Chemistry and Thermodynamics of the Nucleation in R CrB star shells

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Abstract. The chemistry of the nucleation process for R CrB stars is investigated and the chemical pathway to large carbon clusters is outlined for hydrogen poor and one hydrogen rich R CrB star. Based on the chemistry, the thermodynamical conditions of effective dust formation are discussed. Finally the dilemma between the requirement of a low condensation temperature of about 1 500 K and the empirical evidence for dust formation very close to the hot photospheres has been examined.

1. Introduction

For a variable hydrogen deficient star, the crucial characteristic to be classified as an R CrB star is the appearance of the remarkable R CrB-type declines, which are typical like a fingerprint. The uniqueness and distinctiveness of this type of extreme variability immediately convinces that those declines must be produced by *one* uniform physical process. Besides this uniting feature, most of the physical properties of the members of this very small class of objects show an astonishing broad variety. Especially the effective temperatures within a range from 4 000 K to 20 000 K seem to set us riddles in view of the unwavering occurrence of the same type of declines.

With this background, it is obvious that "the most significant problem with respect to R CrB stars is to understand the physics and chemistry of the decline phase", as Peter Cottrell claimed at the beginning of this conference. Consequently, since the publication of the first model in the thirties (Loreta 1934, O'Keefe 1939), much effort has been made to elucidate the decline process of the R CrB stars. But – in spite of a large number of phenomenological and semi-quantitative models which have been proposed during the last three decades – reduced to a common denominator, our *reliable* knowledge of the decline process has only made marginal progress since O'Keefe: R CrB's still play their tricks with us, and we wonder what's going on.

The possibly most serious controversy in this context is the question after the *distance* of the obscuring material from the stellar photosphere, which corresponds to the question after its *origin*. Nearly all recent models agree with the basic idea of the Loreta/O'Keefe-model of carbon dust, condensing from time to time from the gas phase, which causes the occultations: All R CrB stars show an at least slight carbon overabundance, and the extinction of the dust corresponds to some kind of solid carbon. The only exception from this picture is represented by a binary model (Humphreys & Ney 1974), which proposes formation of dust in the vicinity of the secondary, so that the existence of the obscuring material is independent from the thermodynamic conditions in the envelope of the primary. Since this model has the same two difficulties like all binary and "orbiting clouds"-scenarios, which are the significant asymmetry of the lightcurves of most declines and the absence of any evidence of a secondary, we here ignore this possibility. If we accept the formation of fresh carbon dust from the gas phase at the beginning of a decline event, the thermodynamical conditions of the decline process are clearly based on the chemistry of carbon condensation. This statement holds irrespective of the controversy of different geometries of the dust shell (e.g. toroidal formation) or the ideas of occultation by preexisting dust.

For this reason, in this paper we will have a closer look at the chemistry in the envelope of an R CrB star. Based on some arguments from nucleation theory, we will discuss the scope of thermodynamical conditions which are the stage for those processes which cause the decline events. The results will provide a basis for the following controversial discussion of the distances from the photosphere, where carbon condensation may occur.

2. Carbon Chemistry

The initial condition of the condensation process in the envelopes of R CrB stars, which is a gas (resp. cold plasma) with the typical chemical composition in those stars, is characterized by two peculiarities:

- The envelope is more or less hydrogen deficient, typically the hydrogen abundance falls below the carbon abundance by some orders of magnitude, but at least by a factor of two. There is one remarkable exception from this rule, V 854 Cen, but also for this star helium is the most abundant element (Rao 1995).

- All R CrB stars are carbon overabundant, whereby the C/O ratios show a rather broad variety of close to 1 to about 10. Here, one exception also seems to exist (V CrA), which we have to comment later on.

Besides these characteristics, the abundances of the other elements apparently do not show any R CrB specific behavior. We here only have to consider the nitrogen abundance, which never significantly exceeds the carbon abundance, and the fact that all other metals are at least one order of magnitude less abundant than carbon.

