

## Abodes for life in carbonaceous asteroids?

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### ABSTRACT

Thermal evolution models for carbonaceous asteroids that use new data for permeability, pore volume, and water circulation as input parameters provide a window into what are arguably the earliest habitable environments in the Solar System. Plausible models of the Murchison meteorite (CM) parent body show that to first-order, conditions suitable for the stability of liquid water, and thus pre- or post-biotic chemistry, could have persisted within these asteroids for tens of Myr. In particular, our modeling results indicate that a 200-km carbonaceous asteroid with a 40% initial ice content takes almost 60 Myr to cool completely, with habitable temperatures being maintained for ~24 Myr in the center. Yet, there are a number of indications that even with the requisite liquid water, thermal energy sources to drive chemical gradients, and abundant organic “building blocks” deemed necessary criteria for life, carbonaceous asteroids were intrinsically unfavorable sites for biopoesis. These controls include different degrees of exothermal mineral hydration reactions that boost internal warming but effectively remove liquid water from the system, rapid ( $1\text{--}10\text{ mm yr}^{-1}$ ) inward migration of internal habitable volumes in most models, and limitations imposed by low permeabilities and small pore sizes in primitive undifferentiated carbonaceous asteroids. Our results do not preclude the existence of habitable conditions on larger, possibly differentiated objects such as Ceres and the Themis family asteroids due to presumed longer, more intense heating and possible long-lived water reservoirs.

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### 1. Introduction

Despite abundant organic molecules of pre-biotic relevance (e.g., Wolman et al., 1972; Cooper et al., 2001; Meierhenrich et al., 2004), evidence for the past occurrence of liquid water (e.g., Zolensky et al., 1989), and other well-documented histories of aqueous processes (e.g., Kerridge and Bunch, 1979), asteroids from which we have samples apparently did not witness the origin of life (Nagy et al., 1961; Anders et al., 1964; Nagy, 1975). That these asteroids hosted natural combinatorial pre-biotic organic chemistry laboratories over millions of years, yet remained abiogenic, suggests that either (i) some minimum time is required for biological organisms to arise in an otherwise habitable milieu or (ii) this environment was not as habitable as it ostensibly appears.

Numerical models of the thermal evolution and habitable potential of asteroidal parent bodies of carbonaceous chondrite meteorites provide a baseline for the exploration of the first possible abodes for life in the Solar System. Chondrites in general are characterized by the presence of chondrules, or small spherules composed primarily of olivine and pyroxene with a debated origin

(King, 1983). That chondrules are preserved in some meteorites is taken to mean that their parent bodies did not differentiate to completion, such that bulk compositions remained relatively homogeneous and primordial with respect to solar composition. As their name implies, carbonaceous chondrites are rich in carbon; over 400 individually-identified organic compounds have been documented in these meteorites (Cronin et al., 1988), including over 80 different amino acids. These meteorites also contain silicates, oxides, sulfides, large amounts of calcium–aluminum rich inclusions (Dodd, 1981), and later hydrous minerals thought to have been derived from reactions of water and anhydrous minerals (Zolensky and McSween, 1988). Carbonaceous chondrites contain up to 20% of chemically bound water (Mason, 1963), and some appear to contain minute ( $<5\text{ }\mu\text{m}$ ) fluid inclusions (Zolensky, 2010). The different proportions of characteristic minerals are used to define a number of sub-categories of carbonaceous chondrites, and CM chondrites are among the most common and well-studied of this class (Norton, 2002). Consequently, CM chondrite characteristics are useful input parameters to models of how primitive asteroids evolved; however, such models are also applicable to other classes of carbonaceous chondrites to varying degrees, and, to a lesser extent, small asteroids of primarily silicate composition.

Along with organic matter, carbonaceous chondrites are remarkable in that several classes, including CM chondrites, have undergone pervasive aqueous alteration, at least partly within their

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parent bodies (e.g., Bunch and Chang, 1980; Brearley, 2003). Previous modeling studies predicted widespread flow of water throughout the parent asteroid, often in the form of large-scale hydrothermal convection cells (Grimm and McSween, 1989; Young et al., 2003; Cohen and Coker, 2000; Travis and Schubert, 2005). Yet, these results cannot be reconciled with geochemical studies which suggest that alteration was isochemical with very limited flow (e.g., McSween, 1979; Bland et al., 2005; Rubin et al., 2007), and that veins are extremely rare or absent even in altered carbonaceous chondrites (Benedix et al., 2003; Tyra et al., 2009). Petrographic studies by Bland et al. (2009) show relatively high porosities of up to 40%, but with extremely low permeabilities of  $10^{-19}$ – $10^{-17}$  m<sup>2</sup>. Although heating within an asteroid can alter permeability, it generally does not vary by more than an order of magnitude over the ~50 K to 600 K temperature range observed in our models (Shmonov et al., 1995), and these values are approximately six orders of magnitude lower than those used in earlier numerical modeling studies. Such low permeabilities would make water essentially immobile, permitting transport length-scales of 100's  $\mu$ m at most, even at timescales of 1 Myr. It should be noted, however, that the Bland et al. (2009) study was conducted on only one meteorite and may not be representative of all CM parent bodies.

