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Ceres' evolution and present state constrained by shape data

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ABSTRACT

We model Ceres' thermo-physical-chemical evolution by considering a large range of initial conditions as well as various evolutionary scenarios. Models are constrained by available shape measurements, which point to a differentiated interior for Ceres. We address the role played by hydrothermal activity in the long-term evolution of Ceres and especially the evolution of its hydrosphere. We suggest that models with times of formation shorter than about 5 My after the production of calcium–aluminum inclusions are more likely to undergo hydrothermal activity in their early history, which affects Ceres' long-term thermal evolution. We evaluate the conditions for preserving liquid water inside Ceres, a possibility enhanced by its warm surface temperature and the enrichment of its hydrosphere in a variety of chemical species. However, thermal modeling of the hydrosphere needs to be further investigated. We show that shape data can help constrain the amount of hydrated silicate in the core, and thus the extent of hydrothermal activity in Ceres. We discuss the importance of these results for the *Dawn* mission's arrival at Ceres in 2015.

1. Introduction

Ceres, Vesta and Pallas stand alone in the inner Solar System, defining a distinct class of objects (McCord et al., 2006). They are larger and more intact than asteroids, but smaller than the terrestrial planets. They are large enough to have attained a spheroid shape and experienced some planetary processes, but they are not called planets. Rather, the current name assigned to this class of objects is dwarf planets, although they often but inappropriately are referred to as asteroids or more appropriately as protoplanets. It is thought that, in the sequence of accretion from the Solar nebula, the terrestrial planets were formed from this class of objects (e.g., Canup and Agnor, 2000; Weidenschilling, 2006), but today only these three remain in the inner Solar System. Thus, Ceres and Vesta have become the targets of the NASA Discovery-class mission, *Dawn* (Russell et al., 2006) (Pallas's inclined orbit requires too much energy for *Dawn* to reach). *Dawn*'s successful launch in September 2007 has drawn more attention to these objects.

Ceres has been studied less than Vesta despite the intriguing indicator that Ceres contains about 25 wt.% water in the form of ice and/or bound to minerals, evidenced by its bulk density. A recent study of the current knowledge of Ceres and the possible thermal evolution scenarios (McCord and Sotin, 2003, 2004, 2005) indicated that Ceres is likely differentiated and highly thermo-chemically evolved, has retained most of its original water (some perhaps still in liquid form today), and underwent processes similar to those expected or observed in icy outer planet satellites, especially Europa. McCord and Sotin's differentiated Ceres model correctly predicted Ceres' shape; later confirmed with imaging from the *Hubble* Space Telescope (Thomas et al., 2005).

We continue the study of Ceres' evolution and current state, following the McCord and Sotin approach (Section 2). In our study we extend the range of possible initial conditions and update model parameters based on recent observations and calculations (Section 2.1.1). We focus on the evolution of Ceres' core and hydrosphere by comparison with other icy objects such as Europa, as well as relevant models for these bodies (Section 3). Especially we explore the possibility that the internal heating within the silicate core could lead to temperatures high enough for the hydrated silicates to dehydrate. Results of our models are discussed in Section 4. These models and their implications can be used for planning future observations by the *Dawn* spacecraft for its arrival at Ceres in 2015 (Section 5).

2. Thermo-physical modeling

2.1. Observational constraints

McCord and Sotin (2005) reviewed the available information about the physical and surface properties of Ceres, mostly from ground-based telescope observations. Since then, additional knowledge of Ceres primarily comes from observations using the *Hubble* Space Telescope (*HST*) Advanced Camera for Surveys

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(ACS) (e.g., Thomas et al., 2005; Li et al., 2006; Parker et al., 2006). Derived from these data are Ceres' global shape and a spatially resolved photometric map in three wide-band filters at 535, 335, and 223 nm. Carry et al. (2008) also recently published independent shape and compositional maps derived from observations with the Keck Telescope. We summarize below important aspects of this information for our study.

2.1.1. Size, density, and shape

A crucial constraint on Ceres' internal structure is Ceres' shape, recently and measured by Thomas et al. (2005) and Carry et al. (2008). These two datasets resulted in somewhat different shape determinations. Thomas et al. (2005) inferred from their observations with the *HST* that Ceres' mean radius is 476.2 ± 1.7 km, which is remarkably close to the value of 475 km derived by McCord and Sotin (2005) from a compilation of previous measurements. However, Carry et al. (2008) found a mean radius of 467.6 ± 2.2 km, which is closer to the occultation-based determination published by Millis et al. (1989). Both the *HST* and *Keck* studies showed that Ceres could be described as a rotationally symmetric, oblate spheroid. The major and minor equatorial radii are *almost* equal (within the measurement uncertainty of about 2 km) and in agreement with Ceres' shape's being in equilibrium with its current rotation period, which is ∼9.074 h (Chamberlain et al., 2007). However, the equatorial and polar axes determined by Thomas et al. (2005) and Carry et al. (2008) also differ by up to 10 km.

The recent mass determination of Ceres during its encounter with asteroid (5303) Parijskij (Kovačević and Kuzmanoski, 2007), combined with the Thomas et al. (2005) determination of its volume, yields a density of 2077 kg/m^3. McCord and Sotin (2005) derived from the literature an average density of 2100 kg/m^3, which they used in their models.

The difference between the equatorial and polar radii, which is related to the mean moment of inertia of the dwarf planet, has thus been found to be 32.5 ± 1.95 km (Thomas et al., 2005), 35.3 ± 2 km (Carry et al., 2008), and 25.3 km or 31.5 km (Millis et al., 1989) using different processing approaches for interpreting their stellar occultation dataset. While these determinations are in general agreement, the Thomas et al., measurements have been obtained over a much wider range in longitude than in other studies. Thus we use that determination as the main constraint on our modeling.

The absence of large topographic features at the spatial resolution of the HST observations, of the order of 60 km (Thomas et al., 2005) is evidence that Ceres is mostly relaxed. This is a striking difference from asteroids and Vesta. Considering that its current surface temperature is close to or greater than the creep temperature for known icy compositions, it is no surprise that Ceres' icy shell should be in hydrostatic equilibrium. However, we need gravity measurements and refined shape determination in order to determine whether or not its core is also hydrostatically relaxed. Schenk and McKinnon (2008) have suggested that the small deviation of Enceladus' shape from hydrostatic equilibrium could be the expression of large non-hydrostatic shape anomalies in the core of that object. Most models presented below indicate that Ceres' core could become relatively warm, up to 1000 K, which would have favored its relaxation.

From their measurements, Thomas et al. (2005) inferred that the body is differentiated into a core, probably with a hydrated silicate density (2700 kg/m^3), and an outer icy shell made of water (average density of 1000 kg/m^3). This is consistent with predictions inferred from thermal models by McCord and Sotin (2003, 2004, 2005). The Millis et al. results imply greater differentiation with more density concentration in the interior than implied by the Thomas et al. measurements. On the other hand, the Carry et al. (2008) measurements overlap with the upper bound of the Thomas et al. (2005) determination. Note that the upper bound of these shape data goes beyond the theoretical value expected for a fully undifferentiated Ceres. There is an infinity of possible models (within a class of models) that can explain the shape data and we address below the most realistic ones from a thermal evolution point of view.

2.1.2. Composition

McCord and Sotin (2005) noticed that Ceres' density is close to the density expected for a solar composition at Ceres' orbital semi-major axis (2.8 AU). They suggested that Ceres has probably lost little of its initial water content, and that the abundance of water in Ceres, as compared to Vesta, could be due to the difference in the time at which the two objects accreted.

Ceres' spectroscopic properties share similarities with carbonaceous chondrites (Cc). Its low radar albedo is also consistent with Cc mineralogy (Mitchell et al., 1996). Yet, Ceres' integrated-surface, visible-wavelength albedo of slightly less than 10% (Li et al., 2006) is higher than Cc material. The surface shows evidence of OH-bearing material from an absorption in the 3-μm spectral region (e.g., Lebofsky, 1978), suggesting aqueous alteration. OH–fluorescence has been reported near the North Pole from International Ultraviolet Explorer (IUE) Earth-orbiting telescope observations, suggesting loss of OH or H_2O (A'Hearn and Feldman, 1992). However, that feature seemed to be transitory, and such an observation has not been reproduced. While water is not stable on most of Ceres' surface, Fanale and Salvail (1989) demonstrated that it can be stable a few tens of meters below a regolith layer, and that loss from a water-rich subsurface source could supply the observed fluorescent material over geologic time.

