. 1). Even if this experiment remains far from CSE conditions, e.g.,  $P \ll 10^2$   
 103 Pa, which are technically impossible to achieve at present, we show in the following how such  
 104 high temperature condensates resulting from fluxed chondritic gas at atmospheric pressure in a  
 105 severe thermal gradient help us to put stringent constraints on dust formation in stellar outflows.  
 106





**Fig. 2:** Photographs of the condensates on T-shape graphite rod after experiment. Notice the change of the structure (e.g., wetting, flaking) and the grain size of the condensates from top (high temperature) to bottom (low temperature). See text.

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## Results

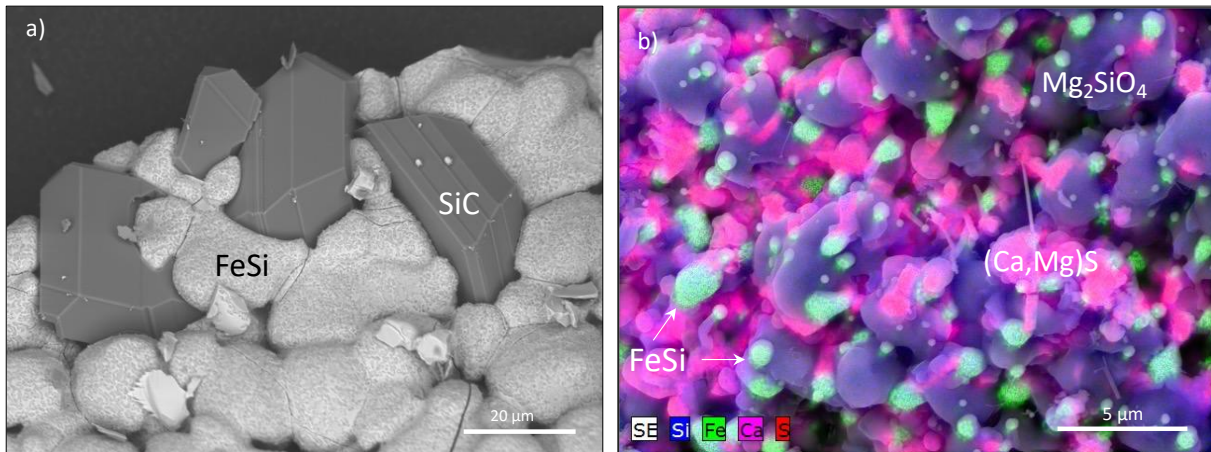
Owing to this large volume device, the recovery of several hundred grams of high temperature condensates obtained at high C/O ratio is a première. The 3D thermal regime inside the chamber as well as the trajectory and velocity of fictive particles (Fig. 1 and Extended Data Fig. 1) have been obtained using the ANSYS Fluent computational fluid dynamics software (see Methods<sup>26</sup>). While condensation occurred in the whole condensation chamber, the T-shape graphite rod holder offers enough material (Fig. 2) to detail the chemistry (Extended Data Table 2) and the mineralogy (Extended Data Table 1) of the condensates between 2400 K to 1300 K at ambient pressure and C/O ratio  $\approx 0.93$ . The high C/O ratio is due to and regulated by the consumption of graphite from the 3 electrodes during the experiment (see Methods and discussion below).

125

X-Ray diffraction (XRD) pattern and secondary electron (SE)- and back scattered electron (BSE)-Scanning Electron Microscopy (SEM) characterization reveal that condensates obtained at the highest temperatures, i.e.,  $>2050$  K, are dominated by iron silicides ( $\text{Fe}_x\text{Si}_y$  with  $x/y$  atomic ratio  $\approx 1.2$ ). They formed millimeter-sized droplets wetting the T-shape graphite rod

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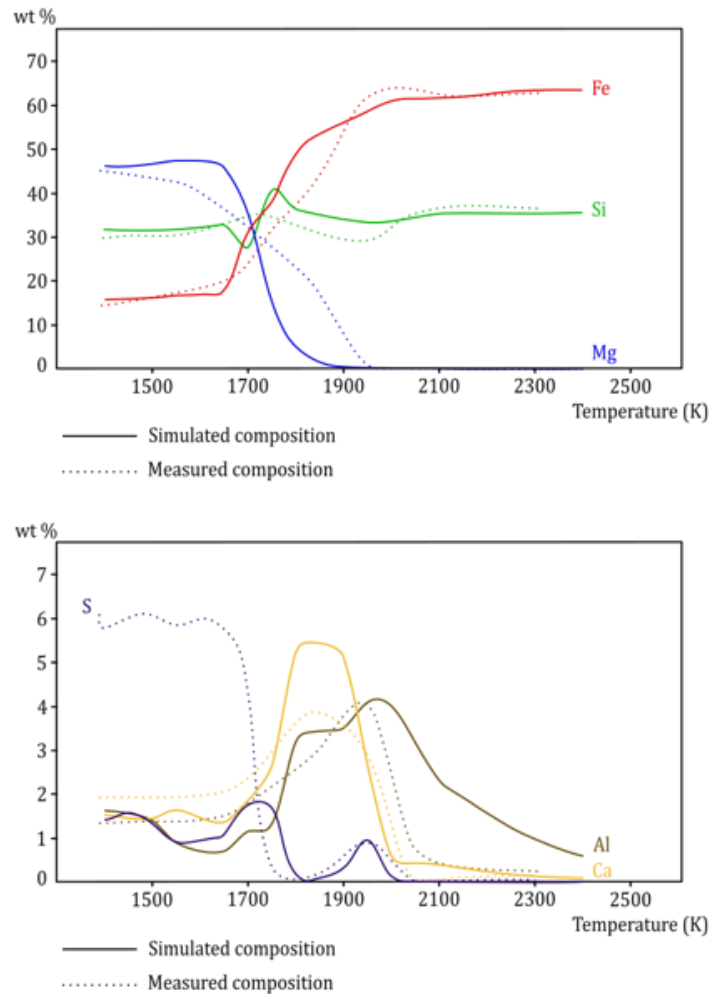
130 (Fig. 2). Well crystallized SiC are bathed in the silicides together with rarer and smaller crystals  
 131 of Al<sub>4</sub>SiC<sub>4</sub> and TiC (Fig. 3 and Extended Data Fig. 3).  
 132



133 **Fig. 3:** Representative scanning electron microscope images of high temperature  
 134 condensates obtained at high C/O ratio. a) Well crystallized SiC bathed in molten FeSi  
 135 (now solid) from sample #13 condensed at temperature around 2150K. b) Overlapped X-  
 136 ray elemental map in Ca (pink), Fe (green), Si (blue) and S K $\alpha$  (red) and SE map of # 8  
 137 condensates obtained at temperature 1700K showing an association of oldhamite (CaS-  
 138 MgS), Mg-rich olivine (Mg<sub>2</sub>SiO<sub>4</sub>) and molten droplets of iron silicide (FeSi).  
 139  
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141  
 142 A temperature of about 2050 K marks the onset of condensation of oxygen-bearing and sulfur-  
 143 bearing phases with the occurrence of calcium-aluminate (silica poor) glass and of CaS-MgS  
 144 oldhamite, respectively. Calcium-aluminates, that are initially molten, wet the immiscible FeSi  
 145 molten droplets and most of the already condensed crystalline phases, including SiC. Oldhamite  
 146 condenses first as Ca-rich phase and shifts to an MgS-rich composition as temperature drops.  
 147 AlN (some of which are whiskers) and TiN nitrides appear below on the T-rod in a narrow  
 148 interval of temperature between 2000-1900 K. In the same range of temperature, olivine  
 149 Mg<sub>2</sub>SiO<sub>4</sub> starts to crystallize from the melt (now glassy and enriched in MgO and SiO<sub>2</sub>) in close  
 150 association with FeSi and SiC. Below a temperature range of 1850-1800 K, X-ray diffraction  
 151 analysis reveals a critical shift in the condensate composition. Graphite becomes the dominant  
 152 phase, while carbides are no longer detectable. Low Ca-pyroxene MgSiO<sub>3</sub> starts to condense  
 153 below 1700 K forming remarkable 1-D whiskers by a FeSi catalyst-assisted VLS (vapor-liquid-  
 154 solid) growth process as shown in the Extended Data Fig. 3. Iron silicides, Fe<sub>x</sub>Si<sub>y</sub> have x/y  
 155 atomic ratio close to 2 in these low temperature condensates. Crystals of periclase MgO have  
 156 also been found in the lowest temperature part of the condensates. Finally, a clear decrease by  
 157 one order of magnitude in the average size of condensed phases from tens of microns to tens of  
 158 nanometers is noticeable as condensation temperature drops from top to bottom of the T-shape  
 159 graphite rod.  
 160

161 Extended Data Table 1 shows the bulk chemistry (Si, Ti, Al, Ca, Mg, Fe, Mn, Na, K, P, C and  
 162 S) of both the starting NWA 869 chondrite composition as well as the 14 aliquots of condensates  
 163 sampled on T-shape graphite rod holder measured by Inductively Coupled Plasma Optical  
 164 Emission Spectrometry (ICP-OES).



165 **Fig. 4:** Composition patterns for the main major and minor elements of the condensates  
 166 considering a kinetically limited condensation with various  $f$  values for the phases (see  
 167 text). The solid lines correspond to the modeled compositions and the dashed lines to the  
 168 measured ones.  
 169  
 170

171 As condensation proceeds downward in the chamber, condensates are first enriched in Fe, Si,  
 172 Ti and C, then become enriched in Al, Ca, S, and next in Mg, a change in chemistry in good  
 173 agreement with their mineralogy (Fig. 4). Sulfur is however enriched in the low temperature  
 174 condensates ( $< 1600$  K). Only trace amounts of Na are found in the lowest temperature  
 175 condensates while K is totally absent of this high C/O ratio condensation sequence.  
 176

## 177 Discussion

### 178 A. Laboratory condensation of chondritic gas at high C/O ratios

180 Our results show a sequence of carbides, sulfides, nitrides, and oxides that are generally  
 181 consistent with calculations made in previous studies that correspond to the low-pressure  
 182 conditions of protoplanetary disks or stellar atmospheres at high C/O ratios<sup>14,27,28,29,30</sup>.  
 183 However, there are some differences due to the duration and the high-pressure conditions ( $\approx$   
 184  $10^5$  Pa) of the experiment. Carbon in our experimental condensates is mainly in the form of  
 185 carbides at high temperatures (above 1850 K) and transitions to graphite at lower temperature.  
 186



187 No evidence of amorphous carbon has been found. The most important difference is the stability  
188 of liquids in these conditions, namely iron silicide metallic liquid and oxide/silicate liquid,  
189 which are immiscible with each other. As is well known in materials science, the liquid acting  
190 as a catalyst promotes mass transfer in the VLS system and controls the growth and shape of  
191 the crystals. The large SiC crystals that crystallize from FeSi liquid<sup>31</sup> and the various 1D  
192 crystals/whiskers of AlN, MgSiO<sub>3</sub> catalyzed by liquid FeSi droplets on their tips provide  
193 convincing examples of the VLS process and its importance at high-pressure condensation  
194 conditions (Fig. 3 and Extended Data Fig. 3).

195

196 Regarding the chemistry of condensates (Extended Table 1), the calculated compositions based  
197 on thermodynamic equilibrium or fractional condensation do not match the measured  
198 compositions, while the calculated mineralogical sequences do (see Methods). In other words,  
199 this suggests that an equilibrium condensation sequence, i.e., the order of phase appearance  
200 during condensation, is not a good discriminant for identifying the exact process of  
201 condensation (see below). We thus explore a partial fractional condensation model (Extended  
202 Data Fig. 4) where only a fraction  $f$  of what was expected to condense in equilibrium could  
203 effectively condense due to kinetic limitations (See Methods).

204

205 The condensation pattern of Si, Fe, Al and Ca determined with the model fits well with the  
206 experiments (Fig. 4). Fe concentrations in the condensates remain high (~ 60 %) until 1950 K,  
207 when phases other than FeSi start condensing (SiC, AlN, CaS, oxide melt). The modelled  $x/y$   
208 ratio of the Fe <sub>$x$</sub> Si <sub>$y$</sub>  molten alloy ranges from 1 to about 2 as the temperature decreases, which is  
209 perfectly consistent with the measured compositions. The Si concentration remains almost  
210 constant along the rod, showing a roughly constant condensation of this element in various  
211 phases: FeSi, SiC, oxide melt, followed by silicates. Ca concentration shows a sharp increase  
212 until CaS becomes stable (Fig. 4). Its concentration increases until it reaches a maximum at  
213 1900 K. At this temperature, CaS is no longer stable, and Ca is mainly partitioned in the oxide  
214 melt. Al concentrations show a rather similar pattern, with a sharp increase when AlN becomes  
215 stable, followed by a short decrease until it reaches a plateau at 1900 K when AlN is no longer  
216 stable, and Al condenses in the oxide melt. Both Ca and Al concentrations sharply decrease  
217 after 1800 K when Ca-poor and Al-poor phases start condensing (i.e., olivine and periclase).