The goals of the present work are threefold: (i) Re-assess post-accretion heating and cooling of carbonaceous chondrite parent bodies in light of new data suggesting low permeabilities and lack of water circulation, (ii) Expand on previous modeling studies by further exploring parameter space with respect to asteroid diameters and hydration reactions, and (iii) Assess biological potential of CM parent bodies and estimate whether internal conditions could ever have been suitable for life.

To accomplish these goals, we constructed a model based on HEATING 7.3, a general-purpose heat transfer code. Model parameters are reported in Table 1, with the main difference of this work from previous studies being a lack of water transport through the asteroid due to low permeability. In particular, vapor transport and venting was omitted because no significant gas transport would be expected to occur within the asteroid on the 10–50 Myr timescales of the model (Corrigan et al., 1997; Bland et al., 2009). Heat sources within model asteroids included the decay of <sup>26</sup>Al, the dominant heat-producing short-lived radionuclide that remained available shortly after asteroid accretion (e.g., Russel et al., 1996), as well as heat generated by hydration reactions of olivine and pyroxene forming serpentine (Cohen and Coker, 2000). We modeled the thermal evolution of bodies 75, 100, 150, and 200 km in diameter within the range of sizes for C-type asteroids, and investigated the importance of heat generation by hydration reactions. These diameters are consistent with recent collisional evolution modeling by Morbidelli et al. (2009), who found that the size-frequency distribution of the asteroid belt cannot be reproduced from an initial population of km-sized planetesimals, but rather requires initial planetesimal diameters from ~100 to several 100 km, probably up to 1000 km.

**Table 1**  
Summary of parameters varied in model runs. Run 3 assumes hydration reactions took place before asteroid's accretion.

Run number	Volume fraction of ice accreted (%)	Asteroid diameter (km)	Hydration reactions
1	20	75	Yes
2	20	100	Yes
3	20	100	No
4	20	150	Yes
5	20	200	Yes
6	30	100	Yes
7	40	75	Yes
8	40	100	Yes
9	40	150	Yes
10	40	200	Yes

## 2. Modeling technique

The thermal state evolution of asteroids was modeled using HEATING 7.3, a multidimensional, finite-difference heat conduction code developed at Oak Ridge National Laboratory. The model asteroids were represented on a spherically-symmetric, one-dimensional, 500-element grid, where the heat conduction equation (Fourier's Law) was solved numerically using the Classical Explicit Procedure. The thermal and physical parameters of the model were set following Cohen and Coker (2000), with the exception that water vapor was not included. Other significant differences from the Cohen and Coker (2000) work include the modeling of 75-km, 150-km, and 200-km asteroids, modeling a case with no hydration reactions, and the use of a different numerical code. The initial time in our models is set to 3 Myr after nebula collapse: a formation time of 2 Myr less results in very high temperatures at odds with observations, and a formation time of 3.5 Myr results in temperatures that never exceed 273 K due to insufficient <sup>26</sup>Al (Cohen and Coker, 2000). The bottom boundary of the grid represents the center of the asteroid and is therefore insulating, and the top boundary represents the surface of the asteroid, which has an equilibrium temperature of 50 K, the approximate value expected at 3 AU and 3 Myr based on solar nebula evolution models (Cassen, 1994; Dodson-Robinson et al., 2009). The initial post-accretion internal temperature of the model asteroid was set to 90 K.

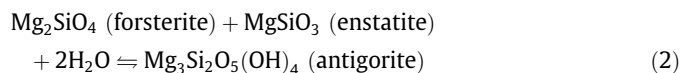
In addition to the heat deposited by accretion, the model asteroid is internally heated by a short-lived radionuclide <sup>26</sup>Al. The heat generated by other short-lived radionuclides is several orders of magnitude smaller (Cohen and Coker, 2000), and they are not included in the model. The total heat production due to the decay of <sup>26</sup>Al is given by

$$Q = mQ_i e^{-\lambda t} \quad (1)$$

where  $m$  is the fraction of rock in the asteroid,  $Q_i$  is  $7.64 \times 10^{-9}$  W kg<sup>-1</sup> and the decay constant  $\lambda$  is  $3.1 \times 10^{-14}$  s<sup>-1</sup>. However, a recent study (Castillo-Rogez et al., 2009) provides a slightly different decay energy for <sup>26</sup>Al: 3.12 MeV per decay as opposed to 2.5 used in this study. The resulting difference in heat generation can be compensated for by adjusting the formation time of the model asteroid from 3 to 2.8 Myr after solar nebula collapse.