Li et al. (2006) have reported surface albedo variations from ∼0.02 to ∼0.16, with 11 surface albedo features suggestive of surface processes such as from tectonics and impact cratering, although no specific geological feature has been identified at the surface of Ceres. Carry et al. (2008) have suggested that the dark albedo areas on Ceres's surface, with the Keck II Observatory near infra-red H-band, could be attributed to the presence of dirty ice or frost. Microwave dielectric measurements by Webster et al. (1988) are consistent with the possibility that Ceres' surface is covered with dry clays, which these authors attributed to impacts from micro-meteorites on hydrothermally altered basic rock or Cc material. However, thermal emission spectroscopy also indicates the presence of iron-poor olivine, i.e., dry silicate, possibly on top of phyllosilicates (Witteborn et al., 2000). It has been speculated that salt minerals may be present on the surface, thereby raising its albedo. Salts have been reported in some Cc meteorites, and are interpreted as having formed from hydrous alteration. Since McCord and Sotin, the spectral signatures of carbonates and iron-rich clays have been identified on the surface of Ceres (Rivkin et al., 2006). Carry et al. (2008) confirmed that the spectral properties of the brightest regions on Ceres can be explained by carbonates and phyllosilicates. Milliken and Rivkin (2009) showed that these carbonates and brucite are globally in constant amount throughout Ceres' surface. These authors suggested evidence for contemporaneous formations of these minerals. Rivkin and Volquardsen (2008) concluded that the presence of such compounds is indicative of significant and widespread aqueous alteration, and Milliken and Rivkin suggested that they could have formed as the result of hydrothermal alteration induced by impacts on Ceres' outer dusty crust or regolith. Ceres is only the third object in the Solar system on which carbonates have been identified, after Earth and Mars.

Vernazza et al. (2005) have also interpreted the presence of a 3.06 μm absorption feature as a possible indicate of ion-irradiated organics mixed with water ice, while King et al. (1992) have attributed it to ammonium saponite.

2.1.3. Surface temperature

Surface temperature is an important boundary condition for thermal modeling. McCord and Sotin summarized what was then the current state of knowledge concerning surface temperature. They used 200 K, while noting the (small) effects of using different surface temperatures in their models. Temperature obviously varies over the surface and with depth. Several studies, including the recent Li et al. (2006) measurements, have calculated, a maximum temperature of 235 K near the equator, with potentially higher estimates for localized low-albedo regions. Temperatures are much lower on the nighttime hemisphere, depending on the thermal inertia of the surface layer. Fanale and Salvail (1989) computed constant, diurnally damped, near sub-surface (a few to 10 m deep) temperatures that vary in latitude from 130 K at the poles to 180 K at their equator. Their model is based on several assumptions (circular orbit, spin vector normal to the orbital plane, same albedo over the surface), and should be reconsidered based on recent mapping of Ceres' surface albedo (Li et al., 2006). We use a temperature of 180 K at the equator for our models as an endmember parameter.

2.2. Initial conditions

By initial conditions, we mean those that reflect the conditions in the Ceres body at the end of its accretion from smaller planetesimals, and as it begins to evolve as an integral solid body. These include: the initial composition, temperature profile, and (most importantly) the time of formation of this object from its planetesimal source material with respect to the production of CAIs, hereafter labeled t_{0-CAIs}.

2.2.1. Possible scenarios for Ceres' origin and time of formation

It is generally thought that Ceres formed *in situ* in the outer main asteroid belt (e.g., Turrini, D., Magni, G., Coradini, A., 2009. Probing the history of Solar System through the cratering records on Vesta and Ceres. Available from: <arXiv:0902.3579v1>). Its dynamical properties support such a scenario: its eccentricity, about 0.08, is slightly smaller the average eccentricity for the asteroids found in this region, while its inclination, about 10.6 deg., is in the average (see http://filer.case.edu/~sjr16/advanced/asteroid.html). Also models of accretion in the Solar system indicate that objects of the mass of Ceres must have been common in the early Solar system (e.g., Weidenschilling, 2008).

There is little or no direct evidence to constrain the time of formation for Ceres. However, Weidenschilling and Cuzzi (2006) and Chambers (2006) present a bulk of evidence that the meteorite parent bodies formed at least 1–3 My after the production of CAIs. As an upper bound, the hafnium/tungsten ratio (Hf/W) anomaly reported by Yin et al. (2002) indicates that inner Solar system objects accreted within 10 My following formation of the Sun. Kleine et al. (2002) dated HED material, suggested to represent Vesta's mantle and core, as 3.8 ± 1.3 My after CAIs. Ghosh and McSween (1998) model investigating the role of ^{26}Al in differentiating that protoplanet suggested a time of formation of about 2.9 My after CAIs.

The difference between the two dwarf planets Vesta and Ceres is puzzling. It has been suggested that Vesta could have formed slightly before Ceres and the latter would have accreted less ^{26}Al (see McCord and Sotin (2005) for discussions of that scenario). Models by Turrini et al. (Turrini, D., Magni, G., Coradini, A., 2009. Probing the history of Solar System through the cratering records on Vesta and Ceres. Available from: <arXiv:0902.3579v1>) actually form these objects in the same timeframe as a result of the interaction of planetesimals inside and beyond the snow line with Jupiter. However, Ghosh et al. (2006) suggested that the increasing duration of accretion with increasing heliocentric distance as a possible explanation for the thermal zoning observed across the asteroid belt. By its location slightly farther from the Sun, by ~0.4 AU, and its volume, about five times larger than Vesta, it is expected that Ceres could have accreted over a longer timescale with respect to Vesta. As a result, even if the two protoplanets started forming at about the same time, Ceres could have been less affected by ^{26}Al decay heating, as it was provided over a longer timescale. Besides, the Turrini et al. (Turrini, D., Magni, G., Coradini, A., 2009. Probing the history of Solar System through the cratering records on Vesta and Ceres. Available from: <arXiv:0902.3579v1>) models demonstrate a preferential accretion of icy planetesimals on Ceres with respect to Vesta as a result of resonant interaction with Jupiter and assuming different scenarios for Jupiter's migration in the early Solar system.

Alternative scenarios have recently been suggested for the origin of Ceres. McKinnon (2008) has suggested that Ceres could have been injected from the Kuiper Belt. In the frame of the Nice model (e.g., Gomes et al., 2005), Ceres would have formed in the transneptunian region, with a temperature lower than 50 K, and on a timescale of several tens to hundreds My, as is considered to be the case for large icy objects in the outer Solar system (e.g., Gladman et al., 2001). Another scenario considers that part of the volatile component of Ceres could result from the inward migration in the disk of planetesimals less than a few meters thick as a result of gas friction (Mousis and Alibert, 2005). This scenario was generalized by Mousis et al. (2008) for explaining the origin of the volatile component in low-density asteroids in the main belt.

Recently Zolotov (2009) suggested that Ceres could have accreted from evolved planetesimals mainly composed of hydrated silicates. That model assumes that Ceres formed after ^{26}Al had decayed so that there was little thermal evolution of the protoplanet after accretion. This implies a time lag of several My between planetesimal hydration as a result of ^{26}Al and their accretion into Ceres. Also, that model implies that Ceres's was actually depleted in volatiles with respect to the ice-rich model considered in this study. Zolotov's (2009) undifferentiated Ceres would have maintained 10–15% porosity after accretion, accounting for the observed density. Britt et al. (2002) estimated that considering its size, Ceres could not preserve more than 7% porosity in bulk. After quantifying and removing the amount of microporosity as observed in meteorite analogs, Britt et al. even concluded that macroporosity is negligible in Ceres. The thermomechanical evolution of such an assemblage of hydrated silicate subject to long-lived radiogenic heating needs to be carried out in order to further assess the viability of this model.

The time and duration of formation of any object with respect to CAIs is important because it determines the amount of heat provided for the first 5 My after accretion. Castillo-Rogez et al. (2007a,b) showed that, depending on the rock mass fraction, the effect of short-lived radioactive isotopes (SLRI), and especially ^{26}Al decay, can tremendously affect the long-term evolution of Iapetus and Enceladus, as was also pointed out for asteroid belt objects by Grimm and McSween (1989), Young et al. (2003), and McCord and Sotin (2005) for Cc parent bodies. Wilson et al. (1999) explored the consequences of intense ^{26}Al heating in the volatile-rich planetesimals that accreted into larger Cc parent bodies. These authors pointed out that planetesimals a few tens km across would likely disrupt (as a result of explosion analog to hydraulic cracking) if they accreted early, and there probably were several such episodes before larger Cc parent bodies could develop. For this study we assume that Ceres could not form earlier than 2 My after the production of CAIs, as before then the ^{26}Al heating would have been very intense. We adopt an upper bound for the time of formation equal to 10 My, when ^{26}Al and ^{60}Fe are no longer active heat producers.

2.2.2. Initial temperature

There are only weak constraints on the temperature of the accretion environment and the initial temperature of the planetesimals from which Ceres accreted. Ghosh and McSween (1998) reviewed available constraints for Vesta formation at about 2.2 AU from the Sun and inferred a temperature range of 90–300 K. Mousis and Alibert (2005) showed that temperatures of about 90 K were realistic in the solar nebula.