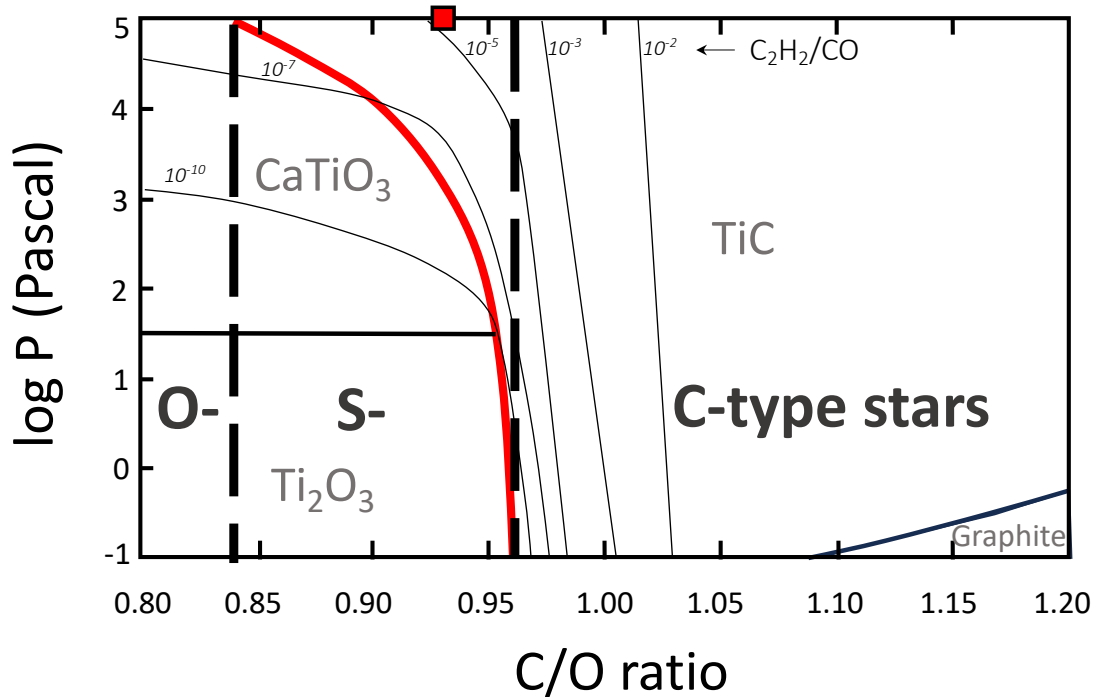
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219 Despite the overall good agreement, some discrepancies between the model and the experiment  
220 can be observed (Fig. 4). The main issue is related to sulfur which has very low predicted  
221 concentration in the low-temperature sections compared with the measured concentrations. The  
222 main S-bearing phase in the thermodynamic simulations is CaS, while the experimental results  
223 are not consistent with the calculated condensation curve for this species: to obtain a CaS phase,  
224 the concentration of Ca should have been much higher than what is observed. Furthermore, no  
225 new sulfide phase was identified in the low-temperature segments of the rod with XRD. There  
226 is thus a clear problem with the sulfur data that could have arisen for several reasons including  
227 i) analytical artifact with the measurement, ii) contamination by the condensation chamber, and  
228 iii) thermodynamic underestimation of the amount of S that could get dissolved in the FeSi,  
229 and/or iv) significant solubility of sulfur in silicate liquids under reducing conditions<sup>32</sup>. Despite  
230 this difference in concentrations, the predicted and observed patterns of S concentrations are  
231 very similar, with a first peak of concentration at 1950 K corresponding to the initial stability  
232 field of CaS and a sharp increase until a plateau around 1750 K corresponding to the second  
233 stability field of CaS.

234

235 Our model, which incorporates a kinetically limited condensation mechanism, effectively  
236 reproduces the experimental results for most major elements at high C/O ratios. This provides

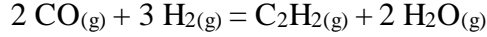
237 the first experimental validation of thermodynamic calculations employed to predict  
 238 condensation sequences under such conditions. Notably, it is also established that the  
 239 kinetically inhibited condensation sequence does not differ from the equilibrium sequence,  
 240 whereas the relative abundances of the condensed phases and the resulting bulk composition  
 241 do. Consequently, the bulk composition, rather than the mineralogical sequence of  
 242 condensation, serves as a more reliable indicator of the extent of kinetic limitations during the  
 243 condensation process.  
 244



245 **Fig. 5:** Pressure versus C/O ratio diagram showing the stability field of first condensates  
 246 using the starting bulk composition of the solar composition from ref<sup>33</sup>, except for the C  
 247 abundance. In this range of P and C/O ratio,  $Ti_2O_3$  and  $CaTiO_3$  are stable at low C/O ratio;  
 248 note that  $Al_2O_3$  (not shown) is stable at lower C/O ratios<sup>28</sup>. At higher C/O ratio, oxides are  
 249 no longer stable, and TiC and graphite are becoming predominant. Red square corresponds  
 250 to our experimental conditions. Thin lines stand for the  $C_2H_2/CO$  ratio in the gas phase at  
 251 the saturation of the first condensates, i.e.,  $Ti_2O_3$ ,  $CaTiO_3$ , TiC or graphite - depending on  
 252 the C/O ratio and the pressure. Notice the significant pressure influence of the transition  
 253 between carbon- and oxygen-bearing phases (red curve). As pressure approaches  $10^5$  Pa,  
 254 the C/O threshold drops well below  $\approx 1$ , indicating a strong destabilization of oxide phases  
 255 in favor of carbides (See text).  
 256

257  
 258 It is crucial to highlight that while the traditional distinction between O-rich and C-rich dust  
 259 chemistry commonly aligns with a C/O value of unity, the C/O ratio derived from our C-rich  
 260 dust-generating experiment dips below this threshold, settling at C/O = 0.93. This reported ratio  
 261 is thus typical of a S-type star rather than that of a C-type star. According to previous  
 262 thermodynamic calculations<sup>28</sup>, the transition between reduced phases (e.g., carbides, nitrides)  
 263 and oxygen-bearing phases (e.g., oxides, silicates) is also observed at a C/O ratio of  
 264 approximately 0.96 at a total pressure of  $10^2$  Pa, indicating a significant pressure influence on  
 265 this transition. This is corroborated by our thermodynamic calculations, as shown in Figure 5.  
 266 Our results confirm a significant pressure-dependent shift in the C/O value required for oxide  
 267 formation. As pressure approaches  $10^5$  Pa, C/O threshold drops well below  $\approx 1$ , indicating a  
 268 strong destabilization of oxide phases in favor of the carbides. This is concomitant to the

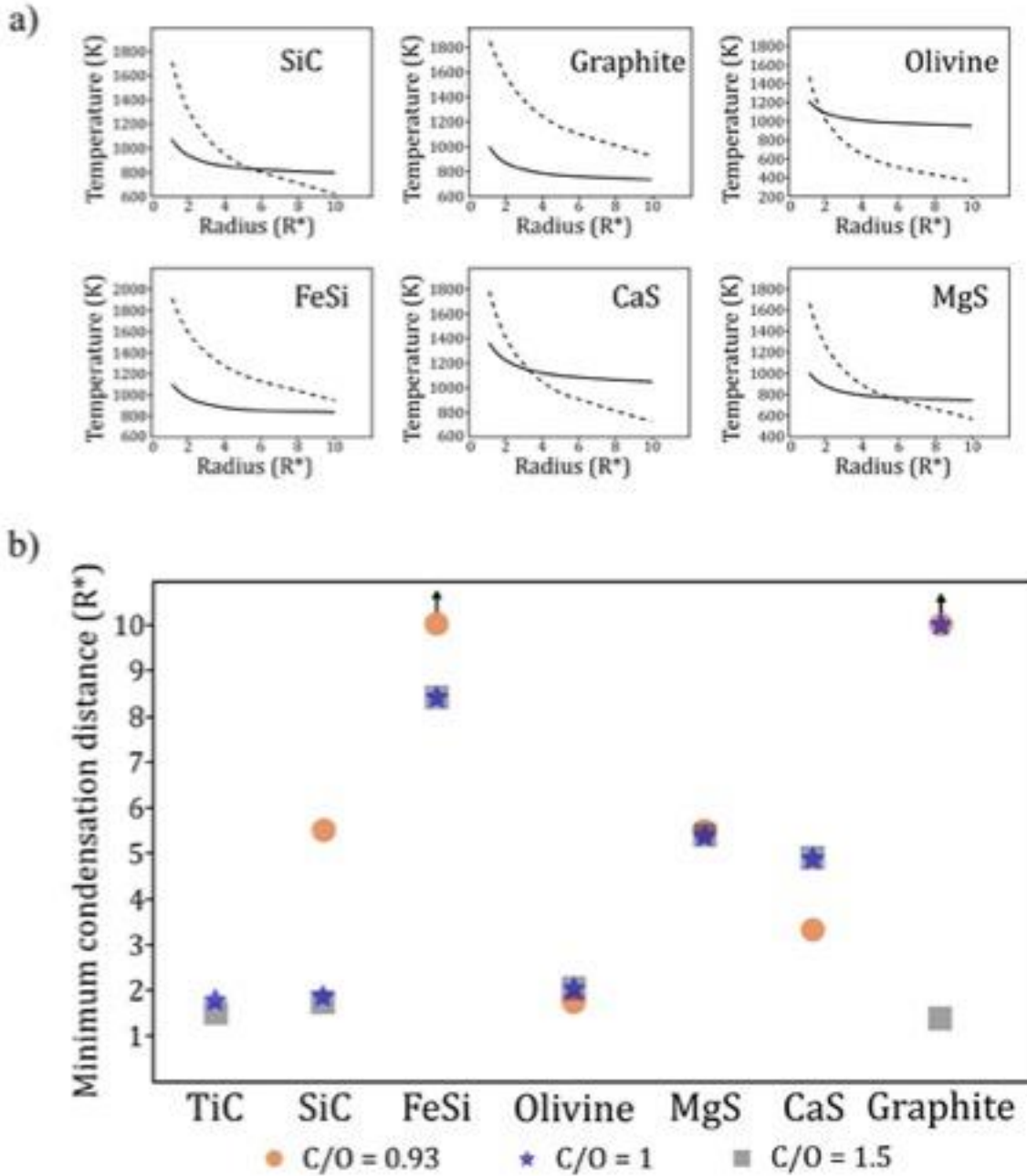
269 dramatic increase in the proportion of carbon-hydrogen bond as pressure rises, as indicated by  
270 the increase of C<sub>2</sub>H<sub>2</sub>/CO ratio of the vapor phase (Fig. 5). The observed preference for C-H  
271 bond formation can be attributed to the inherent weakness of this bond compared to the C-O  
272 bond in carbon monoxide. The C-H bond energy is several hundreds of kJ/mol lower, making  
273 it significantly easier to break and participate in the formation of new reactive carbon species  
274 in the vapor phase under pressure. Such pressure effect can be rationalized by a reaction  
275 involving the main gas species of the type:



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279 which, according to Le Chatelier's principle, will be shifted towards the product side (C<sub>2</sub>H<sub>2</sub>  
280 formation) as pressure increases (PΔV negative). This aligns perfectly with the observed  
281 increasing stability of C-bearing condensed phases at higher pressures and with the presented  
282 experimental data (Fig. 5). In light of this, our condensation sequence at 10<sup>5</sup> Pa with C/O = 0.93  
283 replicates the sequence observed in CSE with higher C/O ratios. In what follows, we explore  
284 the consequence of our thermodynamic calculations extended to low-pressure conditions that  
285 are representative of stellar atmospheres with high C/O ratio such as AGB S- and C-stars.  
286

## 287 **B. Condensation in C-rich stellar atmospheres**

288 Evolution of AGB stars is controlled by two main processes: dredge-ups that bring material  
289 from the inner shell to the most outer layers, thus increasing the C/O ratio of the stellar  
290 atmosphere<sup>34,35</sup>, and mass loss including C through stellar winds<sup>36</sup>. Dust formation by  
291 condensation is crucial since stellar winds are driven by momentum transfer from the photons  
292 emitted by the star to the surrounding dust<sup>3,37</sup>. The accelerated dust then drags the surrounding  
293 gas and stellar winds are formed. The acceleration of dust by radiative pressure depends on the  
294 efficiency of the momentum transfer from the photons to the grains, namely the mean opacity  
295 of the dust. Stellar winds can only form if the radiative pressure force exceeds the local gravity  
296 force of the star, which is when the mean opacity of the dust exceeds a critical value that  
297 depends on the star mass and luminosity. However, momentum transfer is not the only light-  
298 matter interaction that plays an essential role. In particular, the light absorption properties of  
299 some minerals can heat up the grains such that the actual temperature of the dust grains can be  
300 different from the local gas temperature. Thus, these grains can be heavily heated up and their  
301 temperature can then exceed their condensation temperature. Consequently, their condensation  
302 can be inhibited, destabilizing these minerals even though the gas temperature should allow  
303 condensation. This phenomenon has already been described for Fe-bearing olivines around  
304 AGB M-stars<sup>38</sup>. This effect will contribute to increasing the effective oversaturation of this  
305 phase. As the gas and dust flow away from the star, the temperature and pressure decrease such  
306 that at some point the predicted dust temperature shall correspond to its condensation  
307 temperature<sup>39,40</sup>. The evolution of the AGB stars critically depends on the properties of the  
308 condensing grains with respect to light-matter interactions. According to ref<sup>39</sup>, the degree of  
309 heating of a mineral phase will depend on a parameter  $p$  whose value can be calculated if the  
310 dependence of the coefficient of absorption  $Q_{abs}$  as a function of wavelength is known. The  
311 values of  $p$  for mineral phases predicted in our condensation sequence were calculated based  
312 on their optical properties (whenever they were not directly available from the literature) and  
313 are reported in Extended Data Table 4. The  $p$  values were used to compute the actual  
314 temperature of the dust as a function of the distance from the star<sup>40</sup> (See Methods).