The H<sub>2</sub>O (s)–H<sub>2</sub>O (l) phase transition is included in the model. Because of very low permeabilities, liquid water is assumed to be trapped in pores and remain in the liquid phase; thus, the H<sub>2</sub>O (l)–H<sub>2</sub>O (g) phase transition is not included. The critical point of water (647 K) is not reached in any of the runs.

The initial volumetric composition of the model asteroid is 22% forsterite, 17% enstatite, 16% void, 20–40% ice, and 5–25% nonreactive rock. After the first liquid water appears, the following hydration reaction takes place:



This reaction released 69 kJ per mole of serpentine produced. The final assemblage is 60% serpentine, 0–20% leftover water, the initial volume of unreactive rock, and void space. The densities used in the model are 3210 and 3190 kg m<sup>-3</sup> for forsterite and enstatite, respectively, 2470 kg m<sup>-3</sup> for serpentine, and 3630 kg m<sup>-3</sup> for nonreactive rock.

The thermal conductivity is 5.155 W m<sup>-1</sup> K<sup>-1</sup> for forsterite and enstatite, 2.95 W m<sup>-1</sup> K<sup>-1</sup> for serpentine, and 2.8 W m<sup>-1</sup> K<sup>-1</sup> for non-reactive rock. For H<sub>2</sub>O, thermal conductivity varies with temperature as follows:

$$k_{\text{ice}} = 9.828 \exp(-0.0057T) \quad (3)$$

$$\begin{aligned}
 k_{\text{liq}} &= -0.581 + 6.34 \times 10^{-3}T - 7.93 \times 10^{-6}T^2 \quad (T < 410 \text{ K}) \\
 &= 0.9721(-0.142 + 4.12 \times 10^{-3}T - 5.01 \times 10^{-6}T^2) \quad (T > 410 \text{ K})
 \end{aligned} \quad (4)$$

The specific heat is a function of temperature for all components:

$$\begin{aligned}
 \log c_p (\text{forsterite}) &= -11.32 + 13.58(\log T) - 4.25(\log T)^2 \\
 &\quad + 0.44(\log T)^3
 \end{aligned} \quad (5)$$

$$\begin{aligned}
 \log c_p (\text{enstatite}) &= -8.62 + 10.39(\log T) - 3.00(\log T)^2 \\
 &\quad + 0.28(\log T)^3
 \end{aligned} \quad (6)$$

$$\begin{aligned}
 \log c_p (\text{water}) &= 8.25 - 4.18(\log T) - 1.12(\log T)^2 \\
 &\quad - 0.076(\log T)^3
 \end{aligned} \quad (7)$$

$$\begin{aligned}
 \log c_p (\text{antigorite}) &= -0.59 - 1.519(\log T) + 2.82(\log T)^2 - 0.66(\log T)^3 \quad T < 273 \\
 c_p (\text{antigorite}) &= 1145 + 0.048T - 2.65 \times 10^{-7}T^2 \quad T > 273
 \end{aligned} \quad (8)$$

$$\begin{aligned}
 c_p (\text{ice}) &= -49.97 + 9.5T \quad (50 < T < 95 \text{ K}) \\
 &= 126.89 + 7.5T \quad (95 < T < 150 \text{ K}) \\
 &= 152.46 + 7.12T \quad (T > 150 \text{ K})
 \end{aligned} \quad (9)$$

Eq. (3) is from Yen (1981); Eq. (4) is from Touloukian et al. (1970a); Eqs. (5)–(7) are polynomial fits by Cohen and Coker (2000) to the data of Touloukian et al. (1970b), Barin and Knacke (1973), Chase et al. (1985), Knacke et al. (1991), and Lide (1994); Eq. (8) is from Barin et al. (1977) and Touloukian et al. (1970b); Eq. (9) is from Yen (1981).

### 3. Results for carbonaceous asteroids of different diameters

#### 3.1. Thermal evolution of model asteroids

As shown in Fig. 1a, all model runs begin in the same fashion: the temperature in the center of the asteroid increases rapidly at first, then somewhat slower as heat production from  $^{26}\text{Al}$  diminishes. At  $\sim 1$  Myr, the 273 K isotherm is reached and first liquid water appears within the asteroid. This first stage of asteroid heating reproduces the results of Cohen and Coker (2000), and appears independent of asteroid diameter.