After the dissipation of the Solar nebula, in about 3–5 My (see Scott, 2006, for a review of the arguments supporting that estimate), its surface temperature was primarily a function of solar luminosity, which is thought to have been 90% of its current value (e.g., Endal, 1980) and albedo. Thus, Ceres' maximum surface temperature after nebula dissipation could have been close to 150 K.

We consider two values for the initial temperature of planetesimal temperatures: 90 and 150 K. For the former end-member, we assume that ammonia accreted in Ceres. After the nebula dissipated, Ceres' surface temperature was a function of the Sun's luminosity and its surface albedo, with some latitudinal variations. Our models consider the temperature at its equator.

The internal temperature profile of the Ceres body at the end of accretion is a function of the fraction of accretional energy turned into heat, h_a for each layer. If we compute that parameter following Squyres et al. (1988), we find a maximum temperature increase in Ceres as a result of accretional heat of about 60 K, a few tens of kilometers below the surface. The actual contribution of accretional heat on the initial temperature profile is a function of the accretion duration. While many models of asteroids have considered instantaneous accretion (see Ghosh et al., 2006, for a review), recent models of planetary embryo formation show that in the outer main belt embryos need about 1 My to achieve Ceres' mass (Weidenschilling, 2008; Turrini, D., Magni, G., Coradini, A., 2009. Probing the history of Solar System through the cratering records on Vesta and Ceres. Available from: <arXiv:0902.3579v1>). In such case, the contribution of the energy deposited in accreting planetesimals is not significant for the geophysical evolution of the object (see also calculation of impact heating at Ceres by Turrini, D., Magni, G., Coradini, A., 2009. Probing the history of Solar System through the cratering records on Vesta and Ceres. Available from: <arXiv:0902.3579v1>).

The starting times of our models is the end of accretion, which means that we do not consider the effect of ^{26}Al heating provided during the accretion, although the latter could have contributed to early melting, possible aqueous alteration of the silicate phase in the growing protoplanet (Young, 2001; Travis and Schubert, 2005), and possible early degassing (e.g., Schaefer and Fegley, 2007). Detailed modeling of these processes is beyond the scope of our study.

2.2.3. Initial composition

2.2.3.1. Early nature of the silicate phase. An ordinary chondrite composition is usually assumed for the silicate phase incorporated into the planetesimals and into Ceres. However the matrices of Cc, and especially CI and CM chondrites are primarily composed of hydrated and oxidized minerals (e.g., Buseck and Hua, 1993). It has been proposed that some hydration of this material might occur in the solar nebula before accretion (Ciesla et al., 2003). However, this idea is not widely accepted by the meteorite community, and would require in-depth modeling, which is beyond the scope of this study. It is more widely believed that the silicates were aqueously altered and metasomatized in the early planetesimals as a result of hydrothermal activity (e.g., Wilson et al., 1999; Young, 2001). If the planetesimals that formed Ceres, accreted in less than about 5 My after CAIs, the heat from SLRI decay could drive some hydrothermal activity in the early objects, which could have entailed hydration of the silicate phase or even driving off part the water (see also Grimm and McSween, 1989; Wilson et al., 1999; Keil, 2000; Young et al., 2003; Travis and Schubert, 2005; McCord and Sotin, 2005; Palguta et al., 2007). In such conditions, it is also possible that silicate hydration proceeded while Ceres was differentiating following ice melting (e.g., Zolotov and Mironenko, 2008; Castillo-Rogez et al., 2008).

McCord and Sotin (2005) found that even with only long-lived radioactive nuclides (same as accretion after ~7 My after CAIs) most of Ceres' water melts and Ceres becomes differentiated. In such conditions, the silicate may have been less affected by hydration due to less favorable kinetic conditions although Zolotov and Mironenko (2007) show that aqueous alteration in Cc parent bodies could have started at temperatures as low as 186 K, at the eutectic melting of HCl-ice mixtures condensed from the nebula.

2.2.3.2. Composition in radioisotopes. We use dry, ordinary chondrite material to represent the rock component within Ceres and as our reference for calculating the radioisotope content. Ordinary chondrite material has an average density 3510 kg/m^3. For Ceres, this density allows us to infer a rock mass fraction of about 74%, using the current mass and density, which gives a water content of 26% (cf. McCord and Sotin (2005), Fig. 1). Major short-lived and long-lived radioisotopes contents used here for dry, ordinary chondritic material, based on Wasson and Kalleymen (1988), are presented in Table 1. The heat constants for these radiogenic elements are presented in Tables 2 and 3. For the initial concentration of ^{26}Al, we use the canonical abundance by Wasserburg and Papanastassiou (1982). A higher abundance was recently proposed by Young et al. (2005), which differs by 20% from the canonical value (6.5×10^{-5}). However, this higher, "supercanonical" value is being debated, and thus we use the lower, "canonical" value.

The initial concentration of ^{60}Fe is currently the object of intense research. Estimates of the initial $(^{56}Fe/^{60}Fe)_0$ ratio have increased by 10^3 over the past 15 years. Values as high as 10^{-6} have been suggested for that ratio (e.g., Mostefaoui et al., 2005). In their review of these results, Chen et al. (2009) argued that recent measurements of the ratio ^{56}Fe/^{60}Fe equal to 10^{-6} could be affected by instrumental procedures. They suggest $^{56}Fe/^{60}Fe = 0.5 \times 10^{-6}$ as a reasonable upper bound for this initial concentration, and 10^{-7} as a lower bound. This is two orders of magnitude greater than the value used by McCord and Sotin (2005), which they based on Shukolyukov and Lugmair (1993). Measurements of the initial concentration in ^{60}Fe indicate that this isotope was possibly heterogeneously distributed in the inner Solar system (Gounelle and Russell, 2005a,b). The actual presence of ^{60}Fe even existing in the early Solar system is a matter of debate (e.g., Chen et al., 2009). While ^{60}Fe decay contributes at most ~20% to the total heat production resulting from SLRI decay, Castillo-Rogez et al. (2007b) show for a rock-rich object like Enceladus that ^{60}Fe decay can result in a rapid temperature increase in the core during the 10 My following differentiation. In our models we use the bounds on the initial $(^{56}Fe/^{60}Fe)_0 = 0.1–1 \times 10^{-6}$.

2.2.3.3. Composition in volatiles and carbon compounds. The volatile phase of the Ceres-forming material is primarily water, but it would be contaminated with other compounds as a function of pressure and temperature in the sub-nebula, including carbon and perhaps carbon compounds. It is not clear whether the solar nebula provided organics to the planetesimals (as found in Ccs), if they were produced in planetesimals as a result of hydrothermal activity triggered by ^{26}Al decay (see also Guo and Eiler, 2007), or if they were produced in meteorite parent bodies after accretion. Nevertheless, hydrothermal activity, and the resulting serpentinization and associated hydrogen production expected in a rock-rich icy object like Ceres (or Enceladus), provides a context favorable to organic molecules production (e.g., Cohen and Coker, 2000; Matson