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**Fig. 6:** a) Comparison of the thermodynamic condensation temperature (solid line) and the dust temperature (dashed line) as function of the distance from an AGB star with a C/O ratio of 0.93 for six different minerals. The composition of the gas and the pressure profile are from ref<sup>14</sup>. The surface temperature of the star is considered to be 2500 K. Condensation of minerals can only occur when the actual dust temperature is lower than the condensation temperature, i.e the minimum condensation distance is the intersection of the dashed line and the solid line. b) Condensation distances for various mineral phases calculated for C/O of 0.93, 1 and 1.5. The distances are expressed as multiples of the star radius and were obtained using the same approach as in a).

326 The condensation temperatures of dust with a C-star composition were then calculated using  
327 the same thermodynamic database as that used for modeling our experimental condensation  
328 sequence. The starting bulk composition was the solar abundance from ref<sup>33</sup> with an increased  
329 C abundance. The distance where a mineral first condenses was calculated for a temperature



330 and pressure profile in the extended atmosphere of a representative AGB star<sup>14</sup>. In this  
331 calculation, the abundance of C was increased over the solar value starting from a value of 0.93  
332 (corresponding to our experiment) up to 1.5, since most C-rich AGB stars have  $1 < C/O < 1.5$ .  
333 The results of these calculations were then plotted in Figure 6 where dust temperatures are also  
334 reported. In principle, the minimum distance where dust can condensate is located at the  
335 intersection of the condensation temperature and dust temperature curves. For TiC, SiC and  
336 olivine, the distance is close to the star ( $< 2R_*$ ). In these conditions, the pressure is high enough  
337 ( $> 10^{-2}$  Pa) for condensation to occur. However, for CaS, FeSi and C, the condensation can only  
338 take place at distances greater than  $5R_*$ . At this distance, the pressure is lower than  $10^{-5}$  Pa and  
339 the condensation must take place at a much lower rate owing to a lower local density. In order  
340 to further determine whether the formation of FeSi dust could take place despite the low density  
341 at such a large distance from the star, we evaluated the timescale necessary for FeSi dust growth  
342 compared with the timescale of the outflow itself using the approach described in ref<sup>41</sup> using an  
343 appropriate set of parameters (See Methods). The results are shown in Extended Data Fig. 5.  
344 The growth timescale for dust particles between  $10^{-1}$  and  $10^{-3}$   $\mu\text{m}$  is always an order of  
345 magnitude longer than the outflow timescale. This shows that provided the dust temperatures  
346 prevent condensation at a close distance from the star (here  $> 5R_*$ ), the low density in this  
347 environment then becomes prohibitive for allowing a rapid enough grain growth. Consequently,  
348 our kinetic models predict that FeSi is unlikely to form in the outflows of C-rich AGB stars,  
349 despite thermodynamic predictions favoring its condensation under these conditions. In  
350 addition, one could note that the detection of IR signature for FeSi in stellar outflows is itself  
351 difficult<sup>42</sup> due to the lack of distinct spectral features.

352

353 Assuming that our calculations capture the essence of processing affecting dust generated in C-  
354 rich AGB stars, these results can be compared with direct observations of AGB stellar outflows  
355 and presolar grains preserved in primitive chondrites. Mid-infrared (MIR) survey of evolved  
356 stars has revealed a clear dichotomy in the chemical properties of dusty outflows. Carbon dust,  
357 be it amorphous carbon or crystallized graphite<sup>43</sup>, and silicon carbide appear together in the  
358 outflows of C-enriched stars, whereas silicates, alumina and water ice dominate the dust  
359 emission of stars with  $C/O \ll 1$ <sup>44</sup>. C-rich dust, such as graphite, SiC and polycyclic aromatic  
360 hydrocarbons (PAHs) do show emission features at 3-30  $\mu\text{m}$ . The carriers of the 21  $\mu\text{m}$  and 30  
361  $\mu\text{m}$  features in the outflows of C-rich stars are currently still debated<sup>45</sup>. For instance, the feature  
362 observed around 30  $\mu\text{m}$  in the outflows of C-stars is often attributed to MgS but its formation  
363 is unclear<sup>45,46,47</sup>. An important feature is that AGB dust has an extremely low Fe content,  
364 although iron is significantly depleted from the gas phase in both circumstellar and interstellar  
365 environments and  $\sim 90\%$  of iron produced by stars should be in dust grains. These features seem  
366 consistent with our modeling, suggesting the absence of FeSi condensation due to kinetic  
367 constraints.

368

369 Similarly, the mineralogy and composition of presolar grains provide some strong hints about  
370 their birth environment. It is commonly considered that the majority of these grains come from  
371 C-rich AGB with abundant SiC<sup>48</sup> and rare C<sup>49</sup>, CaS and MgS and TiC (but also (Zr,Mo)C has  
372 also been documented as tiny grains<sup>50,51,52,53</sup>). In contrast, the presence of FeSi is very rare and  
373 only mentioned as a small inclusion by ref<sup>53</sup>. Thus, to a first order, our modeling is consistent  
374 with observations in presolar grains. In some cases, TiC has been described as occurring as  
375 inclusions inside SiC or graphite dust grains and it has been suggested in previous studies that  
376 TiC (or ZrC) could have acted as a seed for heterogeneous nucleation<sup>51,54,55,56,57,58</sup>. This could  
377 indeed have been the case when they occur in a central position. However, according to the  
378 observations of ref<sup>53</sup>, their elongated shape seems to preclude a condensation origin for the TiC  
379 inclusions and would suggest also a secondary exsolution.

## 380 **Conclusion**

381

382 Overall, our experiment validates the mineralogical sequence that had been predicted by  
383 equilibrium thermodynamic calculations and shows that under kinetic conditions where  
384 condensation is limited by flow rate, the equilibrium sequence of minerals is preserved, while  
385 the phase abundance is under kinetic control. By including the effect of light interaction with  
386 minerals that have strong IR absorption, our results also show that one can effectively predict  
387 the observed minerals found in C-rich stars, but also in presolar grains. It should be mentioned,  
388 however, that wind characteristics of AGB stars could be significantly affected in the case of  
389 binary systems with closed-by companions which often have an equatorial density  
390 enhancement, accretion disk and complex inner wind dynamics<sup>59</sup>. Nevertheless, this study  
391 suggests that more extensive condensation experiments such as that presented here could  
392 provide novel insights into dust formation in astrophysical environments.

393

## 394 **Methods**

395

### 396 **A. Experimental approach**

397 The experimental work was performed at Mines ParisTech-PERSEE, Sophia-Antipolis, Nice  
398 (Fig. 1). The experimental setup was made of a large volume plasma torch at atmospheric  
399 pressure. A finely ground powder ( $\sim 20 \mu\text{m}$ ) of the NWA 869 ordinary chondrite (bulk  
400 composition given Extended Data Table 1) was injected in a 5000 K Ar-H<sub>2</sub> plasma formed  
401 between 3 graphite electrodes. The total volume of plasma thus formed was about 1 L. Electrode  
402 erosion enriched the vapor with carbon, driving a constant C/O ratio near unity. This ratio is  
403 significantly higher than the initial C/O ratio of the starting chondritic material. The vapor  
404 formed in the plasma flew downwards in a graphite-coated chamber along which condensation  
405 occurred in a temperature gradient. A removable T-shaped graphite rod positioned at the  
406 chamber's center facilitated the retrieval of condensates formed due to the chamber's thermal  
407 gradient. The temperature and flow velocity were determined numerically. The magneto-  
408 hydrodynamic equations of the gas as well as the thermo-mechanical evolution of 2000 virtual  
409 particles were solved using ANSYS Fluent software<sup>26</sup>. From this, we were able to compute the  
410 temperature field inside the condensation chamber (Fig 1.b.) and the gas flow streamlines. The  
411 flow velocity ranged between 1 m/s and 0.6 m/s at the top and end of the chamber respectively,  
412 while the temperature ranged from 2400 K to 1300 K at the top and end of the graphite rod,  
413 respectively. The rod was recovered after the experiment and underwent chemical and  
414 mineralogical analyses. Condensates on the T-shaped graphite rod were collected using a  
415 scraping technique from fourteen, 5 cm long segments along its length (Extended Data Fig. 2  
416 and Extended Data Fig. 3). The chemical and mineralogical compositions of each segment were  
417 then analyzed and are summarized in Extended Data Table 1 and Extended Data Table 2,  
418 respectively.

419

### 420 **B. Thermodynamic simulations**

421 The thermodynamic simulations of the system were done with the FactSage software. This  
422 software computes the equilibrium composition of a system based on Gibbs energy  
423 minimization method, given a composition and the P-T conditions of the system. We used the  
424 FactPS, FTStel and FToxid databases<sup>60</sup>. By calculating equilibrium phase composition as a  
425 function of decreasing temperature, the software is able to simulate condensation starting from  
426 a vapor with a chondritic composition, mixed with Ar, N<sub>2</sub>, H<sub>2</sub> and additional C.

427

428 The system was composed of 600 g of the NWA 869 composition (Extended Data Table 1) and  
 429 an amount of Ar, H<sub>2</sub> and N<sub>2</sub> that correspond to the total amount of gas flowing in the plasma  
 430 torch during the experiment. As the actual C/O ratio of the system could not be easily  
 431 determined, several simulations were performed with a C/O molar ratio ranging from 0.72 to  
 432 1.15. For each simulated composition, the pressure was kept at the constant value of 10<sup>5</sup> Pa  
 433 whereas the temperature ranged between 2700 and 1300 K with temperature steps of 50 K.

434  
 435 For each temperature step, the software computed the expected phases in equilibrium, including  
 436 their composition and total masses. We considered three possible condensation behaviors: an  
 437 equilibrium condensation where the bulk composition of the system remained constant along  
 438 its path, a fractional condensation where all the condensed material was subtracted from the  
 439 vapor composition at each temperature step and a partially fractional condensation where only  
 440 a fraction  $f$  of what was supposed to condense at equilibrium could effectively condense due to  
 441 kinetic effects (see section C. below). For each of these scenarios, we were able to define a  
 442 condensation sequence and the bulk chemical pattern of the condensates with decreasing  
 443 temperature. These results were then compared with the actual sequence and the chemical  
 444 pattern measured on the T-shape rod.

445  
 446

### C. Thermo-kinetic model of condensation

447 Since the data could not be explained by an equilibrium model or a fractional condensation  
 448 model, we designed a kinetic model that considers the kinetics of condensation as the vapor is  
 449 flowing through the condensation chamber. The schematic geometry of the experiment is  
 450 presented in Extended Data Fig. 3. The system is composed of the condensation chamber with  
 451 a radius  $r = 7$  cm. At the center of the chamber, the rod is assumed to be a cylinder with a radius  
 452  $r' = 1$  cm. Only a fraction  $f$  of what was expected to condense in equilibrium could effectively  
 453 condense due to kinetic limitations. To evaluate a value of  $f$  that would be consistent with  
 454 kinetic constraints, we included a model for gas flow through the graphite-coated chamber. We  
 455 considered that the kinetics of condensation was controlled by gas flow, thus neglecting the  
 456 kinetics of nucleation. The vapor was assumed to flow downward through a vertical cylinder  
 457 of diameter  $r$ . If one considers a slice of thickness  $dz$  through the cylindrical tank located below  
 458 the plasma, one can write a mass balance equation for the fluxes (Extended Data Fig. 4):

459  
 460

$$F_{in}(z) = F_{out}(z + dz) + F_{cond}(z) \quad (1)$$

461 where  $F_{in}$  is the advective flux of gas entering at position  $z$ ,  $F_{out}$  is the advective flux of gas  
 462 leaving at position  $z+dz$  and  $F_{cond}$  is the condensation flux on the chamber's inner surface.

463

464 One can then write  $F_{in}$  and  $F_{out}$  as a function of the molecular densities  $\rho(z)$  and  $\rho(z+dz)$   
 465 respectively:

466  
 467

$$F_{in}(z) = \rho(z)Sv$$

468

$$F_{out}(z + dz) = \rho(z + dz)Sv$$

469

470  $S$  is the surface of an axial section through the system, i.e.,  $S = 2\pi(r^2 - r'^2)$ ,  $v$  is the mean vertical  
 471 gas velocity. The condensation of elements follows the Hertz-Knudsen equation:

472

$$F_{cond}(z) = \frac{S'\alpha(P_i(z) - P_{i,sat}(z))}{\sqrt{2\pi MRT(z)}}$$

473  $S'$ , the total condensation surface, is made of the rod and the chamber sides,  $M$  is the molar  
 474 mass of the evaporated species and  $\alpha$  is the condensation coefficient (or sticking coefficient).  
 475 For a small slice of length  $dz$ , the total condensation surface is  $S' = 2\pi(r+r')$   $dz$ .