Once 273 K is reached, subsequent thermal evolution depends on the initial volumetric ice content, asteroid diameter, and the extent of hydration reactions. In all model runs where hydration reactions are present, a rapid rise in temperature takes place as soon as first liquid water appears. This phenomenon is due to the fact that hydration reactions release more heat per mole of water used than is required to melt a mole of ice, and was termed a “thermal runaway” by Cohen and Coker (2000). Fig. 1b shows that this thermal runaway results in substantial heating (sometimes exceeding 500 K) of a large fraction of the asteroid.

The extent of heating by hydration reactions depends strongly on the initial fraction of ice in the asteroid. In model Runs 1, 2, 4, and 5, with a 20% initial ice content, water is close to being the limiting reagent, as essentially all of it is consumed in hydration reactions. This results in a dry, hot asteroid. In contrast, model Runs 7–10, with a 40% initial ice content, have over 20% liquid water left over after hydration reactions. Due to its high heat capacity, water prevents temperatures from getting too high, resulting in a cooler, wet asteroid. Run 6, with a 30% initial ice content, is an intermediate case.

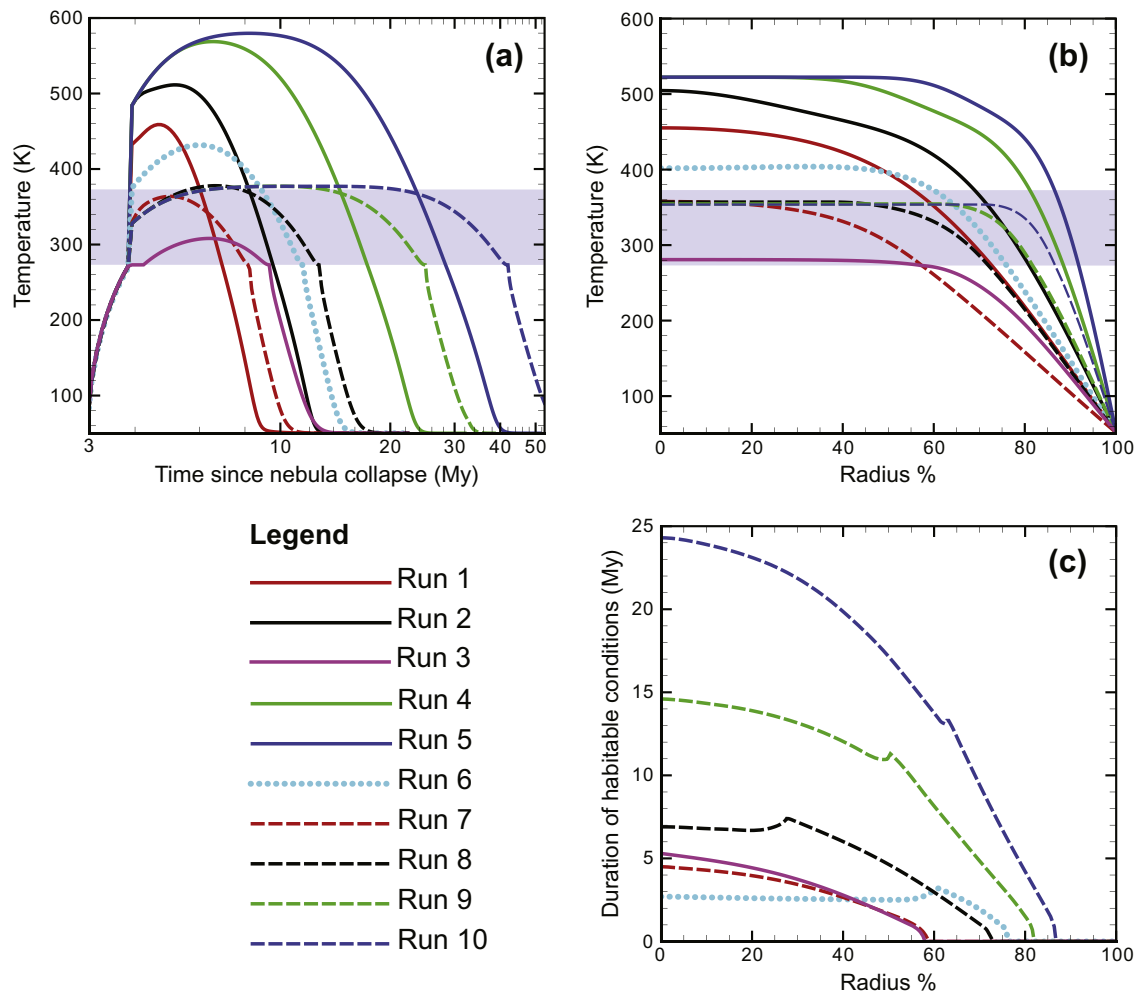
After the thermal runaway, the thermal evolution of an asteroid is governed primarily by its diameter, and, to a lesser extent, water content. Larger asteroids take longer to reach their maximum central temperature, the maximum central temperature is higher, and they take longer to cool. Increasing the initial ice content results in lower maximum central temperatures due to increased heat capacity, peak central temperatures which are reached somewhat later, and the overall greater retention of heat. This agrees with the results of Grimm and McSween (1989), who found that water may play a strong role in controlling chondrite evolution because radiogenic heating would be buffered by the latent heat of fusion and large heat capacity of water. The longest duration of central heating in this study was in a 200-km asteroid with a 40% initial ice content, which took almost 60 Myr to cool completely. The initial water content also affects the shape of the cooling curve and the final percentage of ice in the pore spaces. Asteroids with an initial water content of over 20% have a kink in their cooling curve as a result of the latent heat of freezing. The final asteroid porosity is  $\sim 20\%$ , with the pore spaces either empty (for a 20% initial water content) or filled with water ice to varying degrees (50% of a 30% initial water content, and 100% for a 40% initial water content). This final porosity matches well with petrographic analyses of CM meteorites (Britt and Consolmagno, 2003; Corrigan et al., 1997).