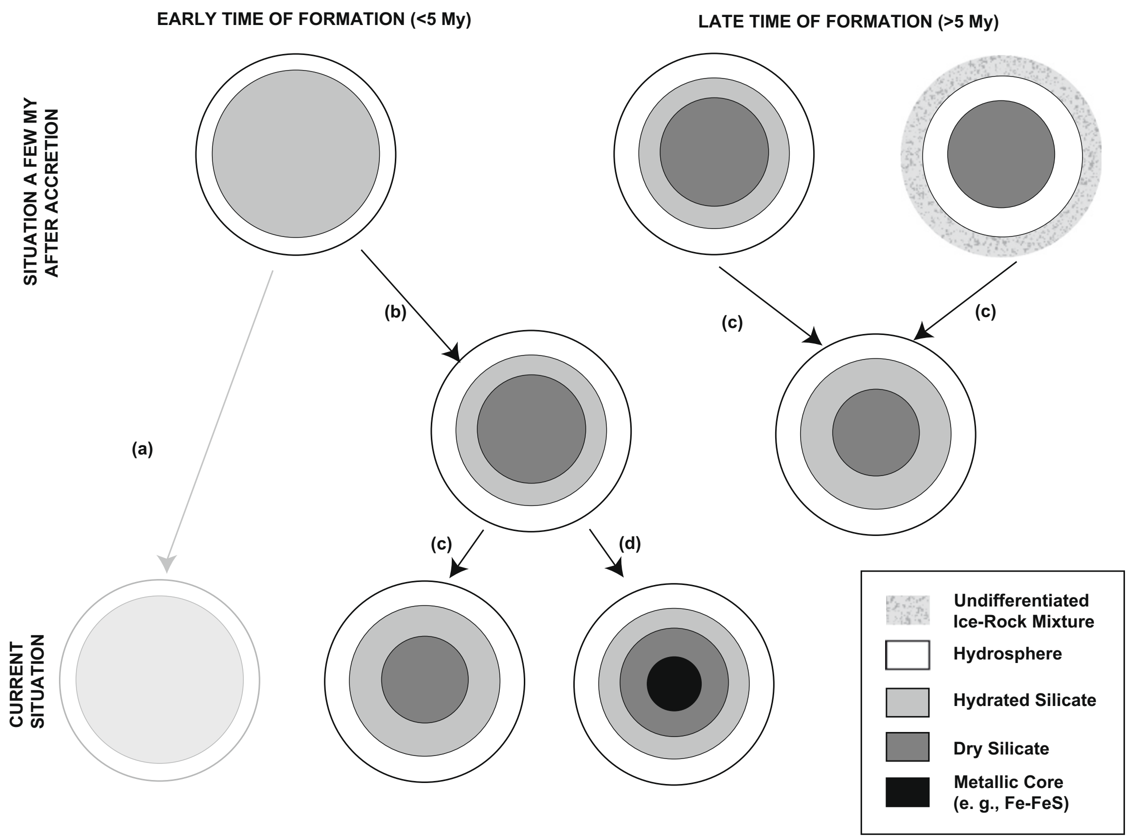

Fig. 1. Evolutionary paths for Ceres' core as a function of initial conditions and the possible extent of hydrothermal circulation. Sketches at the top describe possible conditions a few My following accretion, i.e., function of the nature of the silicate in accreting planetesimals and the amount of heat produced by short-lived radioisotope decay. For times of formation shorter than 5 My after the production of CAIs, it is likely a large part of the silicate phase is hydrated, due to the hydrothermal activity triggered by ^{26}Al decay, in the planetesimals and/or in the accreting planet. It is possible then that the presence of hydrothermal minerals affected the core permeability, limiting hydrothermal cooling. In such a case, hydrated minerals played several roles in warming the core. Temperatures could be reached for silicate dehydration, and possibly melting to occur. For longer times of formation, it is less likely that early history conditions were suitable for silicate hydration to occur, thus more likely that little if any of the silicate minerals were hydrated at the end of accretion. Silicate hydration could occur later driven by cracks opening resulting from the cooling of the core.

Table 1
Composition of the CI and ordinary chondrites in main radioisotopes (after Wasson and Kalleymen, 1988).

	CI chondrite	Ordinary chondrite
Density (kg/m^3)	2756	3510
^{26}Al (ppb)	525	600
^{60}Fe (ppb)	111–222	107.5–215
^{53}Mn (ppb)	23.2	25.7
^{40}K (ppb)	943	1104
^{232}Th (ppb)	44.3	53.8
^{235}U (ppb)	6.27	8.2
^{238}U (ppb)	20.2	26.2

et al., 2007), given the presence of carbon. If Phoebe formed in the Kuiper Belt or accreted planetesimals migrated from that region as suggested by McKinnon (2008) and Mousis and Alibert (2005) (see Section 2.2.1), it is possible that Ceres could have accreted ammonia and possibly carbon dioxide, as well as methanol, a volatile expected to have condensed in the far outer Solar system (e.g., Notesco and Bar-Nun, 1997). Comet observations indicate that that compound could represent a few percent of the volatile phase (e.g., Bockelee-Morvan et al., 2004 for a review). The accretion of methanol and ammonia could decrease the eutectic temperature to as low as 103 K and further promote early and quasi-total differentiation of Ceres.

Table 3
Decay information for the short-lived radioisotopes used in this study. References are gathered in Castillo-Rogez et al. (2007, 2009).

Parent nuclide	^{26}Al	^{60}Fe
Daughter nuclide	^{26}Mg	^{60}Ni
Initial isotopic abundance	^{26}Al/^{27}Al	^{60}Fe/^{56}Fe
	5×10^{-5}	$0.1–1 \times 10^{-6}$
Half-life λ (My)	0.717	1.5
Specific heat production (W/kg)	0.357	0.063

Table 2
Decay information for the long-lived radioisotopes. Adapted from Van Schmus (1995).

Element	Potassium	Thorium	Uranium	
Isotope	^{40}K	^{232}Th	^{235}U	^{238}U
Isotopic abundance (wt.%)	0.01176	100.00	0.71	99.28
Decay constant (y^{-1})	5.54×10^{-10}	4.95×10^{-11}	9.85×10^{-10}	1.551×10^{-10}
Half-life λ (My)	1277	14010–14050	703.81	4468
Specific heat production (W/kg of elements)	29.17×10^{-6}	26.38×10^{-6}	568.7×10^{-6}	94.65×10^{-6}

2.2.4. Initial structure

We assume that the body formed as a homogeneous mixture of ice and rock. The maximum pressure reached in a homogeneous Ceres is about 150 MPa. Whether we start the models at a temperature of 90 K (including ammonia) or at a temperature of 150 K, due to its size, little porosity is expected in Ceres after its accretion.

The different assumptions we make on the early state of Ceres' interior are summarized in Fig. 1.

2.3. Algorithm

The algorithm used to perform the calculation is based on the software by Castillo-Rogez et al. (2007a). We follow the same modeling approach as McCord and Sotin (2005) and assume in the calculations that thermal transfer occurs only by conduction. The variables used in the models are presented in Table 4. We use the material properties presented in Waples and Waples (2004), Wilson et al. (2008), and Castillo-Rogez et al. (2007a). However, we use revised values for the radioisotope heat decay constants (after Castillo-Rogez et al., 2007a, 2009). For each time step, of 10^4 y, our software compares temperature and pressure conditions against the phase diagrams for the different materials involved in Ceres' structure. The models presented in the present study do not take into account lateral variations of temperature. Certainly large variations of temperature between the equator and the poles can be the source of lateral variations of Ceres' shell outer shell properties, as has been modeled for Europa (Tobie et al., 2003).

An important consequence of the significant heating resulting from ^{26}Al decay on a very short time scale is that it can lead to melting of the volatile phase before convection can set on, i.e., on timescales of a few hundred thousand years. For times of accretion 5 My after CAIs and later, convection could start if we assume that the volatile phase does not contain impurities that could depress the ice melting temperature.

We do not model convection in the silicate core, hydrosphere or crust. It is not clear whether convection is likely to take place in Ceres' core. The core is heated from within and thus the convective transfer mode involves the down-welling of cold plumes, as described by Korenaga and Jordan (2002). However, the core is small, and as mentioned above, likely stratified in an outer layer made of low-density hydrated silicate and an internal core made of denser, dehydrated, formerly hydrated silicate. This, the core's sphericity, and the low gravity environment mitigate the development at depth of cold plumes. Whether convection can start or not in such conditions requires further investigation. This is actually a problem inherent to all the studies on medium-sized ice-rock objects. See Castillo-Rogez et al. (2007a) for further discussion for a model of Iapetus' core, which would have about the same size as Ceres' core.

Conditions for convection to start in Ceres' icy shell are discussed in McCord and Sotin (2005). Convection is expected to start when the thermal boundary layer becomes a few tens of km thick. The difference in temperature between the surface and the interior, and thus the ice viscosity gradient, is not as great for the Ceres case as in the case of icy satellites. At the outer planet satellites, the very low surface temperature results in a very thick high-viscosity upper crust, which can never be involved in convection processes (stagnant-lid convection model). Ceres' warmer surface temperature may make it easier for the crust to be disrupted as a result of convective stress, and to involve a plate convection regime as has been suggested in the case of Enceladus by Barr (2008). We consider only thermal conductive transfer in a simplified hydrosphere in our models. Convection modeling in the complex hydrospheric model described below is complex and requires a specific approach that has not been investigated in the case of other objects likely to have undergone hydrogeochemistry. That hydrospheric model involves the presence of insulating salt layers at the base of the ocean (cf. Enceladus' ocean models by Zolotov (2007) and Prieto-Ballesteros and Kargel (2005)) as well as ^{40}K in solution and possibly ^{40}K and ^{238}U-bearin precipitates. By assuming only thermal conductive heat transfer we obtain an upper bound on the thermal evolution of that layer. However we also discuss in details the situation if rapid convective heat transfer would drive Ceres' hydrosphere toward being in thermal equilibrium with its surface temperature.