476 Considering the vapor phase as an ideal gas, one can write:  $\rho_i(z) = \frac{P_i(z)}{RT(z)}$

477 The flux conservation equation thus becomes:

$$478 \quad \rho_i(z)Sv = S' \frac{\alpha(P_i(z) - P_{i,sat}(z))}{\sqrt{2\pi MRT(z)}} + \rho_i(z + dz)Sv$$

479 This equation can be further transformed as follows:

$$480 \quad \left( \frac{P_i(z)}{RT(z)} - \frac{P_i(z + dz)}{RT(z + dz)} \right) Sv = \frac{S' \alpha(P_i(z) - P_{i,sat}(z))}{\sqrt{2\pi RT(z)}}$$

$$481 \quad \frac{d\left(\frac{P_i}{T}\right)}{dz} dz = \frac{2\pi(r + r')dz \alpha(P_i(z) - P_{i,sat}(z + dz))}{Sv} \sqrt{\frac{R}{2\pi MT(z)}}$$

$$482 \quad \frac{T(z) \frac{dP_i}{dz} - P_i \frac{dT}{dz}}{T^2(z)} = \frac{2\pi(r + r')\alpha(P_i(z) - P_{i,sat}(z))}{Sv} \sqrt{\frac{R}{2\pi MT(z)}}$$

483 The final equation is then written and can be integrated numerically:

$$484 \quad \frac{dP_i}{dz} = \frac{2\pi(r + r')\alpha(P_i(z) - P_{i,sat}(z))}{Sv} \sqrt{\frac{RT(z)}{2\pi M} + \frac{P_i}{T(z)} \frac{dT}{dz}} \quad (2)$$

485 The first term of the right-hand side of the equation corresponds to the condensation flux and  
 486 the second term is the pressure variation linked to the temperature gradient  $dT/dz$ , which was  
 487 computed with the calculated temperature from the Fluent software. The saturation pressures  
 488 for the different species in the gas phase were evaluated with the equilibrium values calculated  
 489 with FactSage.

490  
 491 Equation (2) was integrated numerically to calculate  $P_i(z)$  based on the computed thermal  
 492 gradient and the vapor pressure  $P_{i,sat}$  that was calculated in the thermodynamic simulations  
 493 described above. For the sake of simplicity, we focused on elements with a reduced number of  
 494 species in the vapor phase and which condense in a reduced number of phases, such as  $Fe_{(g)}$   
 495 which condenses in the FeSi molten alloy. We also applied this model to  $Si_{(g)}$  in the upper part  
 496 of the rod, as it condenses in the FeSi alloy as well, and  $Ca_{(g)}$  which condenses only in the oxide  
 497 melt and in the oldhamite when  $T > 1600$  K. The fraction of element  $i$  that effectively condensed  
 498 relative to the maximum amount that would have condensed, had we reached chemical  
 499 equilibrium, can be expressed as:

$$500 \quad f_i = \frac{n_i(T) - n_i(T + \Delta T)}{n_i(T) - \overline{n_{i,sat}}(T)} \quad (3)$$

501 where  $n_i(T)$  is the number of moles of  $i$  at temperature  $T$  and  $\overline{n_{i,sat}}(T)$  is the mean number of  
 502 moles of  $i$  in equilibrium over the  $[T, T + \Delta T]$  interval with  $\Delta T = 50$  K. Our thermodynamic  
 503 calculations show that  $\overline{n_{i,sat}}(T) \ll n_i(T)$  at all temperatures in the experiment. Thus, the value  
 504 of  $f_i$  can be approximated with:

$$505$$

$$506 \quad f_i \approx \frac{n_i(T) - n_i(T + \Delta T)}{n_i(T)} \quad (4)$$



507 The  $f_i$  value depends implicitly on the oversaturation of a species  $P_i/P_{(sat,i)}$  in the vapor and on  
508 the condensation coefficient  $\alpha$ , which is a critical parameter to compute the value of  $f_i$ . The  
509 condensation coefficient of iron was determined experimentally<sup>19</sup> at pressures lower than those  
510 of our experiment and reported a value of 1 for oversaturation greater than 10. However, it has  
511 been shown for other elements that the condensation coefficient decreases with pressure. The  
512 measured chemical pattern of Fe (Fig. 4) is best fit by an  $f$  value of 6 to 8%, corresponding to  
513 an  $\alpha$  value of 0.4, which is within the range of condensation coefficients reported in ref.<sup>19</sup>. For  
514 calcium, a value of 0.2 for  $\alpha_{Ca}$  yielded the best fit, which is consistent with published data for  
515 Ca evaporation<sup>61,62</sup> and with the mean value for divalent cation evaporation from silicate  
516 melt<sup>63,64</sup>, especially in H-rich environment<sup>61</sup>. The  $\alpha_{Si}$  is poorly constrained from previous work  
517 and its value was adjusted to 0.45. The values of the condensation factors  $f$  are reported in Table  
518 S3 for the various types of condensates. A best fit was obtained with a constant condensation  
519 fraction for all chemical species of a given phase. For all the elements, we found  $f_i$  values well  
520 below one (see Extended Data Table 3), expressing the kinetic limitation in the condensation  
521 rate due to the effect of gas flow and kinetic barrier represented by the condensation coefficient  
522  $\alpha_i$ .

523  
524 As shown in Extended Data Fig. 4, the condensation fraction  $f$  of Fe assessed with this model  
525 shows a moderate increase from 6% at 2280 K to 8.2% at 1377 K with a mean value of 7%.  
526 The computed  $f_{Si}$  value shows the same pattern with temperature, with a mean value equal to  
527 8.3% in the region in which Si condenses in the FeSi metal. For Ca, two regime stages of  
528 condensation were considered: the first region where Ca only condenses only in the oxide melt  
529 ( $T > 1750$  K) and second a region where Ca condenses both in the silicate melt and in the sulfide  
530 phase ( $T < 1750$  K). This leads to a concave curve with an increase of  $f_{Ca}$  from 1.5% at 1950 K  
531 to 2.6% at 1618 K. Finally, the  $f$  factor of the different phases used for the thermodynamic  
532 calculations are presented in Extended Data Table 3.

533

534

#### D. Optical properties and condensation distances

535 The condensation of dust in the outflow of C-rich stars should to some extent be controlled by  
536 the thermodynamics of solid phase formation with a vapor composition at a high C/O ratio.  
537 However, it has been shown in several studies<sup>65</sup> that the radiative properties of the condensed  
538 dust play a critical role on top of its thermodynamic properties. The photons radiated by the star  
539 will interact with the dust: a fraction of the light will be reflected while another fraction will be  
540 absorbed, and the last fraction is transmitted. If the fraction of absorbed light is significant, it  
541 will contribute to heating the dust to a temperature that could be higher than the temperature of  
542 the ambient gas. In turn, this higher temperature could delay dust condensation. This effect will  
543 contribute to increasing the oversaturation of this phase. As the gas and dust flow away from  
544 the star, the temperature and pressure will decrease such that at some point the predicted dust  
545 temperature shall correspond to its condensation temperature<sup>39,40</sup>. At this radial distance the  
546 dust can condensate.

547

548 In detail, the fraction of absorbed light depends critically on the optical parameters of the dust,  
549 and it has been shown in numerous studies that this depends on the Fe content among other  
550 parameters. When the Fe content increases, the absorption coefficient increases especially in  
551 the frequency domain where radiations are efficient at heating the material. In the case of small  
552 dust particles ( $\mu\text{m}$  scale), the parameter used to describe light absorption is  $Q_{abs}$  and by plotting  
553  $Q_{abs}/a$ , where  $a$  is the diameter of the grain, as a function of photon energy, one can define a  
554 parameter  $p$  that is then used to calculate a dust temperature  $T_d$ <sup>40</sup>. The parameter  $p$  has been  
555 calculated for several oxides and for amorphous carbon but not for the mineral phases that are  
556 predicted to condense in high C/O environment. Based on published optical properties of FeSi,

557 TiC, AlN, SiC and graphite we have calculated the value of parameter p to be able to predict  
 558 the corresponding dust temperature.  
 559 Ref<sup>40</sup> has shown that the distance of condensation of a particular mineral species can be  
 560 calculated based on the value of the parameter p and the temperature at the surface of the star  
 561  $T^*$ :

$$T_d(r) = T^* \left( \frac{2r}{R^*} \right)^{-\frac{2}{4+p}} \quad (1)$$

562  
 563 If the condensation temperature  $T_c$  is known independently from thermodynamic calculations,  
 564 it is then possible to determine the radial distance for condensation of a particular mineral phase  
 565 by setting:

$$T_d(r) = T_c(r) \quad (2)$$

566  
 567 For the purpose of our calculations, we have used the  $T(r)$  and  $P(r)$  curves for a C-rich star  
 568 given in ref<sup>14</sup> and the results of our condensation calculations are presented graphically in figure  
 569 6.  
 570

### 571 E. Calculations of parameter p for mineral phases condensed at high C/O ratio

572  
 573 The value of p was calculated for the following mineral phases based on published optical  
 574 properties: TiC, AlN, CaS and FeSi. In the case of FeSi, the value of  $\alpha_{abs}$  the absorption  
 575 coefficient was calculated using the following equation that depends on the band gap energy<sup>66</sup>:

$$\alpha_{abs} = \frac{A}{\omega} \sqrt{\omega - E_g}$$

576  
 577 Where  $E_g$  is the band gap energy. In the case of FeSi which is a semi-conductor at low  
 578 temperature but a metal at high temperature, the dependence of  $E_g$  on temperature was taken  
 579 into account with the following equation<sup>67</sup>:

$$E_g = E_{g0} - Sh\omega \cdot \left( \coth \left( \frac{h\omega}{2kT} \right) - 1 \right)$$

580  
 581 The value of k, the imaginary part of the refraction index, was then calculated as:

$$k(\lambda, T) = \frac{\alpha_{abs}\lambda}{4\pi}$$

582  
 583 Then, the value of the reflectivity given in ref<sup>68</sup> was used to calculate the value of the real part  
 584 of the complex refraction index ( $n+ik$ ) using the following equation:

$$R = \frac{(n-1)^2 + k^2}{(n+1)^2 + k^2}$$

585  
 586 Finally, the absorption parameter  $Q_{abs}$  was calculated using the following expression<sup>69</sup>:

$$Q_{abs} = 4 \frac{2\pi a}{\lambda} \frac{6nk}{(n^2 - k^2 + 2)^2 + 4n^2k^2}$$

587  
 588 In the case of CaS, the experimental studies reported values of the real and imaginary dielectric  
 589 function as a function of energy<sup>70</sup>. These parameters are directly related to the real  $\varepsilon_1$  and  
 590 imaginary  $\varepsilon_2$  part of the complex refraction index:

$$\begin{aligned} \varepsilon_1 &= n(\omega)^2 - k(\omega)^2 \\ \varepsilon_2 &= 2n(\omega)k(\omega) \end{aligned}$$

591  
 592 From these equations, one can calculate:

$$k(\omega) = \sqrt{\frac{\sqrt{\varepsilon_1^2 + \varepsilon_2^2} - \varepsilon_1}{2}}$$

593  
 594  
 595

596

$$n(\omega) = \sqrt{\frac{\sqrt{\varepsilon_1^2 + \varepsilon_2^2} + \varepsilon_1}{2}}$$

597 The equation given above is then used to calculate  $Q_{abs}$ . In the case of TiC, the absorbance was  
598 directly determined by ab initio calculation<sup>71</sup>. For AlN, the value of  $Q_{abs}$  is a function of  
599 frequency that was directly calculated from the equation based on n and k, as given in ref<sup>72</sup>.

600

601

### F. Modeling the timescale of grain growth relative to the timescale of outflows

602 The time necessary to grow a dust grain starting from seed such as a more refractory grain  
603 highly depends on the local density of the constitutive atoms of the considered dust. If one takes  
604 the example of FeSi (Extended Data Fig. 5), then the growth rate will be limited by the rate at  
605 which individual atoms hit the grain surface. In the case of dust condensation in stellar outflow,  
606 we calculated the maximum rate of condensation by neglecting the rate of evaporation. In all  
607 cases, our calculated rates should be greater than the actual rates. As detailed in ref<sup>34,41</sup>, the  
608 condensation rate of FeSi is limited by the rate of Si abundance since it is lower than that of Fe.  
609 One can thus write the timescale of grain growth as:

$$610 \quad \frac{da}{dt} = \frac{V_0 \alpha (P_{Si} - P_{Si,sat})}{\sqrt{2\pi m_{Si} RT}}$$

611 Where  $V_0$  is the average volume occupied by a FeSi unit.

612 This relation can be further modified following the study of ref<sup>41</sup> by including the relationship  
613 between the local pressure, the density of the gas and the Si abundance:

$$614 \quad P_{Si} = \frac{n_{Si} 2n_{H_2} RT}{n_H V} = \varepsilon_{Si} \rho RT$$

615 In order to calculate the growth timescale as a function of distance from the star, one can use  
616 the equation given in ref<sup>34</sup>:

$$617 \quad \tau_{growth} = \frac{a}{\frac{da}{dt}} = \frac{a \sqrt{2\pi m_{Si} RT}}{V_0 \alpha P_{Si}} = \frac{a \sqrt{2\pi m_{Si} RT}}{V_0 \alpha \varepsilon_{Si} \rho RT} = \frac{2a}{V_0 \alpha \varepsilon_{Si} \rho(r)} \sqrt{\frac{2\pi m_{Si}}{RT}}$$

618 One can also calculate the timescale associated with the stellar outflow. According to ref<sup>47</sup> this  
619 parameter can be evaluated with the following equation:

$$620 \quad \tau_{outflow} = \frac{2}{\Gamma - 1} r \frac{v}{v_{esc}^2}$$

621 Where  $\Gamma$  is defined as the ratio of radiative acceleration to gravitational attraction ref<sup>73</sup>:

$$622 \quad \Gamma = \frac{f_K L_*}{4\pi c G M_*}$$

623 This parameter is increasing outwards and is above 1, ranging between 2 and 5<sup>38</sup> and  $v_{esc}$  is the  
624 escape velocity:

$$625 \quad v_{esc} = \sqrt{\frac{2GM^*}{4R^*}}$$

626 The velocity of the outflow at an infinite distance can be calculated with the following  
627 equation<sup>38</sup>:

$$628 \quad v = \sqrt{\frac{2GM^*}{r_0} (\Gamma - 1) + v_0^2}$$

629 Where  $r_0$  represents the radius where the acceleration starts (the dust condensation radius).  
630 According to ref<sup>38</sup> the initial velocity at  $R^*$  can be approximated as the sound velocity<sup>74</sup> that  
631 can be defined as:

632 
$$v_0 = \sqrt{\frac{C_p^{H_2} RT}{M_{H_2} (C_p^{H_2} - R)}}$$

633 The value of Cp for H<sub>2</sub> was taken from the NIST compilation by ref<sup>75</sup>:

634

635 
$$C_p^{H_2} = 18.563083 + 12.257357 \times T - 2.859786 \times T^2 + 0.268238 \times T^3 + \frac{1.977990}{T^2}$$



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## Author information

G.L. designed the research and performed the experiments with L.F., V-J.R., C.G. and F.C. G.L, C.G, V. G. and P. V. determined the mineralogy of the condensates. M.M., B.B. and G.L. reduced the data and did the thermodynamic calculations and models. G.L. M.M. and B.B. wrote the manuscript under the supervision of E.L for AGB implications.