#### 3.2. Effects of hydration reactions

To illustrate the importance of hydration reactions to the thermal evolution of these types of asteroids, a special case is modeled in Run 3, which represents a 100-km asteroid lacking heat generation by hydration reactions. The assumption is that the asteroid starts out with hydrated minerals (serpentinized). Otherwise, all conditions are identical to Run 2, to which it is meant to be compared. The initial ice content is 20%, none of which is consumed in hydration reactions. Initial heating in this model, up to 273 K, proceeds as before. However, once 273 K is reached, there is no heat from hydration reactions to overcome the latent heat of melting, and the heating curve flattens out briefly as the ice is melted. After melting, the central temperature continues to gradually increase up to a maximum value of  $\sim 300$  K about 3.5 Myr after accretion, and then gradually decays back to the freezing point of water  $\sim 7$  Myr after accretion. It is interesting to note that the overall cooling timescale of  $\sim 10$  Myr for Run 3 is essentially identical to Run 2, which also featured a 100-km asteroid with 20% initial ice content, but with hydration reactions present. Thus, although hydration reactions significantly increase the maximum temperature reached within an asteroid, they do not alter its cooling timescale to an appreciable degree. This is an expected consequence of Fourier's Law: higher central temperatures result in higher heat diffusion and loss rates.

#### 3.3. Duration of habitable conditions within model asteroids

Habitable conditions are loosely defined as temperatures of 273–373 K and the presence of liquid water, and their duration is shown in Fig. 1c. In Runs 1, 2, 4, and 5, almost all of the water is consumed in hydration reactions, and the duration of habitable conditions is therefore essentially zero. As expected, both increasing asteroid diameter and increasing initial ice content positively affect habitable potential. The best case is Run 10, a 200-km asteroid with a 40% initial ice content, which experienced habitable conditions in over 85% of its radius and a duration of conditions suitable for life of over 24 Myr in the center. In general, central regions of the asteroid experienced habitable conditions for longest, with the exception of Runs 6 and 8, which have an optimum some distance away from the center. It is also interesting to note that Run 3, an illustrative case which lacks heat generated by hydration reactions, possessed habitable conditions in the center for longer than Runs 6 and 7.



**Fig. 1.** (a) Temperature in the center of model asteroids as a function of time since nebula collapse. (b) Temperature profiles through model asteroids 1 Myr after accretion, illustrating the approximate maximum lateral extent of melting. (c) Duration of habitable conditions (defined here as temperatures of 273–373 K and the presence of liquid water) throughout model asteroids. Duration of habitable conditions in Runs 1, 2, 4, and 5 is zero because all liquid water is consumed in hydration reactions shortly after melting. The light blue shading in (a and b) denotes habitable temperatures (273–373 K).

### 3.4. Habitable zone migration

In a typical asteroid where hydration reactions are a major heat source, the habitable conditions are confined to the outer regions of the asteroid immediately after the thermal runaway, because the central regions are too hot. Fig. 2 illustrates this in the context of the thermal evolution of a 100-km asteroid with a 30% initial ice content (Run 6). As the asteroid cools, the habitable zone gradually migrates inward at 1–10 mm yr<sup>-1</sup>. Exceptions to this are Run 3, which lacks heat contributed by hydration reactions so that the central temperature does not exceed 373 K, and Run 7, where the asteroid is so small and ice-rich that its temperature likewise does not exceed 373 K. Habitable zone migration rate is slower for model asteroids with a higher initial ice content, which also have a larger habitable zone and longer duration of habitable conditions, as illustrated by Run 8 shown in Fig. 3.