3. Thermal evolution models

We describe the results of our models and particularly the processes expected to have taken place in Ceres as a function of initial conditions. We illustrate various situations with relevant thermal evolution models (Figs. 2 and 3). The models differ in their final core structure depending on (1) the time of formation after CAIs, and (2) the extent of hydrothermal circulation in the core, which are main evolution drivers in our models. McCord and Sotin (2005) used heat decay constants for ^{26}Al that were about 2.5 smaller than the current value for that parameter. As a result, for the same times of formation, our models are warmer than the models computed by McCord and Sotin (2005). For $t_{0-CAIs} < 5$ My, all of our models show the ice melting and differentiation into a silicate core, liquid water mantle and solid ice crust. Our emphasis here is on the extent and type of core development and the potential for liquid water today. This varies with accretion time and other assumptions, discussed below, and involves very complicated and poorly understood processes for a body such as Ceres in its formative period.

3.1. Differentiation and structure post-differentiation

3.1.1. Differentiation and early state of the core

For accretion time $t_{0-CAIs} < 5$ My, conditions are suitable for differentiation to be completed a few My after formation (Figs. 2a, b and 3), regardless of whether ammonia accreted in Ceres. The initial temperature has little consequence with respect to the overall evolution, as the difference between the bounds for this parameter is small compared to the potential temperature increase from ^{26}Al decay.

Table 4
Main parameters investigated.

Model component	Parameter	Cases	Reference
Composition volatiles		Ammonia–water (<10%) or pure water	Mousis and Alibert (2005)
Initial temperature (K)	T_i	90 or 150 K	See discussion in Section 2.2.3
Accretion characteristics	h_a	0.1 or 1	Function of the accretion rate. See discussion in Section 2.2.3
Time of formation with respect to CAIs	t_{0-CAIs}	1–10 My	
Surface temperature	T_s	180 and 200 K	Fanale and Salvail (1989)
Initial concentration in ^{60}Fe	$(^{56}Fe/^{60}Fe)_0$	5×10^{-7}–1×10^{-7}	Chen et al. (2009)
Hydrated silicate thermal conductivity		0.5–1.5 W/K/m	Clauser and Huenges (1995)
Salt layer density	ρ_{salt}	1000–1300 kg/m^3	Kargel et al. (2000) – plays a role in the calculation of the radii

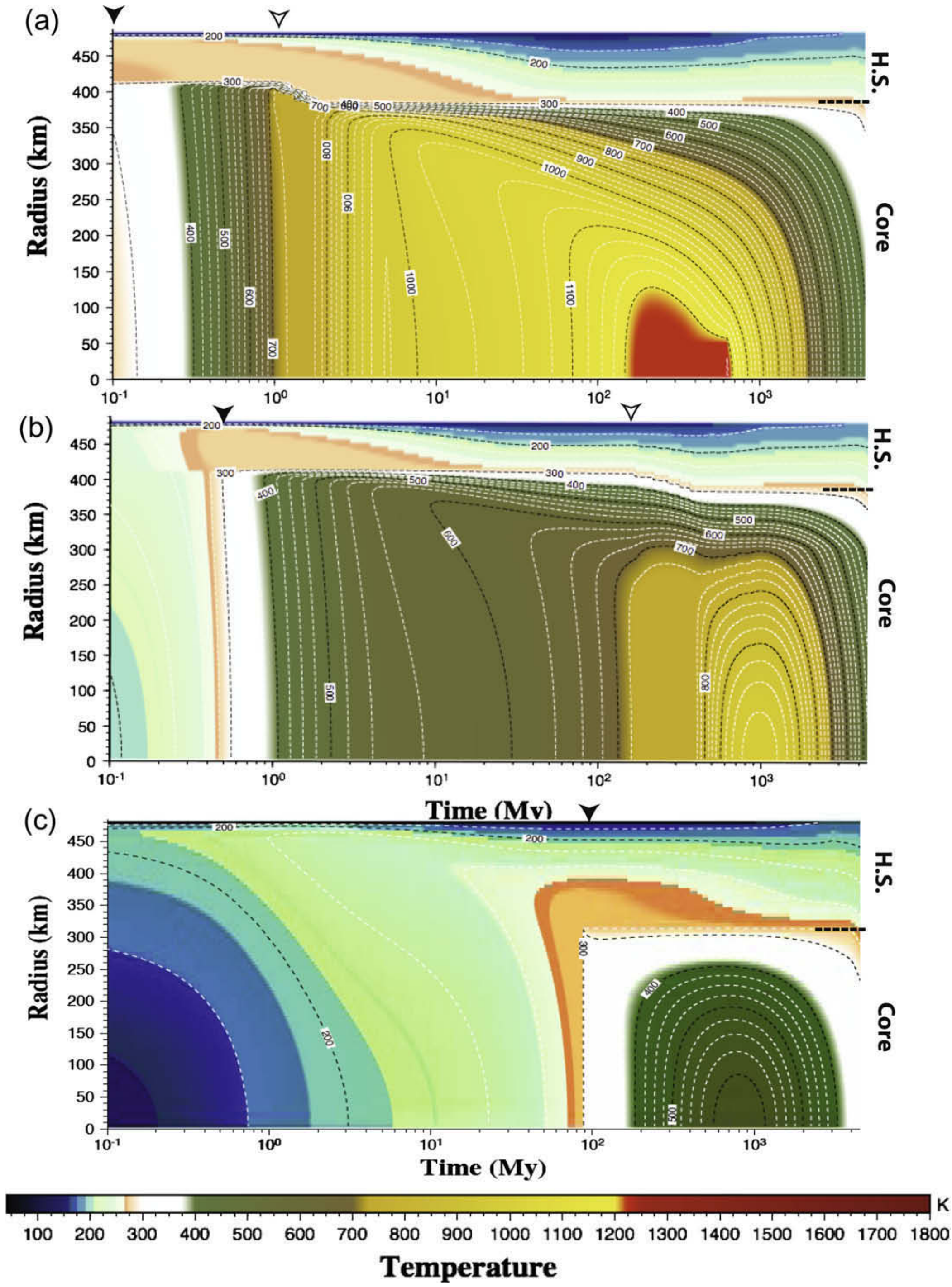

Fig. 2. Examples of thermal evolution models for Ceres. Temperature is plotted as a function of radius and time (on a log scale) since accretion. The time at the extreme left is the start of the model. The time at the extreme right is the present. The temperature contours are every 25 K. Numerical call-outs temperature are in Kelvin. The color scheme indicates geophysically significant temperatures. Times of formation are (a) 2 My after CAIs, (b) 3 My after CAIs, (c) 5 My after CAIs. For all models the surface temperature is 180 K, the initial temperature is 150 K, the initial concentration in $^{60}Fe/^{56}Fe$ is 1×10^{-7}. All models assume a gradual increase in surface temperature in order to reflect solar luminosity evolution. The arrows point to two important events in the evolution of the model: black arrows mark internal differentiation possibly associated with serpentinization of part or all of the silicate phase; white arrows mark the start of silicate dehydration. "H.S." indicates the hydrosphere.

For longer times of formation, i.e., effectively with only long-lived radiogenic heating, Ceres' interior ice still melts and differentiates but the surface of Ceres remains unmelted (as found by McCord and Sotin, 2005). The thickness of this surface layer is dependent on ice composition, and can vary from a few tens of kilometers, for the case of dirty ice, to 100 km for the unlikely case of a pure water–ice crust (Fig. 2c). This crustal layer likely would eventually collapse into Ceres, as it would be gravitationally unstable as discussed McCord and Sotin (2005). Even if it would remain at the surface, for example, if it is sufficiently porous, the presence of volatiles and CO_2 ice could lower the ice creep temperature and melting point, causing this layer to compact and sink, and even partially melt and differentiate. Intense cratering during the late heavy bombardment phase of Solar System evolution as well as