On the other hand, the output of the condensation process is well-known to be some type of pure carbon solid with a microscopic structure still under discussion. To understand the thermodynamics of the formation of this solid material, we need some qualitative ideas about the species and chemical processes in between. For our purpose, those species are of interest, which are chemical reactive and possibly a part of the nucleation chemistry. In the situation drawn above, the first molecule which forms is the CO molecule. Since any other species containing oxygen is much less stable, the oxygen is nearly completely blocked within CO, which is neither reactive (in an oxygen-free surrounding) nor condensable. The next molecule which forms is N_2[1], which also is inert and unable to condense (at the temperatures in question). The remaining nitrogen mostly forms CN, which in any case is significantly less abundant than the remaining carbon itself. These CN groups are reactive enough to participate in the nucleation process, but as a kind of dead end like CH groups, because only the carbon atom has a reactive electron. Thus, except for V 854 Cen, where hydrogen is more abundant than carbon, the sequence of species according to their abundance is

$$\mathrm{He} - (\mathrm{C}_n,\ \mathrm{CO}) - \mathrm{N}_2 - (\mathrm{CN},\ \mathrm{C_2N_2},\ \mathrm{C_2N},\ \mathrm{HCN},\ \mathrm{CNO},\ \mathrm{C_2H},\ \mathrm{C_2H_2},\ \mathrm{CH}) - \\ (\mathrm{CS},\ \mathrm{SiS},\ \mathrm{SiC_2},\ \mathrm{Si_2C},\ \mathrm{SiO}).$$

Thus, the typical R CrB-situation roughly is a chemistry of pure carbon condensation surrounded by an inert gas of helium with some contamination by CO and N_2. The traces of different CN or CH type groups can be neglected, so far we are interested in the thermodynamics of the general nucleation process (although they might be very important for spectroscopy).

Fortunately, in laboratory such a type of chemistry is well-known since the detection of the fullerene-synthesis (Krätschmer et al. 1990). Although the theoretical understanding of this condensation process is still controversial and the scaling of the results according to astrophysical situations is uncertain, it is possible to draw a picture of the chemical processes in R CrB stars which is qualitatively reliable.

The carbon species which are present in such a situation roughly can be classified into three groups (see Fig. 1):

- *Linear unbranched chains:* The smallest pure carbon clusters are linear chains of polyyne type for even numbers and cumulene type for odd numbers n of carbon atoms. For long chains ($n > 6$) the cumulene type becomes more favorable, because (1) the relative amount of energy for the two additional terminal radical sites decreases and (2) the resonance stabilization by delocalization of the π-electrons increases for cumulenes with increasing chain size. Thus, the longer chains are all of cumulene type. There is experimental evidence for chains up to a size of $n \approx 20$ (Broyer et al. 1992).

- *Monocyclic rings:* For long chains, the energy gain of saturating the terminal radical sites by ring closure exceeds the energy loss by bending the chain to a ring. Those rings are much less reactive than a chain, because any reaction requires the opening of one π-bond. As a consequence of the shell structure of the molecular orbits, monocyclic rings with $n = 4i + 2\,, i = 1, 2, 3\ldots$ electrons are significantly more stable than others. The minimum size, where monocyclic rings are predominant, is $n = 10$. In molecular beams monocyclic rings have been identified up to $n = 46$ (Hunter et al. 1993).

[1]This statement at least holds in an equilibrium chemistry. The detailed formation process of N_2 is still unknown.

- *Polycyclic aromatic carbon clusters (PACs):* Above a critical size, the energy gain by forming a hexagonal carbon framework exceeds the expense of energy for the phenyl type radical sites, which characterize the edge atoms of PACs. The energy gain originates in the delocalization energy of the sextett of π-electrons within each hexagon of the framework, an effect which is called "aromaticity". For the same reasons as for monocyclic rings, structures with $n = 4i + 2$ atoms (= delocalized π-electrons) are more stable than $n = 4i$-types, whereas structures with odd numbers of π-electrons (atoms) spontaneously stabilize by separation of one or three C-atoms. To minimize the number of "expensive" radical sites, the PACs reduce their number of edge atoms by introducing pentagons within the framework, thus curving the whole structure like a bowl. The minimum size of such PACs and the degree of curvature for PACs of a particular size are controversial up to now, because the data for theoretical calculations are rather uncertain.