## Data availability

All data needed to evaluate the conclusions in the paper are present in the paper and in the Supplementary Information. Additional data related to this paper may be requested from the authors.

## References

1. Whittet, D.C.B. Dust in the Galactic Environment. (IOP Publishing, Bristol, UK, Third Edition, 2022).
2. Kemper, F., Vriend, W. J., & Tielens, A. G. G. M. The absence of crystalline silicates in the diffuse interstellar medium. *Astrophys. J.*, **609**, 826 (2004).
3. Höfner, S. & Olofsson, H. Mass loss of stars on the asymptotic giant branch. *Astron. Astrophys. Rev.* **26**, 1 (2018).
4. Freytag, B. & Höfner, S. Global 3D radiation-hydrodynamical models of AGB stars with dust-driven winds. *Astronomy and Astrophysics* **53**, 669 (2023).
5. Höfner, S. Starlight and Sandstorms: Mass Loss Mechanisms on the AGB In: *Why Galaxies Care about AGB Stars II: Shining Examples and Common Inhabitants*, **445**, 193 (2011).
6. Iben, I. & Renzini, A. Asymptotic giant branch evolution and beyond. *Annual Review of Astronomy and Astrophysics* **21**, 83 (1986).
7. Luo, Y. R. Comprehensive handbook of chemical bond energies. CRC Press. (2007).
8. Decin, L. et al. Water content and wind acceleration in the envelope around the oxygen-rich AGB star IK Tauri as seen by Herschel/HIFI, *Astron. Astrophys.* **521**, L4 (2010).

9. Sloan, G. C., Little-Marennin, I. R., & Price, S. D. The carbon-rich dust sequence: infrared spectral classification of carbon stars. *The Astronomical Journal* **115**, 809 (1998).
10. Speck, A.K., Cormann, A.B., Wakeman, K., Wheeler, C.H., & Thompson, G. Silicon carbide absorption features: dust formation in the outflows of extreme carbon stars. *Astrophys. J.* **691** 1202 (2009).
11. Anders, E. & Zinner, E. (1993). Interstellar grains in primitive meteorites: Diamond, silicon carbide, and graphite. *Meteoritics*, 28(4), 490-514.
12. Nittler, L. R. & Ciesla, F. Astrophysics with extraterrestrial materials. *Annual Review of Astronomy and Astrophysics*, **54**, 53 (2016).
13. Gail, H. P. & Sedlmayr, E. Physics and chemistry of circumstellar dust shells. (Cambridge University Press, 2013).
14. Agúndez, M., Martínez, J. I., de Andres, P. L., Cernicharo, J., & Martín-Gago, J. A. Chemical equilibrium in AGB atmospheres: successes, failures, and prospects for small molecules, clusters, and condensates. *Astron. Astrophys.* **637**, A59 (2020).
15. Woitke, P. 2D models for dust-driven AGB star winds. *Astron. Astrophys.* **452**, 537 (2006).
16. Tielens, A. G. G. M. Dust formation in astrophysical environments: the importance of kinetics, *Front. Astron. Space Sci., Sec. Astrochemistry*, **9** (2022).
17. Ebel, D. S. Condensation of rocky material in astrophysical environments. In *Meteorites and the Early Solar System II*, 253 (2006).
18. Tsuchiyama, A., Takahashi, T., & Tachibana, S. Evaporation rates of forsterite in the system  $\text{Mg}_2\text{SiO}_4\text{-H}_2$ . *Mineralogical Journal*, **20**, 113 (1998).
19. Tachibana, S. et al. Kinetic condensation and evaporation of metallic iron and implications for metallic iron dust formation. *Astrophys. J.*, **736**, 16 (2011).
20. Matsuno, J. et al. Condensation of Glass with Multimetal Nanoparticles: Implications for the Formation Process of GEMS Grains. *Astrophys. J.*, **911**, 47 (2021).
21. Kim, T. H. et al. Condensation of cometary silicate dust using an induction thermal plasma system I. Enstatite and CI chondritic composition? *Astron. Astrophys.* **656**, A42 (2021).

22. Nuth III, J. A., Rietmeijer, F. J., & Hill, H. G. Condensation processes in astrophysical environments: The composition and structure of cometary grains. *Meteoritics & Planetary Science*, **37**, 1579 (2002).
23. Toppani, A. et al. A 'dry' condensation origin for circumstellar carbonates. *Nature*, **437**, 1121 (2005).
24. Toppani, A., Libourel, G., Robert, F., & Ghanbaja, J. Laboratory condensation of refractory dust in protosolar and circumstellar conditions. *Geochim. Cosmochim. Acta*, **70**, 5035 (2006).
25. Kimura, Y. Tanaka, K. K., Inatomi, Y., Aktas, C. & Blum, J. Nucleation experiments on a titanium-carbon system imply nonclassical formation of presolar grains, *Science Adv.* **9**, eadd8295 (2023).
26. Gautier, M., Rohani, V., & Fulcheri, L. Direct decarbonization of methane by thermal plasma for the production of hydrogen and high value-added carbon black, *International Journal of Hydrogen Energy*, **42**, 28140 (2017).
27. Lodders, K. & Fegley, Jr. B. The origin of circumstellar silicon carbide grains found in meteorites, *Meteoritics*, **30**, 661 (1995).
28. Ebel, D. S. Variations on solar condensation: Sources of interstellar dust nuclei, *J. Geophys. Res.*, **105**, 10363 (2000).
29. Gobrecht, D. et al. Nucleation of Small Silicon Carbide Dust Clusters in AGB Stars, *Astrophys. J.* **840**, 117 (2017)
30. Boulangier, J., Gobrecht, D., Decin, L., de Koter, A., & Yates, J. Developing a self-consistent AGB wind model: II. Non-classical, non-equilibrium polymer nucleation in a chemical mixture, *Monthly Notices of the Royal Astronomical Society*, **489**, 4890 (2019).
31. Yoshikawa, T., Kawanishi, S., & Tanaka, T. Solution growth of silicon carbide using Fe–Si solvent. *Jpn. J. Appl. Phys.*, **49**, 051302 (2010).
32. Namur, O., Collinet, M., Charlier, B., Grove, T. L., Holtz, F., & McCammon, C. Melting processes and mantle sources of lavas on Mercury, *Earth Planet. Sci. Lett.*, **439**, 117 (2016).
33. Asplund, M., Grevesse, N., Jacques Sauval, A., & Scott, P. The chemical composition of the Sun. *Annual Review of Astronomy and Astrophysics*, **47**, 481 (2009).
34. Ferrarotti, A. S. & Gail, H.-P. Mineral formation in stellar winds III. Dust formation in S stars, *Astron. Astrophys.*, **382**, 256 (2002).

35. Karakas, A.I. & Lattanzio, J.C. The Dawes Review 2: Nucleosynthesis and Stellar Yields of Low- and Intermediate-Mass Single Stars. *Publications of the Astronomical Society of Australia* **31**, e030, 62 (2014).
36. Deutsch, A. J. The circumstellar envelope of alpha herculis. *Astrophys. J.*, **123**, 210 (1956).
37. Sedlmayr, E. & Dominik, C. Dust Driven Winds. *Space Science Reviews*, 73, 211 (1995)
38. Höfner, S. Winds of M-type AGB stars driven by micron-sized grains, *Astron. Astrophys.*, **491**, L1-L4 (2008).
39. Bladh, S. & Höfner, S. Exploring wind-driving dust species in cool luminous giants - I. Basic criteria and dynamical models of M-type AGB stars, *Astron. Astrophys.*, **546**, A76 (2012).
40. Lamers, H., & Cassinelli, J. Introduction to Stellar Winds. Cambridge: Cambridge University Press. (2012).
41. Gail, H. in *Astromineralogy*, edited by T. K. Henning, Lecture Notes in Physics (Berlin: Springer), **609**, 55 (2003).
42. Ferrarotti, A., Gail, H. -P., Degiorgi, L., Ott, H. R. FeSi as a possible new circumstellar dust component, *Astronomy and Astrophysics*, **357**, L13-L16 (2000).
43. Speck, A. K., Cormann, A. B., Wakeman, K., Wheeler, C. H., & Thompson, G. Silicon carbide absorption features: dust formation in the outflows of extreme carbon stars. *Astrophys. J.*, **691**, 1202 (2009).
44. De Beck, E., & Olofsson, H. The surprisingly carbon-rich environment of the S-type star W Aql. *Astron. Astrophys.*, **642**, A20 (2020).
45. Volk, K., Sloan, G. C., & Kraemer, K. E. The 21  $\mu\text{m}$  and 30  $\mu\text{m}$  emission features in carbon-rich objects. *Astrophysics and Space Science*, **365**, 1 (2020).
46. Sloan, G. C. et al. Carbon-rich dust past the asymptotic giant branch: aliphatics, aromatics, and fullerenes in the magellanic clouds. *Astrophys. J.*, **791**, 28 (2014).
47. Marini, E., Dell'Agli, F., Groenewegen, M. A. T., García-Hernández, D. A., Mattsson, L., Kamath, D., Ventura, P., D'Antona, F. & Tailo, M. (2021). Understanding the evolution and dust formation of carbon stars in the Large Magellanic Cloud via the JWST *Astron. Astrophys.*, **647**, A69.
48. Amari, S., Zinner, E., & Gallino, R. Presolar graphite from the Murchison meteorite: An isotopic study. *Geochim. Cosmochim. Acta*, **133**, 479 (2014).
49. Wopenka, B., Yu, X. C., Zinner, E., & Amari, S. Murchison presolar carbon grains of different density fractions: A Raman spectroscopic perspective. *Geochim. Cosmochim. Acta*, **106**, 463 (2013).

50. Bernatowicz, T. J., Amari, S., Zinner, E. K., & Lewis, R. S. Interstellar grains within interstellar grains. *Astrophys. J.*, **373**, L73 (1991).
51. Bernatowicz, T. J., Amari, S., & Lewis, R. S. Refractory carbides in interstellar graphite. In *Lunar and Planetary Science Conference*, **25**, 103 (1994).
52. Bernatowicz, T. J., Cowsik, R., Gibbons, P. R., Lodders, K., Fegley, B., Amari, S., & Lewis, R. S. (1996). Constraints on Stellar Grain Formation from Presolar Graphite in the Murchison Meteorite. *Astrophys. J.*, **472**, 760 (1996)
53. Singerling, S. A., Liu, N., Nittler, L. R., Alexander, C. O. D., & Stroud, R. M. TEM analyses of unusual presolar silicon carbide: Insights into the range of circumstellar dust condensation conditions. *Astrophys. J.*, **913**(2), 90 (2021).
54. Nittler, L. R. Presolar stardust in meteorites: recent advances and scientific frontiers. *Earth Planet. Sci. Lett.*, **209**, 259 (2003).
55. Croat, T. K., Bernatowicz, T. J., & Jadhav, M. (2014, September). Isotopic Anomalies Preserved Within Internal Grains in High-Density Presolar Graphites. In *77th Annual Meeting of the Meteoritical Society* (Vol. 77, No. 1800, p. 5354).
56. Hynes, K. M., Croat, T. K., Amari, S., Mertz, A. F. & Bernatowicz, T. J., Structural and isotopic microanalysis of presolar SiC from supernovae. *Meteoritics*, **45**, 596 (2010).
57. Gyngard, F., Amari, S., Zinner, E., & Marhas, K. K. (2018). Correlated silicon and titanium isotopic compositions of presolar SiC grains from the Murchison CM2 chondrite. *Geochim. Cosmochim. Acta*, **221**, 145 (2018).
58. Kodolányi, J., Vollmer, C., Hoppe, P., & Müller, M. Structural Investigation of Silicon Carbide X Grains: Constraints on Condensation in Supernova Ejecta. *Astrophys. J.*, **868**(1), 34 (2018).
59. Decin, L., Montarges, M., Richards, A. M. S., Gottlieb, C. A., et al. (Sub-)stellar companions shape the winds of evolved stars. *Science*, **369**, 1497 (2020).
60. Bale, C.W., Belisle, E., Chartrand, P., Decterov, S.A., Eriksson, G., Gheribi, A.E., Hack, K., Jung, I.H., Kang, Y.B., Melançon, J., Pelton, A.D., Petersen, S., Robelin, C., Sangster, J., Spencer, P., Van Ende, M.A. FactSage thermochemical software and databases, 2010-2016. *Calphad: Computer Coupl. Phase Diagrams Thermochem.* **54**, 35 (2016).
61. Alexander, C. O. D. Chemical equilibrium and kinetic constraints for chondrule and CAI formation conditions. *Geochim. Cosmochim. Acta*, **68**, 3943 (2004).