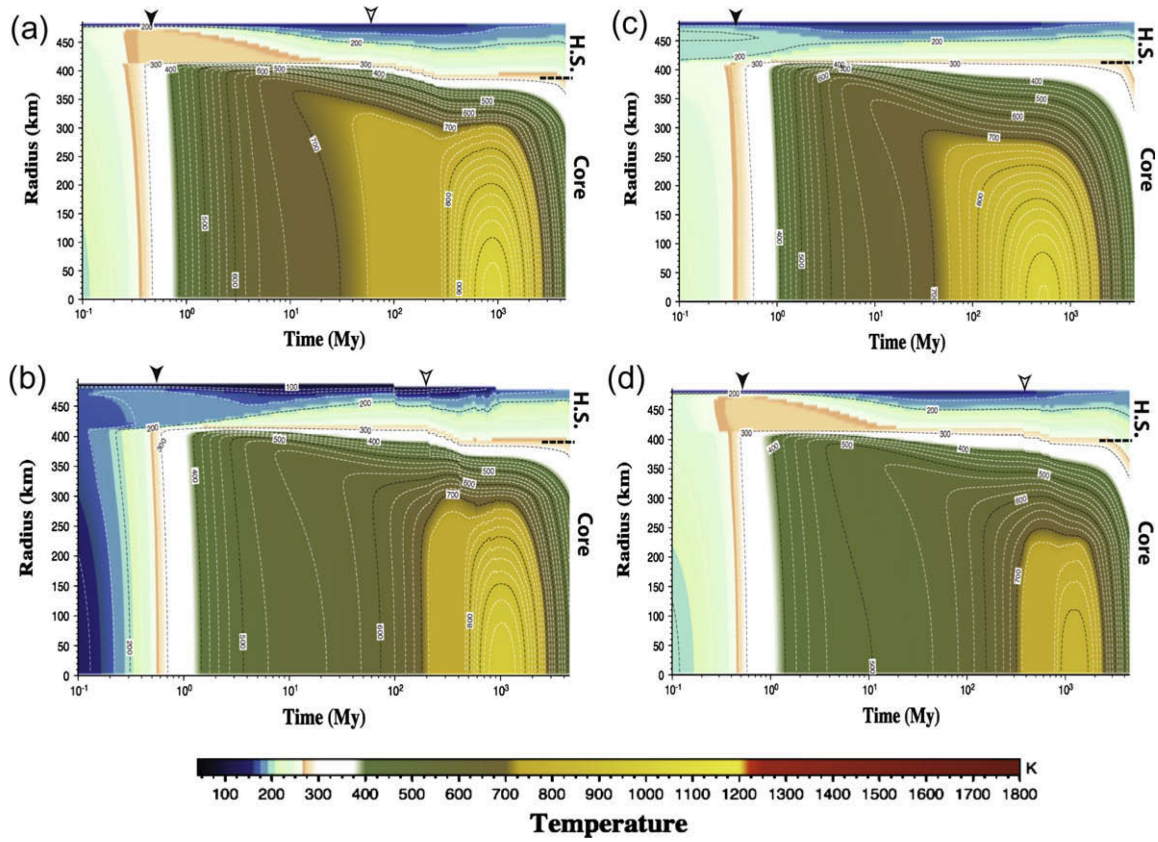

Fig. 3. Variations of the models presented in Fig. 2b by changing one parameter at a time: (a) The initial concentration $^{60}Fe/^{56}Fe$ is 1×10^{-6}; (b) accretion of ammonia for an accretional temperature of 90 K; (c) assumption that after differentiation the silicate phase has not been hydrated; (d) assumption that part of the long-lived radioisotopes present in the rock phase are released to the ocean during an early hydrothermal phase. Then the carbonaceous chondrite composition in K, Th, and U is used for computing the thermal evolution of the core. These elements are ''stored'' at the interface between the core and the ocean, but the consequences on heat transfer in the outer shell is not properly modeled. "H.S." indicates the hydrosphere.

large-scale tectonics associated with global dimensional change due to freezing and melting would further contribute to destabilizing this layer, as discussed by McCord and Sotin (2005) and Zolotov (2009). In summary, it is doubtful that a rock-rich body like Ceres could retain its original crust until present, even assuming only long-lived radionuclide heating.

It has been suggested in early meteorite chemistry and parent body studies, and in more recent small planet evolution studies (Grimm and McSween, 1989; Cohen and Coker, 2000; Keil, 2000; McCord and Sotin, 2005; Young et al., 2003; Travis and Schubert, 2005; Palguta et al., 2007; Castillo-Rogez et al., 2007a,b), that ^{26}Al decay heating probably triggers rapid differentiation, during which conditions are favorable for hydrothermal activity, metasomatism (i.e., chemical alteration of rock by hydrothermal and other fluids) and particularly serpentinization (aqueous alteration of ultramafic rock). This heat production might be regulated by hydrothermal cooling (convection and differentiation). On the other hand, the hydration could become a runaway process, as silicate hydration is exothermic (233 kJ/kg of silicate, i.e., about 100 times the specific heat of 1 kg of Ceres' material). Silicate alteration is a process that happens on a less than a hundred year timescale and its kinetics is enhanced when the temperature reaches 50 °C and becomes optimum for a temperature of 250 °C (e.g., Allen and Seyfried, 2004).

There is more uncertainty about the extent of silicate hydration at the end of differentiation. If Ceres formed less than 5 My after CAIs, it seems like its silicate phase could be partially hydrated, starting in the planetesimals, and then during early aqueous alteration. If Ceres formed later, then, it is still probable that at least part of its silicate would be hydrated as a result of aqueous alteration during differentiation. It has recently been suggested that aqueous alteration may have started at temperatures as low as 186 K (Zolotov and Mironenko, 2007). Further work (especially laboratory work) is needed to better estimate hydration kinetics for temperatures near the water ice freezing point.

In our models we consider the long-term evolution of two end-members: full silicate hydration, and no silicate hydration at the end of differentiation (Fig. 1).

3.1.2. Internal state after differentiation

The structure of the core and chemical nature of the liquid mantle after differentiation are of prime interest in this study. An important unknown concerning the ocean chemistry following differentiation is the temperature and pressure. These determine the saturation of the ocean in H_2 and the redox conditions in the ocean, i.e., the production and stability of oxidized (e.g., sulfates) or reduced species (e.g., sulfides). Most Cc material shows an abundance of oxidized minerals such as sulfates, which indicates that the conditions in their parent bodies were oxidizing. This is discussed by McKinnon and Zolensky (2003). The amount of H_2 stored in the ocean is a function of various parameters. High internal pressure in large objects accreting in a H_2-rich nebula favors the saturation of the ocean in H_2 (McKinnon and Zolensky, 2003). However, degassing of H_2 may have occurred in small planetesimals if they were subject to hydrothermal processes, for example triggered by ^{26}Al decay. The release of iron to the ocean as a consequence of aqueous alteration is another parameters that makes the ocean a more reducing environment. Thus assessing what the redox conditions were in the liquid phase of differentiated meteorite parent bodies requires specific modeling that is beyond the scope of the present paper. The key point is that a variety of minerals can form as a result of hydrothermal geochemistry and can affect the long-term evolution of the icy shell. If such minerals were found at the surface, they would be likely evidence for interior thermodynamic evolution and the conditions experienced (e.g., Deer and Zussman, 1992). We discuss some of these effects here based on terrestrial analogs and thermodynamical studies to illustrate the rich chemistry involved and the variety of product that might be observed by *Dawn* and other techniques.

3.1.2.1. Silicate chemistry. In the presence of CO_2, serpentine can react to form talc, magnesite, and water. Given sufficient pressures and temperatures, olivine, and plagioclase can react with water to produce orthophyroxene, horneblend, and spinel. Pyroxene-rich rock produces additional minerals.

3.1.2.2. Ocean chemistry. Theoretical modeling of icy satellites chemistry (e.g., Kargel et al., 2000; Zolotov and Shock, 2001; Zolotov, 2007) using Cc as the starting composition indicates the magnesium-, potassium-, and sodium-sulfates, hydrates, carbonates, and chlorides are the primary constituents accumulating in the ocean. Furthermore, a layer of hydroxides could be deposited at the surface of Ceres' core as proposed for Titan's core (Fortes et al., 2007). Clathrate hydrates could also be stable under Ceres' conditions (Mathieu Choukroun, personal communication) and could store methane, H_2S, argon, etc. as also suggested by (Prieto-Ballesteros et al., 2005) in the case of Europa.

3.1.2.3. The fate of ammonia. Reactions involving ammonia could lead to the production of molecular nitrogen, as has been observed in Enceladus' geyser, which Matson et al. (2007) and Glein et al. (2008) suspect to be of hydrothermal origin. Ammonia might also transform into ammonium salt, as predicted by chemical models (Kargel, 1992; Fortes et al., 2007) and/or amino acids (e.g., Schulte and Shock, 1995). The reported detection of an ammonium compound (suggested to be ammoniated saponite) by King et al. (1992) supports such models but this unique detection needs to be confirmed by future observations. The presence of an ammonium compound would also help constrain model parameters because it requires that secondary temperatures inside Ceres, at least in some places, did not exceed 400 K.

3.1.2.4. Organic chemistry. The abundance of organic compounds identified in Cc is an illustration that geochemistry took place in meteorite parents bodies (see also discussion in Section 4.3). Carbon species are expected to give rise to a complex chemistry. Europa's chemical models (e.g., Zolotov and Shock, 2001; McKinnon and Zolensky, 2003) indicate that carbonates can form in ice-rock objects subject to hydrothermal activity. Terrestrial vents show a profusion of molecules produced in hydrothermal conditions (e.g., Seyfried, 1987; Sleep et al., 2004; Kelley et al., 2005). Metals such as Cr and Ni, as well as hydrated silicates play a role in enabling the reaction kinetics (e.g., Pearson et al., 2002). Also, using 'clumped-isotope' thermometry of carbonates found in CM chondrites, Guo and Eiler (2007) concluded that the conditions in CM-meteorite bodies were suitable for the production of methane in hydrothermal context. Conditions in Ceres can be such that water reaches its supercritical point of 678 K and 30 MPa at about 15 km depth in Ceres' core, a situation that optimizes silicate hydration and leaching, phenomena well known in terrestrial hydrothermal vents (e.g., Hovland et al., 2006). This phenomenon has been recently identified as a probable past, and maybe even current event in the history of Enceladus (Matson et al., 2007; Glein et al., 2008).