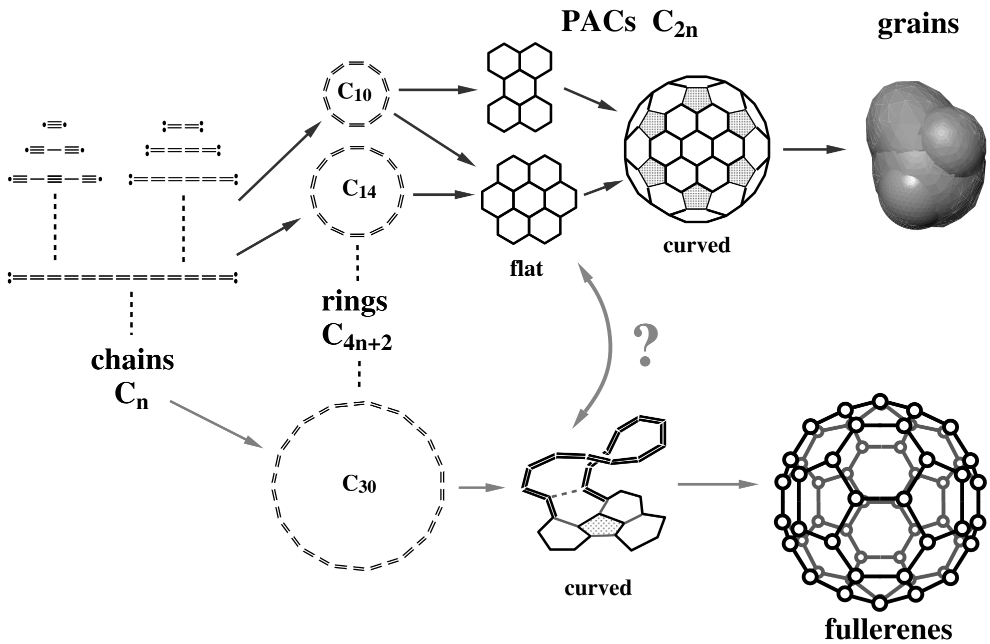

Figure 1. The chemistry of carbon nucleation in R CrB star envelopes. Carbon clusters are represented by their σ- and localized π-bonds alone. Atoms, unpaired (radical) electrons and aromatic π-electrons are omitted. The structures can be classified into three distinct types: I) linear chains, II) monocyclic rings and III) polycyclic aromatic carbon clusters (PACs). For details see text.

The process of condensation, according to this chemistry, occurs by the following steps: At higher temperatures, short chains (especially the C_3-radical) completely predominate the chemistry. With decreasing temperature the chains grow successively, and with increasing length of the chains the energy of the first vibrational mode (the bending of the complete chain) rapidly decreases. At the temperatures considered (at least significantly above 1 000 K), the long chains are in fact wildly wriggling, with subsequent rapid ring closures and reopenings. With further cooling, the molecules prefer the closed isomer.

Up to this point, theories and experiments are quite in agreement with each other. But for larger clusters, there are contradictory hypotheses of the process of ring collapse towards aromatic structures. One is based on the idea that the reaction enthalpy of a ring-ring addition enables the cluster to overcome the activation barrier towards the energetically favorable PAC (Goeres & Sedlmayr 1991, Goeres & Sedlmayr 1993). In this model, the addition of a small linear C_n-unit to a monocyclic ring is believed to lead to redissociation of the side chain before relaxation of the activated complex. This version is shown in the upper part of Fig. 1. The second one is based on the idea that monocyclic rings are able to grow by C_2-addition, until they reach sizes beyond $n = 60$. These very large rings are supposed to anneal directly to a curved framework af hexagons and pentagons which closes to a fullerene, which than shrinks by thermal dissociation of C_2-units, until it reaches a stable structure (McElvaney et al. 1993). Nevertheless, whether the yield of this process compared with ring redissociation is sufficient to explain the synthesis is still controversial. This last version of the chemical pathway is shown in the lower part of the figure.

The most profound difference between the models is the prediction of effective fullerene production in the second case, whereas in the first model only the formation of larger fullerenes ($n > 70$) should be kinetically possible. A decision between the two hypotheses requires (1) better data of the free enthalpies of PAC-radical sites, (2) a reliable value for the addition reaction rate of a ring and a C_2-unit or (3) experimental prove of the occurrence of special intermediate structures. On the other hand, observation of the dust in the beginning of an R CrB-decline should allow to obtain an upper limit for the abundance of fullerenes, and thus a simple method of an experimental distinction between the models.

As we see, besides our interest for the thermodynamics of carbon dust nucleation, the envelopes of R CrB stars may provide an excellent laboratory for a crucial experiment to elucidate the formation process of carbon clusters, especially of fullerenes.

The Chemistry of V 854 Cen and V CrA

As we have mentioned above, there are two exceptions from the general chemical composition of R CrB star envelopes, which have to be discussed separately. The first exception, V 854 Cen, differs from the other R CrB stars by its untypical high hydrogen abundance of $H/C \approx 2$. In this case, the formation of the first molecules differs from the general case by the predominance of acetylene ($HC{\equiv}CH$) instead of C_3, because the hydrogen prefers to saturate the radical sites of the carbon clusters. As a consequence, the activation energy of the ring closure reaction for small rings (especially $n = 6$) is much less than in the hydrogen free case: The carbon atoms of the chain attach a hydrogen atom, thus forming a hexagon without strain energy. Consequently, the chemistry of V 854 Cen has to resemble the chemistry of ordinary C-stars with its typical PAH-chemistry (Goeres 1993) and should show the typical C-H features (see Fig. 2).