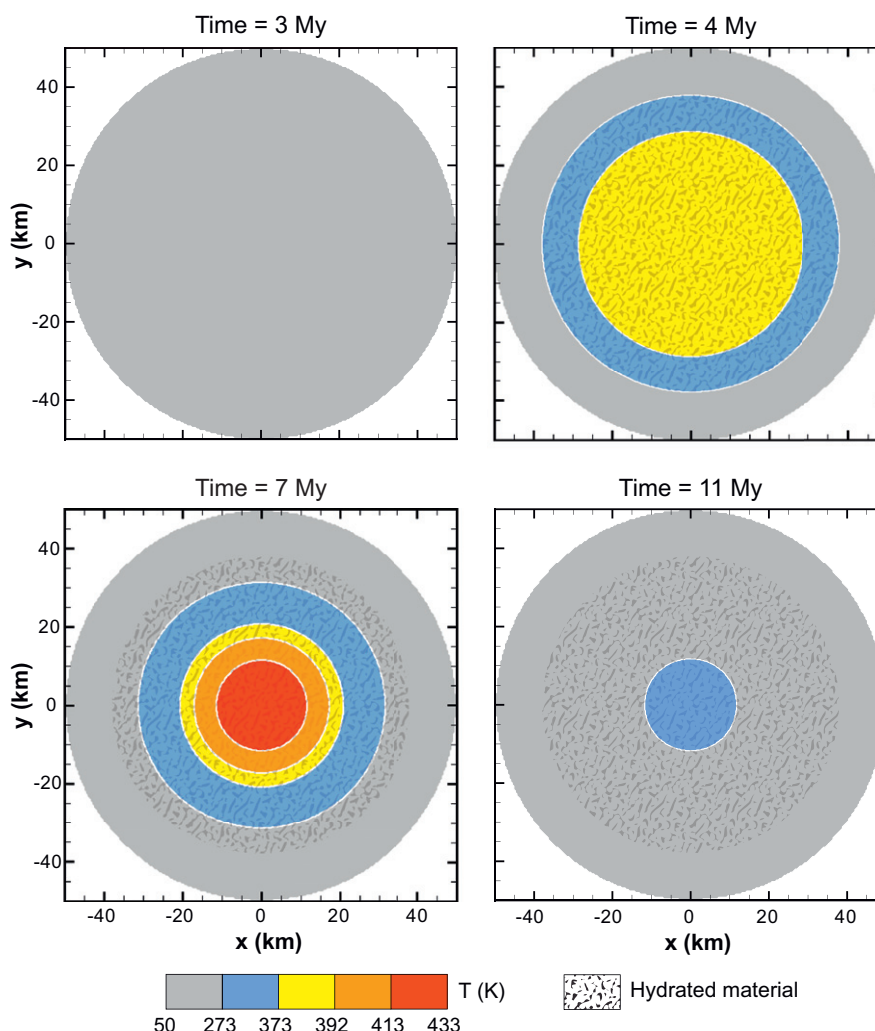
## 4. Discussion

### 4.1. Limitations to early habitability of carbonaceous asteroids

At first glance, carbonaceous chondrite parent bodies appear to have sustained liquid water and moderate temperatures for millions of years, and thus represent potential sites for the prebiotic

steps towards life in the first few tens of millions of years of the Solar System. However, there are a number of important caveats to this viewpoint: (i) Hydration reactions may have removed all or most of liquid water. If significant hydration reactions took place within an asteroid after accretion, and the initial volumetric ice content was under 20%, all water would be tied up in hydrated minerals shortly after the melting of ice (Cohen and Coker, 2000). (ii) Habitability is confined to relatively narrow, migrating zones in most models (Fig. 2). For example, although temperatures over 273 K in the center of the asteroid in Run 6 persisted for over 8 Myr (Fig. 1a), the duration of habitable conditions did not exceed ~3 Myr anywhere in the asteroid. (iii) As suggested by the Bland et al. (2009) study and references therein, there may have been virtually no water flow within carbonaceous chondrite parent bodies due to extremely low permeability. This in turn suggests that even if some prebiotic chemistry were to occur, it would have remained very narrowly confined. Bland et al. (2009) estimated water flow at length scales of 100's μm at most. (iv) Furthermore, Bland et al. (2009) report a geometric mean pore-size of 5–50 nm observed in a primitive carbonaceous chondrite Acfer 094, and suggest that other carbonaceous chondrite parent bodies had a similar pore diameters. This presents a first-order problem for life, since the smallest known non-virus living organism, *Nanoarchaeum equitans*, is 400 nm in diameter (Huber et al., 2002). (v) Asteroid fracturing due to impacts may have permitted faster water vapor diffusion