62. Nagahara, H., Ozawa, K., & Tomomura, S. Kinetic condensation of silicate melt and its role in the chemical diversity of chondrules. In *Chondrites and the Protoplanetary Disk*, **341**, 456 (2005).
63. Richter, F. M., Davis, A. M., Ebel, D. S. & Hashimoto, A. Elemental and isotopic fractionation of Type B calcium-, aluminum-rich inclusions: Experiments, theoretical considerations, and constraints on their thermal evolution, *Geochim. Cosmochim. Acta*, **66**, 521 (2002).
64. Fedkin, A. V., Grossman, L., & Ghiorso, M. S. Vapor pressures and evaporation coefficients for melts of ferromagnesian chondrule-like compositions, *Geochim. Cosmochim. Acta*, **70**, 206 (2006).
65. Zeidler, S., Posch, T., Mutschke, H., Richter, H., & Wehrhan O. Near-infrared absorption properties of oxygen-rich stardust analogues: The influence of colouring metal ions, *Astron. Astrophys.*, **526**, A68 (2011).
66. Udono, H., Kikuma, I., Okuno, T., Masumoto, Y., Tajima, H., & Komuro, S. Optical properties of h-FeSi<sub>2</sub> single crystals grown from solutions. *Thin Solid Films*, 461, 182 (2004).
67. O'Donnell, K. P. & Chen, X. Temperature dependence of semiconductor band gaps, *Appl. Phys. Lett.*, **58**, 2924 (1991).
68. Paschen, S., Felder, E., Chernikov, M. A., Degiorgi, L., Schwer, H., Ott, H. R., Young, D. P., Sarrao, J. L. & Fisk, Z. Low-temperature transport, thermodynamic, and optical properties of FeSi, *Phys. Rev.*, **B 56**, 12916 (1997).
69. Zeidler, S., Posch, T., Mutschke, H., Richter, H., & Wehrhan, O. Near-infrared absorption properties of oxygen-rich stardust analogues: The influence of colouring metal ions, *Astron. Astrophys.*, **526**, A68 (2011).
70. Shaukat, A., Saeed, Y., Ikram, N., & Akbarzadeh H. First principles calculations of structural, electronic and optical properties of various phases of CaS. *Eur. Phys. J.*, **B 62**, 439 (2009).
71. Kim, W., Mesbah, A., Deschanel, X., Bernard, S., & Lebegue, S. First principles investigations of the optical selectivity of titanium carbide-based materials for concentrating solar power applications. *Journal of Materials Chemistry C*, **9 (24)**, 7591 (2021).

72. Jones, D. J., French, R. H., Müllejans, H., Loughin, S., Dorneich, A. D. & Carcia, P. F. Optical properties of AlN determined by vacuum ultraviolet spectroscopy and spectroscopic ellipsometry data. *J. Mater. Res.*, **14**, 4337 (1999).
73. Lamers, H., & Cassinelli, J. Introduction to Stellar Winds. Cambridge: Cambridge University Press (1999).
74. Lewis, J. S. Physics and chemistry of the Solar System, *Academic Press*, 556 pp (1995).
75. Chase, M. W. Jr., NIST-JANAF Thermochemical Tables, Fourth Edition, *J. Phys. Chem. Ref. Data*, **9**, 1951 pp (1998).
76. Papoular, R. J., & Papoular, R. Some optical properties of graphite from IR to millimetric wavelengths. *Monthly Notices of the Royal Astronomical Society*, **443**, 2974-2982 (2014).
77. Pégourié, B. Optical properties of alpha silicon carbide. *Astron. Astrophys.*, **194**, 335-339, (1988).
78. Jäger, C., Dorschner, J., Mutschke, H., Posch, T., & Henning, T. Steps toward interstellar silicate mineralogy-VII. Spectral properties and crystallization behaviour of magnesium silicates produced by the sol-gel method. *Astron. Astrophys.*, **408**, 193-204 (2003).
79. Alao, A. A., Wu, W. N., & Hsu, W. D. Sticking coefficient and Si/C ratio of silicon carbide growth species on reconstructed 4H- SiC (0001<sup>-</sup>) surface by ab-initio calculations. *Vacuum*, **205**, 111414 (2022).

## Extended data

### Extended Data Table 1 Chemical Composition:

Chemical compositions in wt % of the chondrite starting material and of the bulk composition of sampled condensates shown in Extended Data Fig. 1.

Chemistry			Si	Al	Fe	Mn	Mg	Ca	Na	K	Ti	P	O	C	S
NWA 869 chondrite bulk composition			19.28	1.20	19.01	0.28	15.24	1.54	0.69	0.10	0.07	0.11	43.28	0.12	2.38
Det. Limit			0.02	0.02	0.01	0.01	0.02	0.02	0.01	0.02	0.01	0.04			
Calculated average temperature* in K	# sample from top of T-rod	Depth of sampling in mm													
2308	#14	0-50	24.95	0.16	42.81	0.02	0.03	0.09	< d.l.	< d.l.	0.14	< d.l.		26.28 ^	0.04
2142	#13	50-100	26.59	0.24	44.40	0.02	< d.l.	0.07	< d.l.	< d.l.	0.14	< d.l.		23.55 ^	0.04
2042	#12	100-150	31.61	0.79	57.07	0.12	< d.l.	0.06	< d.l.	< d.l.	0.25	< d.l.		2.59 ^	0.02
1949	#11	150-200	14.43	1.99	30.40	0.11	0.33	1.44	< d.l.	< d.l.	0.07	0.11		43.59 ^	0.43
1833	#10	200-250	13.70	1.24	18.18	0.13	8.46	1.68	< d.l.	< d.l.	0.04	0.13		38.37 ^	0.04
1741	#9	250-300	23.37	1.42	20.31	0.30	18.92	1.86	< d.l.	< d.l.	0.04	0.21		0.40	0.33
1685	#8	300-350	22.67	1.10	14.62	0.36	22.27	1.49	< d.l.	< d.l.	0.03	0.21		1.34	3.42
1615	#7	350-400	18.74	0.84	11.01	0.34	22.76	1.16	< d.l.	< d.l.	0.02	0.18		6.59	3.50
1556	#6	400-450	15.97	0.72	8.82	0.35	22.12	1.00	< d.l.	< d.l.	0.02	0.16		8.78	3.06
1502	#5	450-500	15.38	0.70	8.09	0.39	22.05	0.98	< d.l.	< d.l.	0.02	0.15		10.06	3.08
1453	#4	500-550	15.64	0.70	7.76	0.45	22.57	0.99	< d.l.	< d.l.	0.02	0.15		10.74	3.11
1395	#3	550-600	15.88	0.71	7.74	0.51	24.32	1.01	0.02	< d.l.	0.02	0.14		10.24	3.08
1389	#2	600-650	16.36	0.73	7.87	0.52	24.81	1.05	0.03	< d.l.	0.02	0.15		9.08	3.35
1365	#1	650-700	-	-	-	-	-	-	-	-	-	-		8.23	3.08

\* Temperature calculated using the ANSYS Fluent computational fluid dynamics software (see methods).

^ Carbon contamination of samples stuck to the carbon T-rod during sampling

## Extended Data Table 2 Mineralogy:

Mineralogy of the condensates sampled on the T-shape graphite rod holder as determined by Scanning Electron Microscopy and X-Ray diffraction.

Mineralogy			C	FeSi	SiC	TiC	Al <sub>2</sub> SiC <sub>4</sub>	CaS	MgS	AlN	TiN	Si-glass	MgAl <sub>2</sub> O <sub>4</sub>	Mg <sub>2</sub> SiO <sub>4</sub>	MgO	MgSiO <sub>3</sub>	Notes
Calculated average temperature* in K	# sample from top of T-rod	Depth of sampling in mm															
2308	#14	0-50	-	✓	✓-6H	✓	✓										
2142	#13	50-100	-	✓	✓-6H												
2042	#12	100-150	-	✓	✓-6H			✓		✓		✓ (Al-rich)					
1949	#11	150-200	-	✓	✓-6H			✓		✓	✓	✓		✓			
1833	#10	200-250	-	✓	✓-6H							✓	✓				
1741	#9	250-300	✓	✓								✓		✓			
1685	#8	300-350	✓	✓				✓	✓			✓		✓	✓		(✓)
1615	#7	350-400	✓	✓								✓		✓	✓		
1556	#6	400-450	✓	✓								✓		✓	✓		
1502	#5	450-500	✓	✓								✓		✓	✓		
1453	#4	500-550	✓	✓								✓		✓	✓		
1395	#3	550-600	✓	✓								✓		✓	✓		
1389	#2	600-650	✓	✓								✓		✓	✓		
1365	#1	650-700	✓	✓								✓		✓	✓		

**Extended Data Table 3 Bulk Chemistry:** Bulk composition of the starting material and values of condensation factors used in the modeling. The composition of the experiment corresponds to a C/O of 0.93 and calculated considering that 600 g of NWA869 ordinary chondrite were introduced with 4 Nm<sup>3</sup> of Ar and 2Nm<sup>3</sup> of H<sub>2</sub>.

<u>Element</u>	mass (g)	Phase	<i>f</i> %
Fe	111.5	<u>FeSi</u>	8
Mn	1.617		
Ti	0.390	<u>SiC</u>	3
Ca	9.045		
K	0.575	<u>AlN</u>	5
Ar	7132	<u>CaS</u>	2
S	13.96		
P	0.648	Silicate <u>melt</u>	4
Si	113.1	Aluminates	2
Al	7.061		
Mg	89.41	Olivine	8
Na	4.061		
O	248.63	MgO	5
N	150	<u>TiC</u>	5
C	173.58		
H	179.94	Graphite	8

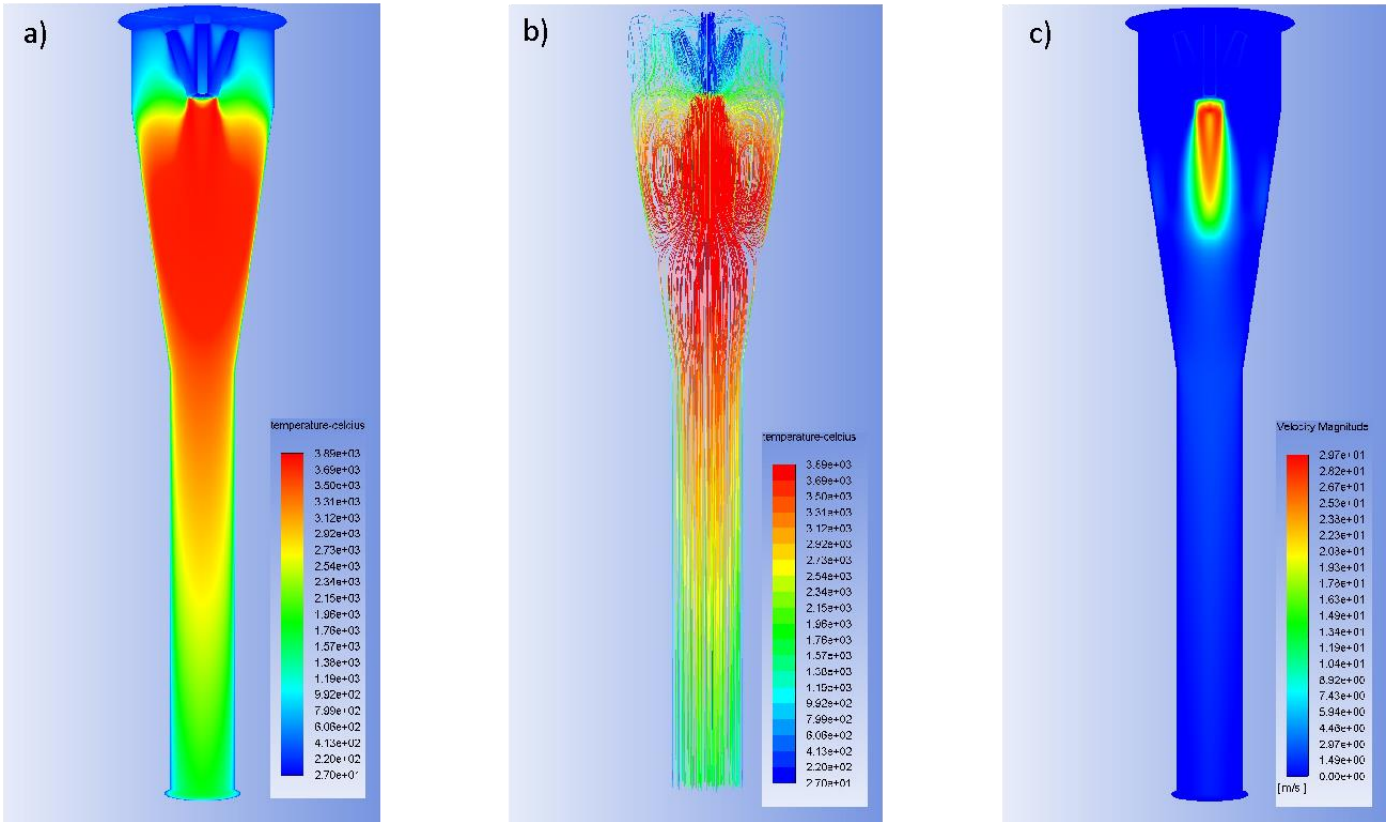


**Extended Data Table 4 Optical Parameter:** Optical parameter  $p$  of various mineral phases.

<b>Phase</b>	<b><math>p</math></b>	<b>Reference</b>
Graphite	2.0	76
SiC	0.3	77
TiC	0.8	71
FeSi	2.2	68
AlN	-0.35	72
CaS	0.82	70
Mg <sub>2</sub> SiO <sub>4</sub>	-0.9	78
MgSiO <sub>3</sub>	-0.5	39