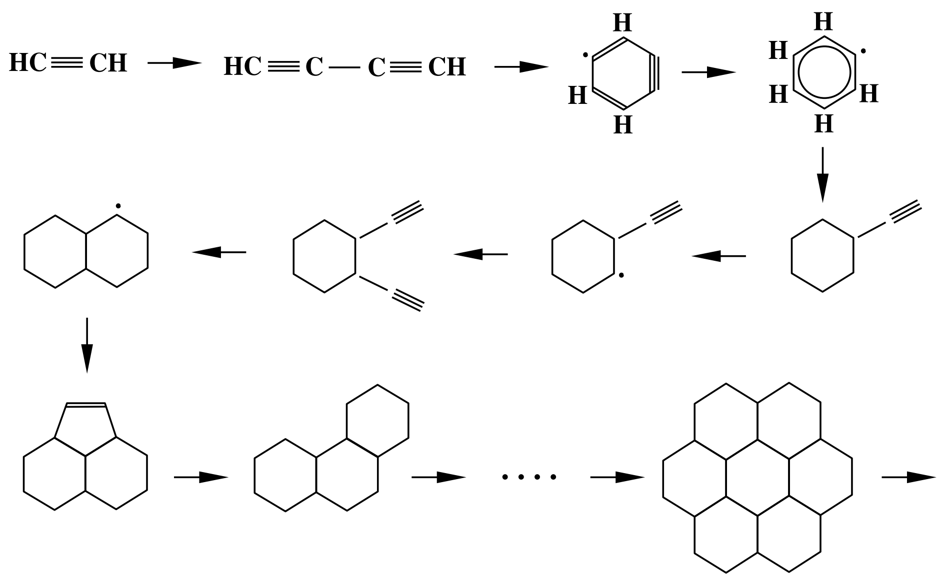

Figure 2. The chemistry of carbon nucleation, expected in the envelope of the hydrogen rich R CrB star V 854 Cen. Hydrocarbon molecules are represented by their σ- and localized π-bonds alone. H and C atoms and aromatic π-electrons are omitted, whereas radical sites (unpaired electrons) are symbolized by dots. The polycyclic structures are the typical polyaromatic hydrocarbons (PAHs) which most probably form in ordinary C-star shells.

In the case of V CrA, the most recent data of the chemistry shows approximately equal abundances of C, N and O, with the logarithms of the relative abundances of 8.7(O), 8.6(C,N), 8(H), 7.6(Si) <7.6(rest) (Rao 1995). With this chemical composition, we get the following sequence of molecules: The most stable molecule again will be CO, which comprises nearly all carbon and oxygen. The nitrogen again prefers to form N_2. The rest of the atoms O, C and N, together with hydrogen and silicon, forms molecules like C_2H_2, CN, CH, HCN, C_2O, OH, H_2O, CS, SiS, SiC_2 and SiO. The last two of this molecules (besides acetylene) are the only ones which are candidates for a primary condensation process. Since the (logarithmic) abundances of these molecules will never exceed a value of about 5 (most of the silicon remains atomic or ionized), nucleation should be at least six orders of magnitudes less effective than for other R CrB stars. Contrariwise, the lightcurve proves V CrA to be one of the most active R CrB stars, and the gradient of the decrease, which should be roughly proportional to the growth reaction rates along the chemical pathway, does not at all differ from that of other R CrB stars.

From the chemical point of view, the extreme effective nucleation process in R CrB star envelopes requires an at least significant carbon overabundance of C/O≈1.2 to allow for a satisfying chemical explanation.

3. Nucleation Physics

To get a quantitative analysis of the thermodynamical conditions, which control the nucleation chemistry outlined in the previous section, it is helpful to use the concept of the "critical cluster" from classical nucleation theory. The main qualitative result of classical nucleation theory is the finding that the whole nucleation process is controlled by *one* single reaction step, which is the "critical reaction" or "bottleneck" of the chemical pathway to nuclei. Thus, to calculate the efficiency of the formation of solids, it is sufficient to (1) identify the critical reaction, to (2) calculate its critical rate and (3) to know the growth rate of large nuclei. Here, our interest is not to calculate the nucleation yield, but to investigate the thermodynamical conditions of a condensation process of maximum efficiency. For this purpose, we apply classical nucleation theory only to identify the critical reaction, but then take our detailed chemistry to calculate the critical and the growth rate. The question then is, which temperatures and pressures are necessary, to allow for such a critical rate, which is compatible with the observed efficiency of the condensation process.