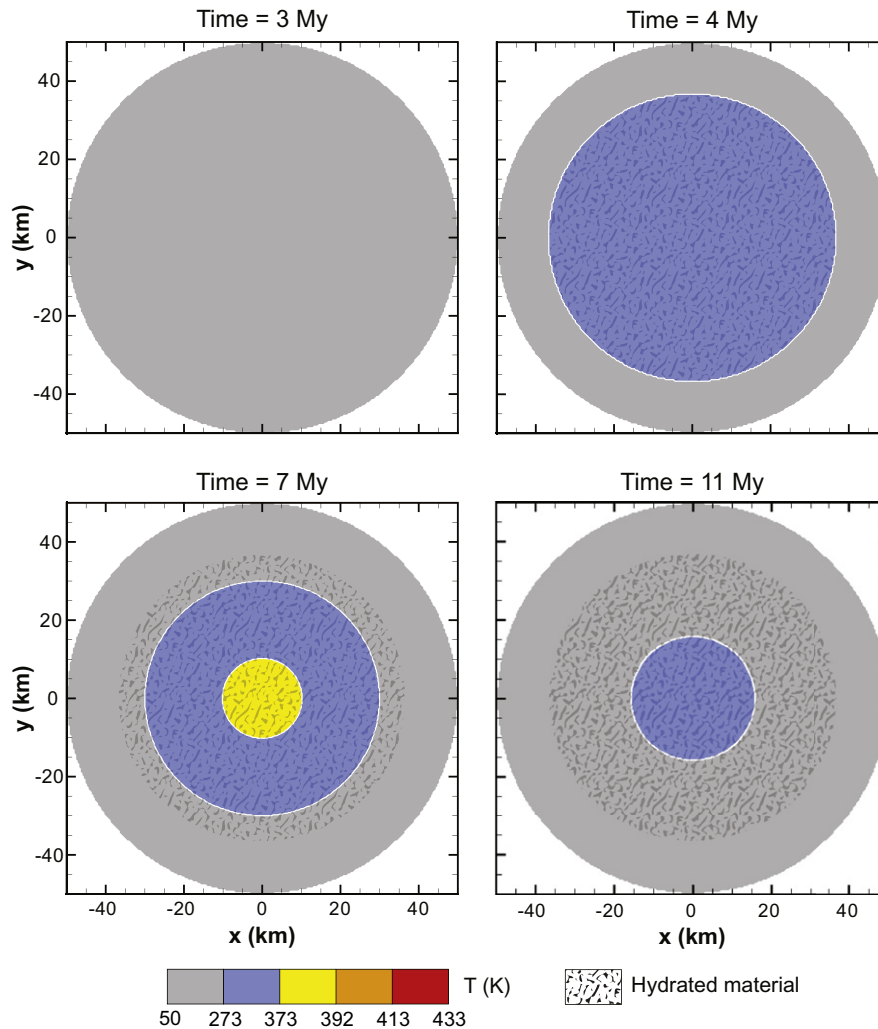
**Fig. 2.** Temperature evolution within a model asteroid 100 km in diameter with 30% initial ice content (Run 6), illustrating initial formation and subsequent inward migration of the habitable zone, shown in blue. The extent of hydration is also shown. Timesteps are labeled in time after nebula collapse, at  $t = 3$  Myr for all runs.

and loss by increasing bulk permeability, particularly closer to the surface. The fracture densities of asteroids shortly after accretion are not well understood, and are not included in this study. However, this mechanism may have actually reduced the duration of habitable conditions reported here by removing water and heat.

Put together, these caveats suggest that carbonaceous chondrite parent bodies were likely not ideal sites for the origin of life or even significant pre-biotic chemistry, despite evidence for liquid water and moderate temperatures within their interiors. Larger, differentiated asteroids such as Ceres (950 km in diameter) and the Themis family parent body (390–450 km, Marzari et al., 1995) are more promising targets for astrobiological exploration. This is underlined by recent ground-based infrared detections of prevalent water ice and organic compounds on the surface of Asteroid 24 Themis (Campins et al., 2010; Rivkin and Emery, 2010), as well as modeling of the thermal histories of Ceres (Castillo-Rogez and McCord, 2010) and the Themis family parent body (Castillo-Rogez and Schmidt, 2010). Those models predict a liquid water ocean lasting millions of years, possible hydrothermal activity, and, in the case of Ceres, an interior that may still relatively warm and support liquid water today. That said, the study of carbonaceous chondrite parent bodies is instructive for learning what organic compounds can form relatively quickly in confined pore spaces and how volumetric limitations to pre-biotic chemistry may be important for the early biological potential of the Solar System.