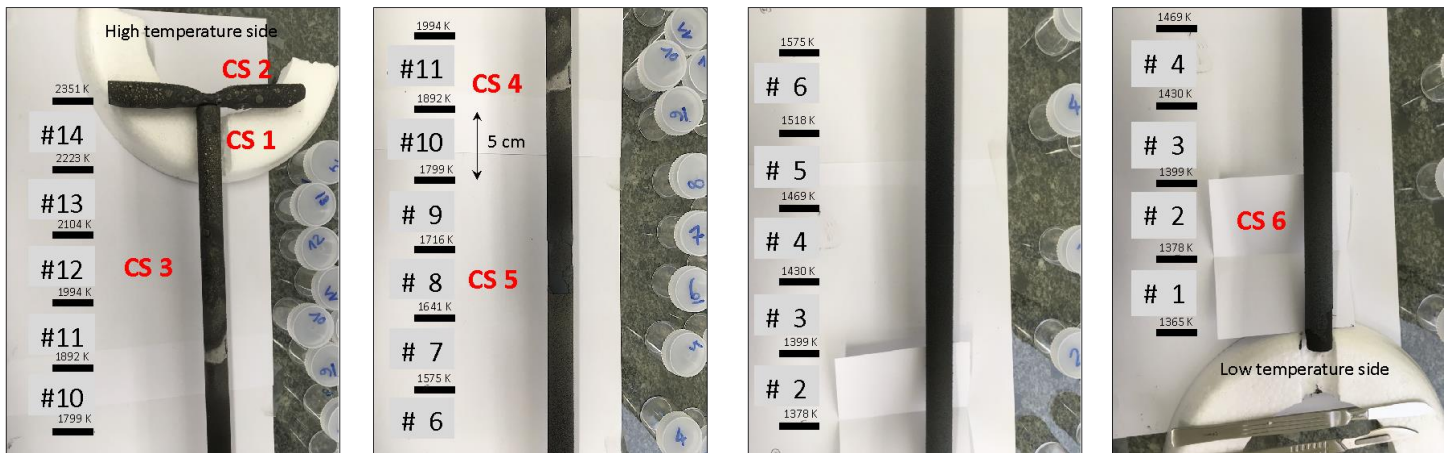
### Extended Data Fig. 1 2D Thermal Regime.

The 2D thermal regime (a) inside the chamber as well as the trajectory (b) and velocity of fictive particles (c) have been obtained using the ANSYS Fluent computational fluid dynamics software (see Methods).



### Extended Data Fig. 2 Samples.

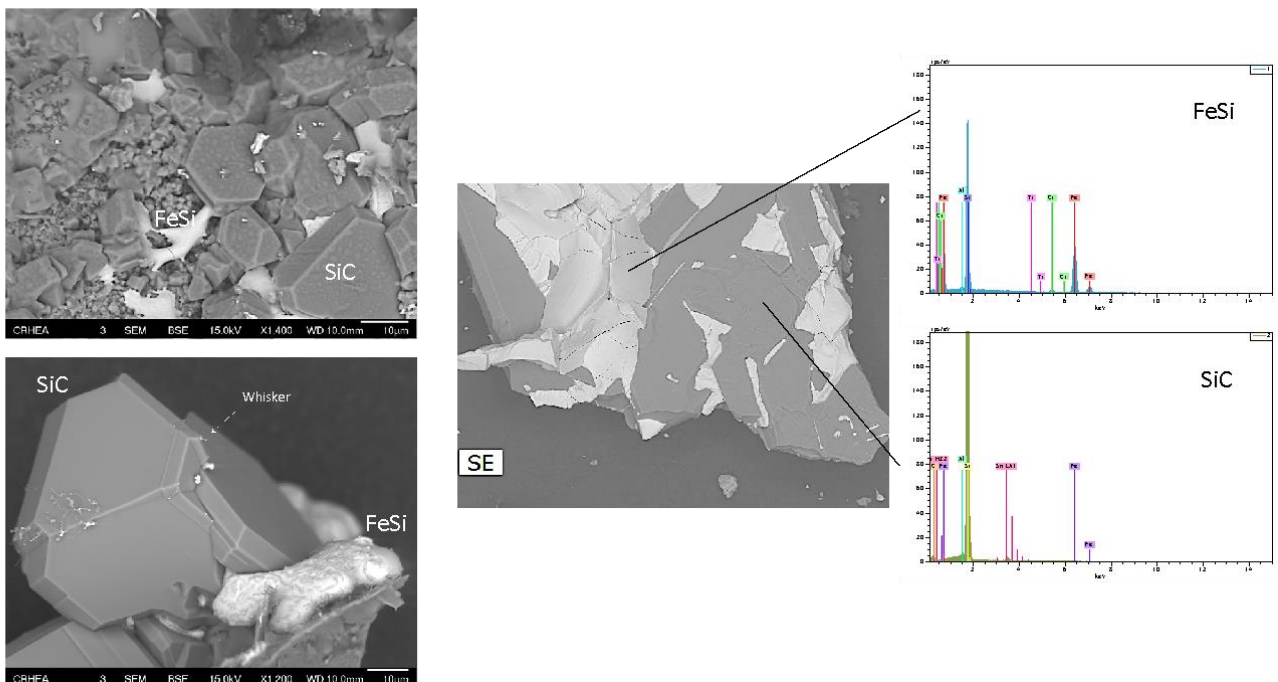
Photograph of the graphite rod sample holder after the experiment that collected the condensates. As shown, 14 segments of 5 cm each have been sampled for bulk chemical analysis. CS1-CS6 correspond to sampling for detailed mineralogy depicted in Extended Data Fig. 3. See the chemistry and mineralogy of the condensates in Extended Data Table 1 and Table 2, respectively.



### Extended Data Fig. 3 Further Mineralogy.

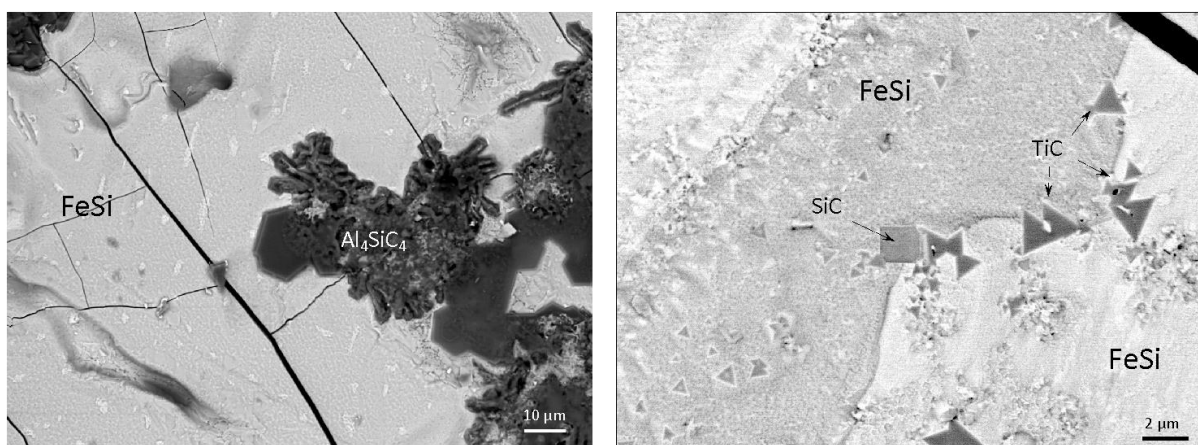
Further mineralogical and chemical characterization of condensed phases sampled on the graphite T-rod sample holder with location indicated on Extended Data Fig. 3. All images and analyses by scanning electron microscopy (SEM) and energy dispersive X-ray (EDX) analysis, unless specified.

CS1 and CS2 (#14)



Notice in the highest temperature condensates the abundance of crystallized hexagonal SiC bathed in an iron silicide liquid, now crystallized in a mixture of naquite (FeSi), hapkeite (Fe<sub>2</sub>Si) and possibly xifengite (Fe<sub>5</sub>Si<sub>3</sub>).

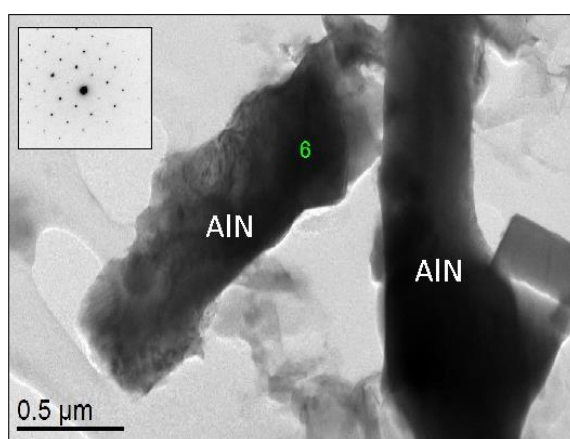
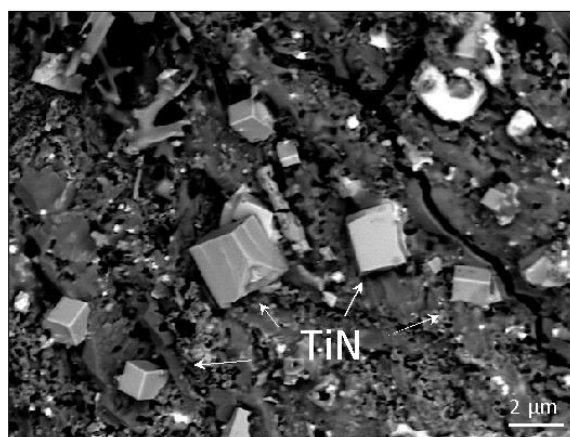
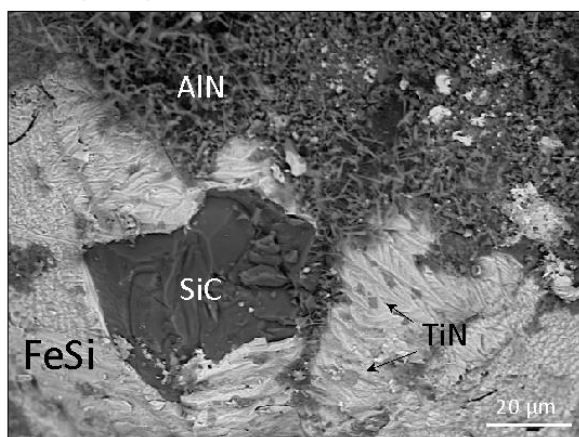
CS1 and CS2 (#14)



Titanium (TiC) and aluminum (Al<sub>4</sub>SiC<sub>4</sub>) carbides are also present in close association with the iron silicides.