To firstly present the concept of the critical cluster, we investigate the phase transitions between a gas of a given temperature and pressure and the surface of clusters of different sizes (Fig. 3). The phase transition is controlled by the balance between vaporization from the cluster surface (black arrows) and growth by taking up molecules from the gas phase (white arrows). At sublimation temperature T_s of the actual pressure, evaporation and growth rates are in equilibrium (see first line, right cluster, which represents a solid surface). Since for smaller clusters the surface binding energy decreases, evaporation more and more overcomes growth, and those clusters will *evaporate* at T_s. For lower temperatures (second line in Fig. 3), the evaporation rate decreases exponentially, but the growth rate only decreases with the collision velocity, which is proportional to $\sqrt{T}$. As a consequence, the point of equilibrium is shifted towards *smaller* cluster sizes: Clusters which are smaller than this equilibrium size still evaporate, whereas larger clusters grow unlimitedly. With further decrease of the temperature, we reach a temperature T_{min}, where equilibrium (theoretically) occurs above a single gas particle. Below this temperature of spontaneous condensation *any* gas particle immediately grows. If we increase the actual pressure of the gas under consideration, only the growth rates increase proportional with pressure. Consequently, the equilibrium size is shifted towards smaller sizes, which is equivalent to an increase of the temperatures T_s and T_{min}.

This equilibrium size therefore separates the space of size and temperature into two regimes of evaporation (upper left) and condensation (lower right). The clusters of these sizes are called the "critical cluster" at a given pressure and temperature, and they exist only between the sublimation temperature T_s and the temperature of spontaneous condensation T_{min} in a metastable, subcooled situation. Above T_s condensation (without any preexisting nuclei) is absolutely impossible, whereas below T_{min} (net) thermal evaporation does not occur. As far as local thermal equilibrium holds, the condensation process has to occur at some temperature T_c between T_s and T_{min}. (For a review of classical nucleation theory see Feder et al. (1966).)

Thus, we have the following thermodynamical situation in an R CrB like envelope: The gas has to cool down far below sublimation temperature T_s. Then

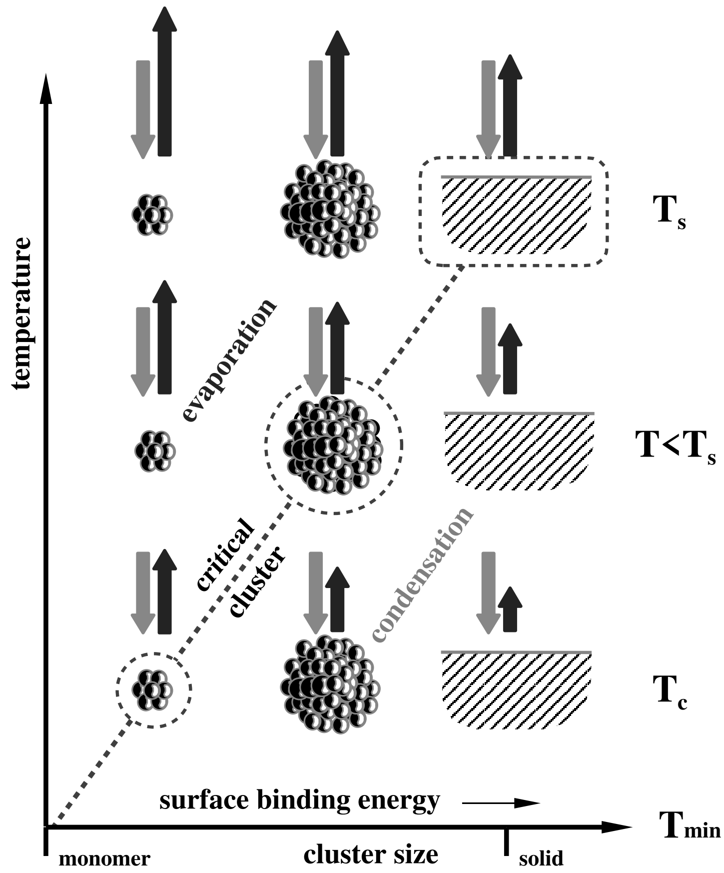

Figure 3. The critical cluster at different temperatures and a fixed gas pressure in a size-temperature diagram. The very right symbols represent solid surfaces, T_s is the sublimation temperature. Arrows symbolize rates per surface unity: Growth rates (light) predominate for larger clusters (grains), evaporation rates (dark) for smaller ones. The size of metastable equilibrium defines the critical cluster.

the gas is highly supersaturated with respect to graphite, but relaxation towards chemical equilibrium at first is hindered by a nucleation barrier which is represented by the critical cluster. Molecules *smaller* than the critical cluster make a random walk in the space of cluster sizes, where one growth step is followed by an evaporation step with a probability of approximately unity: The growth and redissociation reactions nearly hold detailed balancing. Molecules *larger* than the critical cluster, however, undergo preferably growth reactions until the chemistry is completely frozen as a consequence of the constantly decreasing pressures.