#### 4.2. Implications for amino acid racemization

Cohen and Chyba (2000) investigated seven  $\alpha$ -hydrogen amino acids commonly found in CM meteorites, and found that the entire suite of amino acids is completely racemized within a few thousand years when contained within a 350–400 K solution. Moreover, thermal destruction of amino acids investigated by Cohen and Chyba (2000) is expected to exceed 90% at  $>473$  K (Rodante, 1992). This is potentially at odds not only with the presence of abundant amino acids in CM meteorites, but also with the finding by Cronin and Pizzarello (1997) of the L-enantiomer excess of  $\sim 10\%$  in amino acids derived from a CM meteorite. Cohen and Coker (2000) suggest that the only areas within a model asteroid which could produce CM-like meteorites (with aqueous alteration and non-racemic amino acid proportions) are zones which never get hotter than 298 K but still contain hydration. These conditions are not present in most of the model runs presented here, except in narrow bands, with the exception of Run 3, which does not incorporate hydration reactions. The non-hydration model fits the amino acid constraints well; the maximum temperature reached in the core is just over 300 K, and less than 300 K throughout most of the rest of the asteroid. This is further consistent with estimates for alteration temperatures in CM meteorites of 273–308 K (e.g., Zolensky et al., 1989; Benedix et al., 2003; Guo and Eiler, 2007), and may suggest that hydration reactions were not a major heat



**Fig. 3.** Temperature evolution within a model asteroid 100 km in diameter with 40% initial ice content (Run 8), illustrating overall lower temperatures but longer duration of habitable temperature conditions, shown in blue. The extent of hydration is also shown. Timesteps are labeled in time after nebula collapse, at  $t = 3$  Myr for all runs.

source within CM parent bodies, unless they accreted with a much higher proportion of ice than thought and initially resembled comets in their bulk composition (Grimm and McSween, 1989; Wasson and Wetherill, 1979). This possibility may be supported by a theoretically predicted increase in surface density by a factor of 2–4 around the  $\text{H}_2\text{O}$  ice line of the solar nebula (Lecar et al., 2006; Dodson-Robinson et al., 2009).

## 5. Conclusions

We modeled asteroids of four different diameters (75, 100, 150, and 200 km) as well as three different initial volumetric ice contents (20%, 30%, and 40%), and investigated the importance of hydration reactions for the thermal history of an asteroid. Our results are well in line with those reported by Cohen and Coker (2000) for asteroids of the same size and water content (Runs 2, 6, and 8), although their model asteroid cools up to 50% faster in water-rich models due to heat removal by water vapor venting. The centers of our model asteroids reach the melting point of water in  $\sim 1$  Myr in all models, at which point the thermal runaway due to hydration reactions results in a rapid rise in temperature. The magnitude and radial extent of the temperature increase are governed by the diameter and the amount of water within the asteroid. Large asteroids with 20% initial ice experience the greatest heating, and smaller asteroids with 40% ice the least. The extent

of aqueous alteration ranges from  $\sim 58\%$  by radius (or  $\sim 20\%$  by volume) for a 75-km asteroid with a 40% initial ice content to  $\sim 92\%$  by radius (or  $\sim 78\%$  by volume) for a 200-km asteroid with a 20% initial ice content. The exception is Run 3, in which 100% pre-accretionary alteration was assumed.

After the thermal runaway, thermal evolution of an asteroid is governed primarily by its diameter, and, to a lesser extent, its water content. The maximum central temperature reached in this study was  $\sim 580$  K in a 200-km asteroid with a 20% initial ice content, and the longest time for complete cooling was almost 60 My, for a 200-km asteroid with a 40% initial ice content. In Run 3, which lacks a thermal runaway due to hydration reactions, the maximum central temperature reached was much lower at  $\sim 300$  K. However, it appears that although hydration reactions significantly increase the maximum temperature reached within an asteroid, they do not alter its cooling timescale to an appreciable degree. Also, Run 3 appears the most consistent with alteration temperatures obtained from analyses of CM meteorites, unless their parent bodies accreted with a much higher proportion of ice than thought.

Increasing asteroid diameter and initial ice content positively affect habitable potential. The best case is Run 10, a 200-km asteroid with a 40% initial ice content, which experienced habitable conditions in over 85% of its radius and a duration of habitable conditions of over 24 Myr in the center.

Despite the presence of sustained liquid water and moderate temperatures for millions of years in these model asteroids, there are indications that they were not suitable sites for biopoesis. These include possible dehydration by chemical reactions or venting of water vapor, rapid migration of habitable zones in most models, and indications of very low permeabilities and pore sizes in carbonaceous chondrite parent bodies. Instead, we suggest that larger, differentiated asteroids such as Ceres and the Themis family parent body hold more potential for astrobiological discoveries due to longer duration of heating, likely presence of long-lived liquid water oceans, and the presence of organics.

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## Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at [doi:10.1016/j.icarus.2011.03.003](https://doi.org/10.1016/j.icarus.2011.03.003).

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