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Abodes for life in carbonaceous asteroids?

Oleg Abramov [a,b,*], Stephen J. Mojzsis [b]

[a] Lunar and Planetary Institute, Universities Space Research Association, Houston, TX 77058, USA
[b] Department of Geological Sciences, University of Colorado, Boulder, CO 80309, USA

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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 (1–10 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.

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 μm) 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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* Corresponding author. Address: Lunar and Planetary Institute, Universities Space Research Association, 3600 Bay Area Blvd., Houston, TX 77058, USA. Fax: +1 281 486 2173.

E-mail address: Abramov@lpi.usra.edu (O. Abramov).

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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^2. 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 μm 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 ^{26}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 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 ^{26}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 ^{26}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 ^{26}Al is given by

$$Q = mQ_i e^{-\lambda t} \tag{1}$$

where m is the fraction of rock in the asteroid, Q_i is 7.64×10^{-9} W kg^{-1} and the decay constant λ is 3.1×10^{-14} s^{-1}. However, a recent study (Castillo-Rogez et al., 2009) provides a slightly different decay energy for ^{26}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_2O (s)–H_2O (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_2O (l)–H_2O (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:

$$\begin{aligned} &\mathrm{Mg_2SiO_4}\ (\text{forsterite}) + \mathrm{MgSiO_3}\ (\text{enstatite}) \\ &\quad + 2\mathrm{H_2O} \leftrightharpoons \mathrm{Mg_3Si_2O_5(OH)_4}\ (\text{antigorite}) \end{aligned} \tag{2}$$

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^{-3} for forsterite and enstatite, respectively, 2470 kg m^{-3} for serpentine, and 3630 kg m^{-3} for nonreactive rock.

The thermal conductivity is 5.155 W m^{-1} K^{-1} for forsterite and enstatite, 2.95 W m^{-1} K^{-1} for serpentine, and 2.8 W m^{-1} K^{-1} for non-reactive rock. For H_2O, thermal conductivity varies with temperature as follows:

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