Finally, the nucleation rate simply is given by the growth rate of the critical cluster, the partial pressure of which can be calculated by the detailed balancing condition. Effective nucleation occurs, as soon as the critical cluster (by decreasing temperature) is small enough to show sufficient densities.

4. Thermodynamics of Carbon Nucleation

The thermodynamical conditions for effective carbon condensation, based on the discussion of the previous section, now can be quantified by application of the law of mass action. The absolute upper limit of condensation in local thermal equilibrium is given by the sublimation temperature of graphite, which represents the solid-gas phase transition in the p-T phase diagram of carbon. The course of the transition line is given by

$$T_s = \frac{41\,550\,K}{16.9 - \log p_C} \tag{1}$$

with p_C being the partial pressure of (hypothetically atomized) carbon in [dyn cm^{-2}] (Palmer & Shelef 1968). To get an expression of the temperature where effective nucleation occurs, we have to know the identity of the critical cluster, which strongly depends on the actual temperature, thus determining the nucleation efficiency. To get an estimation of the upper limit of the actual condensation temperature, we choose the most stable molecule in the range of sizes which are typical for critical clusters in dust forming stellar envelopes. This molecule is totally dehydrogenized coronene C_{24} (coronehexyne). Most probably condensation actually occurs at temperatures which are 10 to 50 K lower. From the free enthalpies of coronehexyne we can calculate the temperature, where the molecule reaches the partial pressure of the critical cluster in the case of effective nucleation, as a function of the partial pressure of the carbon gas,

$$T_c \approx \frac{27\,500\,K}{13.8 - \log p_C}\ , \tag{2}$$

which is again in [dyn cm^{-2}]. Both temperatures are shown in Fig. 4, which demonstrates the scaling of the laboratory situation towards the extreme low pressures in a stellar envelope.

To finally derive an estimate of the particular condensation temperature, we need an independent estimate of the carbon densities within the condensation zone of the stellar envelope. There are several possibilities, and we here choose two simple estimates: (1) using the column densities from the optical depth of the dust cloud and (2) the collision rates, based on the gradient of the decreasing branch of the lightcurves. With the first method, we presume a degree of condensation of unity for a decline of 8 magnitudes, a typical thickness of the dustshell of one stellar radius, and the opacity of amorphous carbon for the dust grains, and obtain $\log p_C \approx -5.3$ [dyn cm^{-2}]. The second method is based on the gradient of the fading of R CrB from 1972. Assuming three dimensional particle growth with a sticking coefficient of unity and again a thickness of the dust forming region of one stellar radius, we derive a minimum carbon pressure of $\log p_C \approx -5.9$, if the fading is caused by dust formation all over the stellar disc (Goeres 1992). Including tangential expansion of the opaque region, the limit will be even lower. Roughly we have to expect partial pressures of carbon between 10^{-6} to 10^{-5} dyn cm^{-2} or gas particle densities (for C/He = 0.01) of 10^8 to 10^9 cm^{-3}. This range of values is also indicated in Fig. 4, and shows the condensation temperature to be restricted to values between 1 400 K and 1 500 K. Incidentally, this result is in total agreement with the measurements of