3.1.2.5. Consequences for long-lived radioisotopes. Silicate alteration would lead to the depletion in key radioactive elements as a result of low-temperature mobilization. Low-temperature mobilization has been identified as a probable mechanisms for explaining the scattering in the Th/U ratios measured at various Cc (e.g., Rocholl and Jochum, 1993; Goreva and Burnett, 2000). Chen et al. (1993) have identified that about 20% of the uranium is present in labile sites that these authors associated as the result of aqueous alteration. Besides, Shinotsuka et al. (1995) identified the concentration of uranium in the breccious components of Cc, probably in resistate minerals, such as phosphates, that tend to concentrate actinides (see also Goreva and Burnett, 2000). It is also interesting to note that CI chondrite, which is thought to be pervasively aqueously altered material, is depleted in radiogenic elements: potassium by up to 15% with respect to ordinary chondrites, and in thorium and uranium by up to 25% (Table 1, based on Wasson and Kalleymen, 1988). Moreover, the average Cc indicates depletion in potassium by up to 50%. The mobility of potassium has also been included in icy satellites models (e.g., the model of Zolotov and Shock, 2001, for Europa or that of Zolotov, 2007 for Enceladus). Uranium mobility is happening terrestrial subduction zones (e.g., Bailey and Ragnarsdottir, 1994) enhanced in carbonates are present in solution. Potassium is known to be very mobile under hydrothermal conditions as well (e.g., Dreibus et al., 2008). In both cases, the conditions need to be oxidative and that leaching could have happened in the planetesimals. Likely detection of ^{40}Ar in Enceladus' plume by Cassini Ion and Neutral Mass Spectrometer (Waite et al., 2009) has been interpreted as evidence for the leaching of K and ^{40}Ar from Enceladus' rock phase (cf. Zolotov, 2007).

This results in depriving the core of some of its main long-term radiogenic sources. Assessing the amount of potassium released to the ocean as a result of hydrothermal activity requires in-depth geochemical modeling, which is beyond the scope of this study. Nonetheless, we can estimate that if Ceres' core were entirely deprived of potassium as a result of a very efficient early leaching phase, this would entail a heat deficit past 1 By after formation and deprive the core from reaching its melting temperature.

3.1.2.6. Summary. The goal of this study is not to quantify the amount of hydrothermal activity taking place during differentiation of ice-rock objects in general, or in Ceres in particular. Rather, it is to point out that better modeling of this aspect of ice-rock body differentiation is crucial, partly because the extent of silicate hydration determines the composition of the ocean, its long-term evolution. In summary, the potential state of the core at the end of the differentiation process is sketched in Fig. 1 as a function of the initial conditions.

3.2. Long-term evolution

The long-term evolution of the core and hydrosphere greatly depends on their respective composition after differentiation. For example, (1) silicate hydration is a major heat source, (2) hydrated silicates affect the core permeability, (3) there can be a significant transfer of key elements from the silicate core to the hydrosphere, including long-lived radioisotopes (Castillo-Rogez et al., 2008), which affects the long-term evolution of the hydrosphere, and (4) hydration would cause major dimensional change/expansion of Ceres (McCord and Sotin, 2005).

Hydrates, sulfur compounds, clathrate hydrates, and hydrated silicates have thermal conductivities lower than ice and as low as 0.5 W/m/K, which plays a role in storing heat released from the core. On the other hand, the thermal conductivities of oxides are at least one order of magnitude higher than those for water ice and enable increased heat flow from the core. Accurate modeling of heat transfer within an object that was affected by hydrothermal alteration is complex. It requires detailed geochemical treatment, which is beyond the scope of this study.

3.2.1. Long-term evolution of the core

The silicate material forming the core is likely to have experienced hydrothermal alteration, and to have some of the more soluble elements transferred to the ocean, as discussed above. The mineralization process would have contributed significantly to the heat energy affecting Ceres evolution. Also, hydration causes a significant increase in volume, resulting in significant dimensional changes in Ceres (McCord and Sotin, 2005). The long-term evolution of the core after formation is primarily a function of the core temperature and pressure. In the simplest models, heat is transferred out by conduction, but even in this case, the type of material present and their thermal properties must be known. Further, the role played by hydrothermal cooling to enhance the transfer of heat out of the core must be understood. The extent of hydrothermal circulation is a function of many parameters. No models so far have provided realistic modeling in icy objects that integrates the feedback between hydrothermal chemistry and physics. Various scenarios for Ceres' core history are sketched in Fig. 1, as a function of the initial state of the silicate and assumptions on the penetration depth of hydrothermal flows. One important possibility is dehydration of the inner core' hydrated material, creating a two-part core.

3.2.1.1. Hydrothermal cooling. Heat transfer through hydrothermal circulation in the core is a function of several, competing parameters. The penetration depth is mainly a function of gravity and rock permeability, which is not well constrained. Development of cracks in the core as it cools enhances hydrothermal activity with time, and the work of Vance et al. (2007) demonstrated that crack penetration could reach depths of the center of the core in an object like Ceres (Steve Vance, personal comunication). The models presented in this study do not calculate the potential cooling effect of hydrothermal circulation. Flow penetration to the deeper core increases with time. At the same time, heat from hydration is large, 233 kJ/kg of rock, and might compensate for the heat removed by hydrothermal circulation (Allen and Seyfried, 2004). So the cooling of the core as a result of hydrothermal circulation could be significant but is poorly understood. However, studies of mineral assemblages and isotopic analyses indicate that in most cases aqueous alteration occurred in the parent bodies of carbonaceous chondrites at temperatures cooler than 150 °C (Keil, 2000).

Our models consider that the early core could be stratified into an inner core of formerly hydrated silicate that was then dehydrated (metamorphosed) and an outer hydrated silicate layer. The hydrated silicate outer core layer thickness reduces permeability and slows inward flow velocity in a body whose gravity is only $\sim$0.27 m/s^2 (Cohen and Coker, 2000).

The settling of a hydrated salt layer at the base of the hydrosphere in Europa, as modeled by Spaun and Head (2001), is expected to limit significant hydrothermal interaction at the surface of the core (see also discussion of McKinnon and Zolensky, 2003). If sulfur is present in its reduced form, its compounds can seal the core, limiting hydrothermal cooling over the long-term (McKinnon and Zolensky, 2003).

In summary, if silicate hydration was limited during Ceres' differentiation, then the development of cracks at the surface of Ceres' core as it cools may be the only possibility for hydrothermal interaction between the core and the ocean. However, the chemical evolution associated with silicate alteration tends to compete with further hydrothermal circulation, and it is possible that hydrothermal activity in Ceres' core is not supported over the long-term.

3.2.1.2. Core silicate dehydration. In models formed after 5 My after CAIs the core remains colder than 600 K (Fig. 2c) until present. It is more likely that the hydrated silicates in these models undergo little dehydration.

The rest of this section focuses on models formed in less than 5 My after the production of CAIs. Hydrothermal alteration of Ceres' silicate core during differentiation might have been somewhat limited under these conditions. The extent of this phenomenon is uncertain, so we modeled the evolution of the core with a variety of assumptions about the core hydrated silicate layer thickness and composition (or thermal conductivity) after differentiation. Based on arguments mentioned in the previous section, we included the (extreme) assumption of no hydrothermal circulation within the core.

After differentiation, the core heats up as a result of the decay of radioisotopes. The short-lived isotope ^{60}Fe can provide enough heat to increase the core temperature up to 400 K over a period of ten My following differentiation. After this, longer-lived radioisotopes provide the main heat source. However, the low thermal conductivity of the hydrated silicate will contribute to warming the core by insulating it from heat loss. The average thermal conductivity for serpentine is about 1.5 W/K/m (Clauser and Huenges, 1995). This value is about half the thermal conductivity of dry silicate.

For a given time of formation after CAIs, the maximum temperature reached in the deep core is then a function of the hydrated silicate layer thickness and its thermal conductivity. If the core is fully hydrated, then its thermal conductivity can be as low as 0.5 W/m/K. The core thermal conductivity is a function of its mineralogical composition. Certain minerals can either decrease (e.g., brucite) or increase (e.g., magnetite) the average thermal conductivity of a hydrate assemblage. We see that a thick hydrated silicate layer, with a thermal conductivity of about 1 W/m/K keeps the core warm over the long term (Figs. 2 and 3a and b). In this case, the silicate solidus temperature can be reached a few hundred My after formation (Fig. 2a and b).