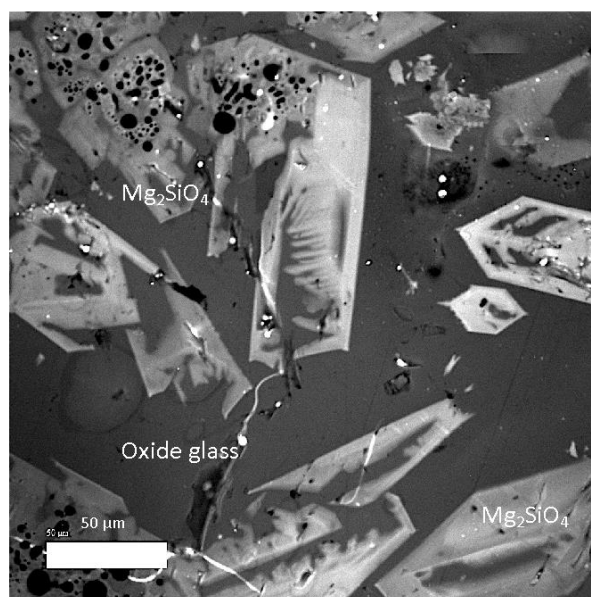
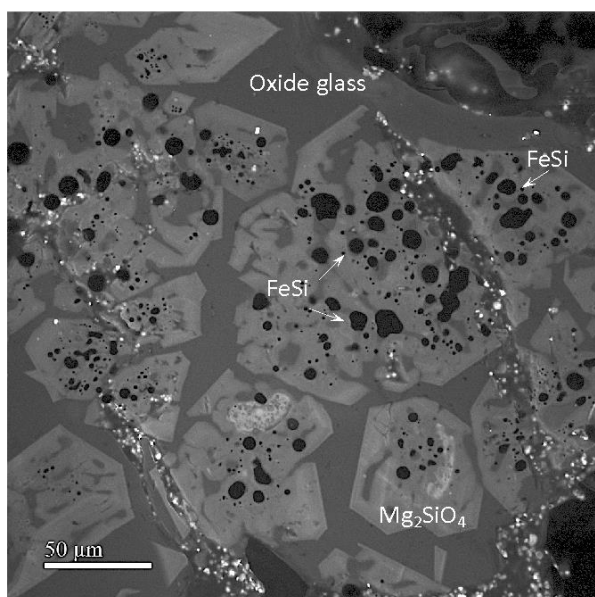


CS4 (#11)



Intermediate condensates contain aluminum (AlN) and titanium (TiN) nitrides. Notice the remarkable 1-D whisker of AlN formed by a FeSi catalyst-assisted VLS (vapor-liquid-solid) growth process. All 3 first images by SEM, excepted the bottom one right which corresponds to transmission electron microscopy (TEM) analysis and the obtained diffraction pattern of AlN.

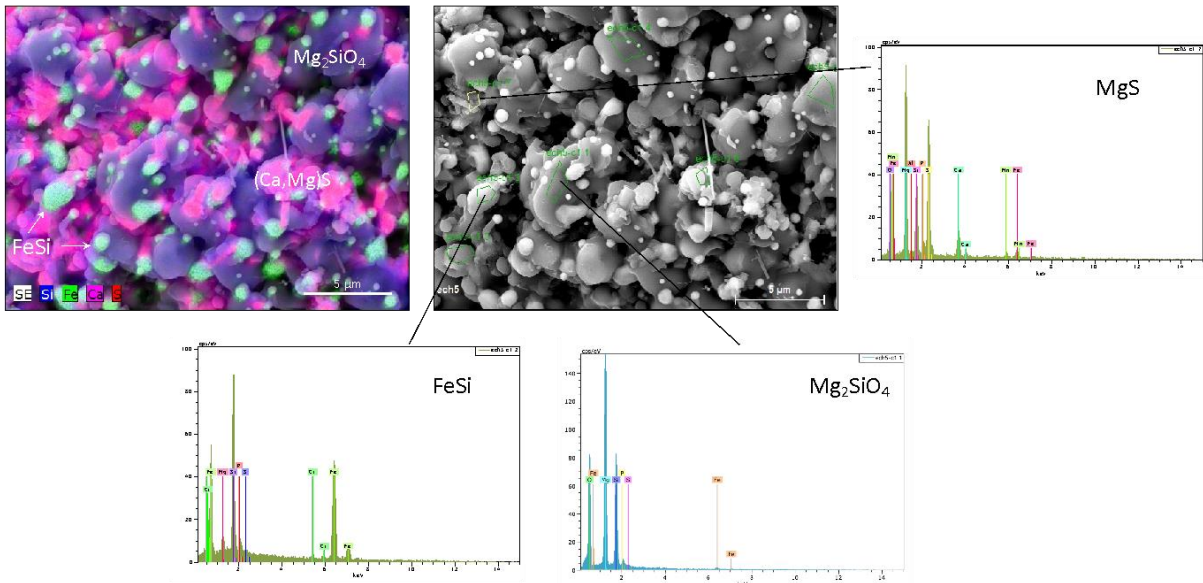
CS4 (#11)



Between 2000-1900 K  $Mg_2SiO_4$  starts to crystallize from the melt (now glassy and enriched in MgO and  $SiO_2$ ) in close association with FeSi (black beads). Panchromatic images obtained by high resolution cathodoluminescence.

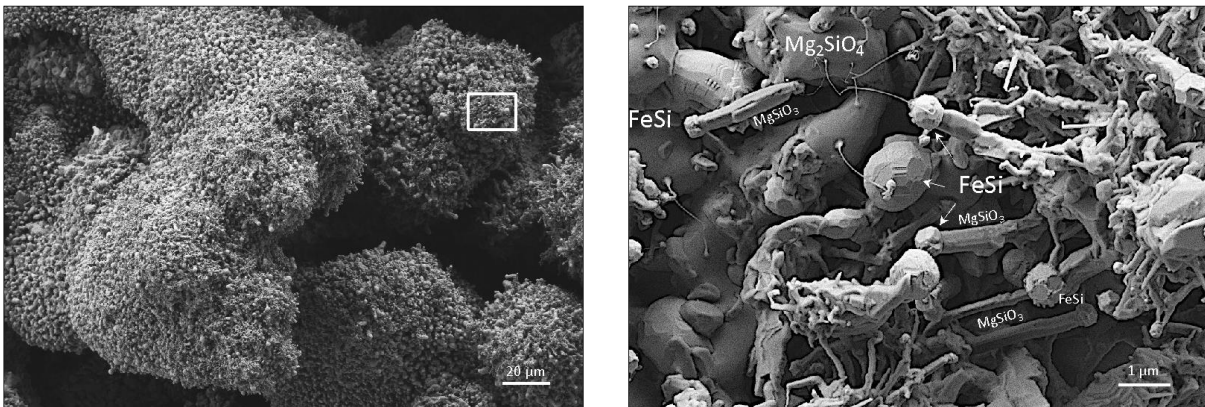


CS5 (#8)



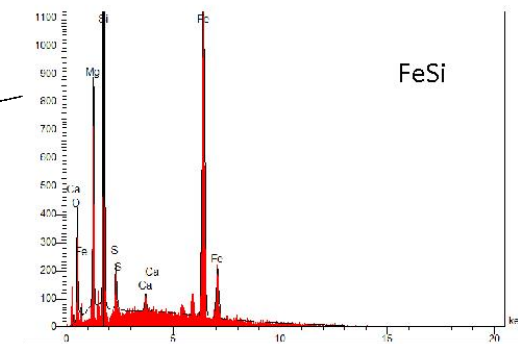
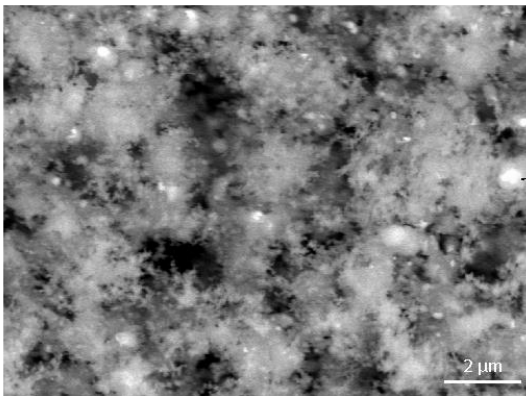
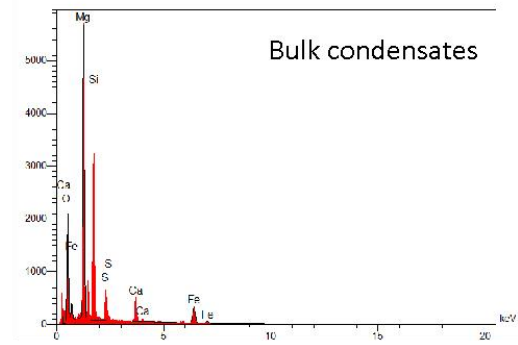
Below a temperature range of 1850-1800 K, carbides are no longer detectable, and olivine, FeSi and sulfides (Ca,Mg)S and graphite are frequently observed..

CS5 (#8)



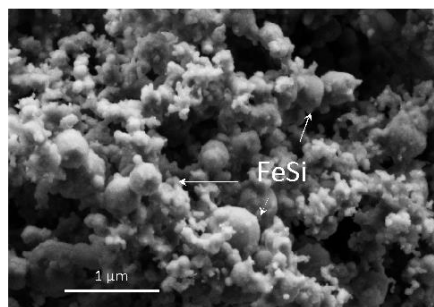
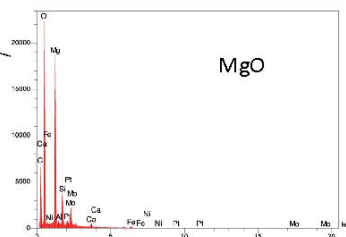
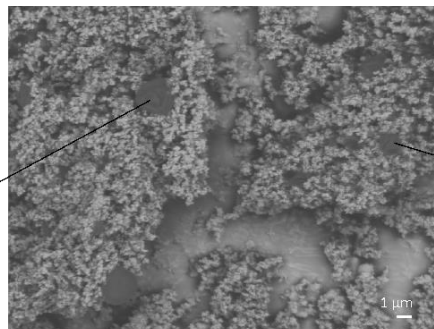
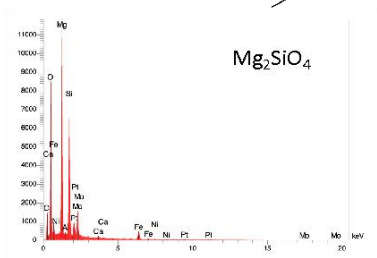
Below 1800K, the average size of condensed phases becomes micron-sized. Remarkable whiskers of enstatite are present.

CS6 (#2)



The lowest condensates on the T-shape graphite holder becomes very fine grains more difficult to identify by SEM. A bulk analysis by EDX of a few  $\mu\text{m}^2$  of condensates reveals a composition similar to that obtained by ICP-MS on a larger sample (Fig.4).

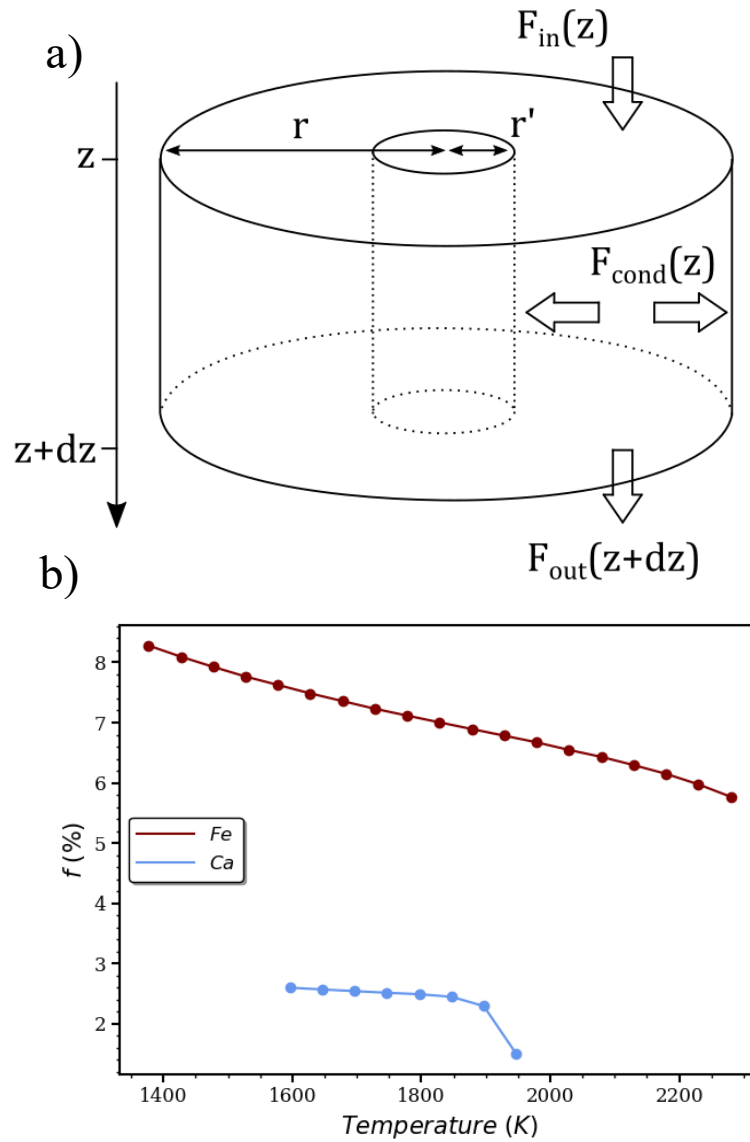
CS6 (#2)



In these range of temperature circa 1400 K, the mineralogy is dominated by magnesian silicates (olivine and pyroxene), sulfides, oxides (MgO), with graphite and silicides ( $\text{Fe/Si} \approx 2$ ).

### Extended Data Fig. 4 Kinetic Model.

Schematic view of the kinetic model. a) The internal cylinder is the graphite rod. The total surface of evaporation corresponds to the graphite rod and the chamber's sides. b) Condensation factor of Ca (red) and Fe (blue). For temperatures higher than 1750 K, Ca partitions only in the oxide melt, then in oxide melt and CaS



### Extended Data Fig. 5 FeSi Growth Timescale.

Calculated timescales of FeSi growth (red) and stellar outflow (blue) as a function of the distance of the star (normalized to star radius  $R^*$ ). Red curves are for Si growth for grains with a size labeled on the curve. Assuming a larger grain diameter would lead to longer timescales. Sticking coefficient of  $\text{Si}_{(g)}$  is taken from ref.<sup>79</sup>.