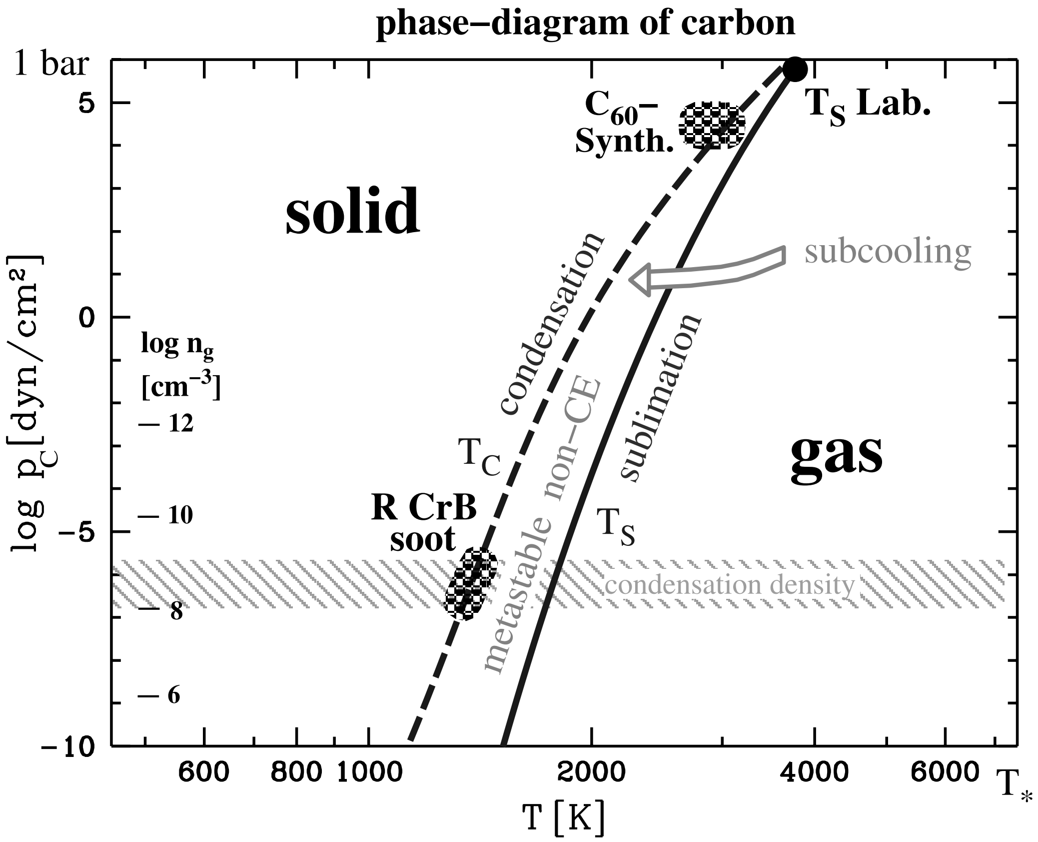

Figure 4. p-T-phase diagram of carbon. Shown is the section of the diagram with graphite (left) and carbon gas (right), divided by the curve of vapor pressure (sublimation temperature T_s) and of effective condensation at the timescales of an R CrB-decline (condensation temperature T_c). The regime between the two temperatures allows a metastable supersaturated gas with hindered condensation.

hot component of the IR-emission and the corresponding radiative temperatures of the dust, which have been found to range from 1 500 K to 1 850 K (Shenavrin et al. 1979): The radiative equilibrium (RE-) temperature of amorphous carbon in the condensation zone typically exceeds the gas temperature ($= T_c$) by 300 to 400 K (Cherchneff et al. 1991).

In the case of V 854 Cen, the chemistry resembles the common C-star chemistry, where the condensation temperature (in particular the vibrational temperature of the smallest PAHs) is significantly below 1 000 K. The difference to the hydrogen free situation is caused by the stabilization of the chains by saturating the terminal radical sites. Ring closure then requires much lower temperatures. This effect of a T_c-dependence from the H/C-ratio only holds, as far hydrogen is more abundant than carbon. Thus, the condensation temperature in the envelope of V 854 Cen can be expected to be somewhere between 1 000 K and 1 400 K.

5. Empirical and Theoretical Constraints on the Nucleation Distance

The calculation of a reliable range of possible condensation temperatures allows for a simple theoretical prediction of the condensation radius r_c, which is the distance from the stellar center, where dust clouds preferably form. Usually, for this purpose for the gas one assumes grey opacities, an optically thin envelope and radiative equilibrium (RE), which leads in the case of R CrB with $T_{eff} = 7\,000\,\mathrm{K}$ for the photosphere and $T_c = 1\,500\,\mathrm{K}$ to a value of $r_c = 10.9\,R_*$. Similarly, if we ask for the minimum distance where dust is able to survive, which is the radius where the RE-temperature of amorphous graphite reaches the actual sublimation temperature $T_s(p_C)$, we obtain roughly the same value: The RE-temperature of solid carbon exceeds the RE-temperature of the gas as well as T_s the condensation temperature T_c (see last section).

With this results, we already theoretically get a serious problem. From our estimate of the partial pressure of the carbon component in the condensation zone we know the minimum gas density at r_c. Assuming a steady radial outflow of sonic velocity (which corresponds to the typical situation in the condensation zone of a dust driven wind), this leads to a minimum mass loss of about $10^{-6}\mathrm{M}_\odot\,\mathrm{yr}^{-1}$. Since the density structure is a *pre*condition of the dust formation, there must be a mechanism to drive such a comparably massive wind *without* radiative pressure on dust. Unfortunately, hydrodynamical models of an R CrB-envelope show that this seems to be impossible. In the case of the hot R CrB stars, where one derives condensation radii up to $50\,R_*$, the problem appears to be even more serious.

On the other hand, from the observational point of view there seems to be increasing evidence for much smaller condensation radii, which already has been outlined recently (Whitney et al. 1993). We here summarize the main arguments:

- During a decline, one sees an emission spectrum which disappears in three distinguishable steps. Typically a few weeks after coverage of the photosphere, the narrow-line high excitation emission (E1) vanishes, followed by the narrow-line low excitation (E2) spectrum after a few months, whereas the broad-line (BL) component remains visible. It is natural to suggest subsequent occultation of the different emission regions by the expanding cloud. In this case, the cloud must form below the source of the E1 emission to sufficiently explain the statistics of the emission spectra of different decline events (Clayton et al. 1992). Since the source of the emission is quite unclear, the argument is more qualitative, favoring condensation as close as possible to the photosphere.

- In many cases strongly blue shifted absorption lines can be seen just in the beginning of a decline event. Assuming the radiative pressure on dust being the essential driving mechanism of the wind, the material has to be accelerated within the time between initial condensation and observation. Assuming a constant acceleration, the opacity of amorphous carbon and the onset of the condensation coinciding with the last luminosity maximum before the fading, the measurement of Alexander et al. (1972) (-208 km/s after 25^{d}) leads to $r_c \approx 5\,R_*$. Considering the uncertainties, one can expect $4\,R_* \lesssim r_c \lesssim 6\,R_*$.

- If one agrees with the model of a radially expanding dust cloud for the recovering from a decline, the gradient of light increase together with an expansion velocity at the same time allows for calculating an absolute distance from the star (Goeres 1992). From the '77/'78 decline of R CrB with 240 km/s 335 days after the onset and 6.7 mag/105$^{\mathrm{d}}$, a radial distance of $r = 880\,R_\odot$ can be obtained (Heinrich et al. 1994). Since this distance does not correspond with the moment of condensation, it has to be traced back with some uncertain assumptions: (1) The lightcurve is a superposition of single cloud formation events occurring every pulsation cycle, and (2) the acceleration is constant during grain growth. With $R_* = 73\,R_\odot$ and the uncertainties we get about $4\,R_* \lesssim r_c \lesssim 7\,R_*$.

- The condition that a single cloud in minimum has to be considerably larger than the stellar disc, together with the calculation of the angular coverage of the cloud from the IR-flux (1972 minimum of R CrB, Forrest et al. (1972)), leads to a minimum distance of the cloud of 4 times the cloud radius 30$^{\mathrm{d}}$ after decline onset. Tracing back with the usual assumptions and reasonable values for the cloud radius leads to $2.5\,R_* \lesssim r_c \lesssim 6\,R_*$.

- The often claimed correlation between the decline onset and the pulsational phase requires a physical connection between photosphere and condensation zone with a constant time scale. This seems to be the more comprehensible, the closer to the photosphere the condensation occurs. This argumentation fails, if photons trigger such a correlation (Goeres 1992).

Although any single argument is based on at least one poor assumption, the sum of those empirical arguments impressingly supports the idea of the condensation to occur rather close to the photosphere. This fact seriously contradicts the basic thermodynamical conditions of carbon condensation.

6. A way out?

To discuss the outlined contradiction, it is useful to examine the reliability of the different assumptions and approaches, the conclusions are based on. Regarding the empirical arguments, there are many observations and a quite impressive number of independent interpretations, which are without exception in sufficient agreement with each other. From the theoretical point of view (large condensation radius) the reliability of the basic theory also is out of doubts. The weakest link of the chain of argumentation obviously is the assumption of radiative equilibrium and grey opacities for calculating the temperature structure of the (static!) envelope. As we know, nearly all R CrB stars show some indications for a hydrodynamical variability of the photosphere. Irrespective of the question, whether the visual variability is caused by radial or nonradial pulsations or large convection cells, in the steep pressure gradient of the outer atmosphere any small variation of the velocity field should produce shock waves in the envelope. In the wake of the shock waves, hydrodynamic effects may cause strong deviations from radiative equilibrium, which has to be considered for a calculation of the temperature structure. Based on this fundamental hydrodynamical effect, which has already been suggested earlier (Clayton et al. 1992), the thermodynamical possibility of carbon condensation within the empirically found range of radial distances is shown in the contribution "Shock induced Condensation in R CrB stars" (Woitke, this proceedings).

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