Pressure and temperature conditions in the core can lead to dehydration of the hydrated silicate phase (Ellis and Wyllie, 1979), and layering of the core 200–500 My after formation. Dehydration occurs in several steps. For the range of pressures relevant to Ceres' core (between 15 and 150 MPa), dehydration of brucite and antigorite will occur when the temperature exceeds 730 K (M. Brown, personal communication). If we assume that little hydrothermal circulation occurred or that the associated cooling was compensated for by heat from serpentinization, the depth at which hydrated silicates are stable is predictable. Our models all yield a dry silicate radius between 320 and 340 km if the content in LLRI is based on an ordinary chondrite composition, and slightly less if we use carbonaceous chondrite composition for the core content in LLRI (Table 1 and Fig. 3d). Using this composition for the hydrated silicate in the core, we see that the core achieves dehydration several hundred My later than any other configuration (Fig. 3d).

In this stratified core, the higher thermal conductivity of the dry silicate would favor heat loss from that region, but the overlaying hydrated phase, having a thermal conductivity two to five times smaller than the dry layer beneath, impedes heat loss from the core. As a result, heat accumulates at the interface between the dry silicate layer and the hydrated silicate layer. This situation could favor the development of partial melting of silicates.

Under the assumption that there would be no hydrothermal cooling, the separation of a metallic core can take place in models formed with t_{0-CAIs} less than 3 My. For the pressures in Ceres, the silicate solidus is between 1210 and 1425 K depending on composition (Senshu et al., 2002; Senshu and Matsui, 2006; Hevey and

Sanders, 2006; Médard and Grove, 2006). Separation of the metal from the silicate is a function of many parameters, especially the melt fraction. However, the density contrast between iron-rich melt and refractory silicate is large. We take the Fe–FeS melt density as 5500 kg/m^3 (e.g., Sohl et al., 2002), thus the density contrast with the silicate phase is about 1800 kg/m^3. Note that the silicate density tends toward forsterite's density after the metal separation, e.g., 3270 kg/m^3. If, in the extreme case for Ceres models, temperatures reach about 1250 K for pressures between 100 and 140 MPa, melting of the silicate occurs, associated with separation of the iron component (e.g., Ghosh and McSween, 1998). The contrast in density between silicate and iron, and the small dihedral angle between the melt and crystals favor rapid separation of the metallic component from the silicate (Newson and Jones, 1990), and we assume that Fe–FeS forms (e.g., Sohl et al., 2002) with a density of 5500 kg/m^3. The amount of sulfur left in the core after an early phase of hydrothermal activity depends once again on silicates leaching efficiency and balances the amount of sulfate hydrates available in Ceres' ocean. If much sulfur was leached from the silicate to the ocean during the protoplanet's early history, then the melting temperature of the metallic phase in the silicate is greater than 2000 K. In this case it is improbable that a metallic core could be present inside Ceres.

Silicate dehydration releases 15 wt.% water. Water saturation is expected to favor magma formation. Magmatic activity is a potentially very efficient way of transferring heat, as has been discussed in the case of Io (Moore, 2003). Intrusion of magmas into Ceres' relatively thin hydrosphere (less than 60 km, similar to the case of Enceladus) would probably significantly impact the hydrosphere and any surface crust (Wilson and Head, 2001). Such events would result in significant hydrothermal activity. The impact on the surface is a function of the thickness of the hydrosphere. Dehydration of the silicate phase when the temperature became favorable would result in the transfer of water from the core to the outer shell. Such an event should cause a significant change in Ceres' moment of inertia, and potentially alter its spin properties, such as angular rate. However, our models indicate that the conditions were always suitable for Ceres to relax to hydrostatic equilibrium, so no evidence of a spin rate change is likely to remain.

3.2.2. Hydrosphere evolution and structure

By hydrosphere we refer to the entire water layer. Our models, regardless of t_{0-CAIs}, predict full melting of the ice component early, perhaps leaving a thin unmelted crust. We discuss here the main parameters that determined the long-term evolution of the water/icy shell: (1) surface temperature, (2) structure of the ocean, and (3) convection in the icy shell.

3.2.2.1. Surface temperature. As stated in Section 2, we assume the surface temperature used in our models would be regulated by the regolith layer, which tempers diurnal temperature variations (cf. Fanale and Salvail, 1989). This characteristic of regolith is an effect of porosity, which can constitute at least 40% by volume (e.g., McKinnon, 2002). Such a high porosity can decrease thermal conductivity by several orders of magnitude (e.g., Shoshany et al., 2002). For example, the thermal conductivity of lunar regolith is estimated to be as low as 0.05 W/m/K (Horai, 1981), and Matson and Brown (1989) have used a thermal conductivity of 0.001 W/m/K at Europa's surface. The overall insulating effect of this layer is highly dependent on its thickness, which is estimated to be no more than a few tens of meters for Ceres.

We consider a linear increase from Ceres' surface temperature after dissipation of the solar nebula (150 K, see Section 2.2.3) to its current surface temperature of 180 K. This increase may be the result of an increase in solar luminosity, and assisted by change in Ceres' surface albedo. The time at which Ceres acquired its present low albedo is unknown.

3.2.2.2. Evolution of the hydrosphere. The long-term evolution of the hydrosphere is strongly controlled by the surface temperature. The various models displayed in Fig. 3 show an interior that is relatively warm and support liquid water today. These are upper bound models because convection in the hydrosphere is not modeled. For the extreme assumption that Ceres is currently in thermal equilibrium with its upper boundary condition, its temperature would be about 167 K on average with a maximum at the equator (180 K) and minimum at the poles (130 K).

A model assuming no silicate hydration, i.e., no chemical redistribution between the core and the hydrosphere, still displays warm temperatures for the present time (Fig. 3c). If ammonia accreted in Ceres (Fig. 3b), it is also expected to play a role in the long-term evolution of Ceres by decreasing the ocean freezing temperature to about 176 K, assuming that it has not been consumed (either decomposed into molecular nitrogen or reacted as ammonium). In such case, even the coldest (and unrealistic) model of Ceres includes a sea of liquid water enriched in ammonia and other species. This liquid layer could be as thick as 10 km at the equator, but might not exist at the poles due to the lower temperature there.

If no ammonia accreted inside Ceres or it has been consumed, then the degree to which a deep ocean inside Ceres has been preserved over the long-term is primarily a function of: (1) the composition (in the sense that it controls the freezing point of the salt mixture), and (2) possibly the presence at the interface between the core and hydrosphere of long-lived radioisotopes due to leaching from the core. Models of Europa's hydrosphere evolution that make use of Cc composition (Zolotov and Shock, 2001) predict that the compounds released during hydrothermal circulation in the rocky phase play a crucial anti-freeze role. A mixture of hydrates, carbonates, and chlorides can decrease water's freezing point to as low as $\sim$190 K (Kargel et al., 2000; Kargel, 1991; Wynn-Williams et al., 2001, for terrestrial analogs in hypersaline regions). We expect that the evolution of the icy shell as it cools down after the primary melting phase follows the same path as described by Spaun and Head (2001) for Europa. These authors show that Europa's hydrosphere should be stratified into an outer layer made of pure ice, and an increasing concentration of salts with depth as the ocean freezes at the salts hydrate eutectic temperature, which ranges from $\sim$190 K to 253 K for salts expected in Ceres. A layer saturated in salt should lie over the core and separate it from a less dense water layer. In such conditions, and after the early phase that resulted in differentiation and silicate hydration, hydrothermal interaction at the surface of the core should be limited (Spaun and Head, 2001). Some chemical and cosmochemical arguments challenge this model by demonstrating that hydrated sulfates might not be present in Europa's ocean (McKinnon and Zolensky, 2003). However, other chemical models involving a variety of compounds with different freezing points support a stratified ocean model (e.g., Prieto-Ballesteros and Kargel, 2005).

In Section 5.1, we further discuss processes that might play a role in increasing the hydrospheric temperature in our cold end-member models.

4. Matching models and observations

Here, we compare the measured shape of Ceres with the shape of Ceres today predicted by our models. The shape measurements presented by Thomas et al. (2005) are:

$a \sim b = 487.3 \pm 1.8$ km
$c = 454.7 \pm 1.6$ km
$a - c = 32.5 \pm 1.95$ km

We assume hydrostatic equilibrium when interpreting the measurements and in computing the main shape radii for the Ceres objects resulting from our models.

4.1. Shape calculation

The shape is computed after the Zharkov et al. (1985) equations. These equations are:

$$a = R\left(1 + \frac{1}{6}qh_f\right) \quad (1a)$$

$$b = a \quad (1b)$$

$$c = R\left(1 - \frac{1}{3}qh_f\right) \quad (1c)$$

where q is the rotational parameter, h_f is the fluid potential Love number, assuming that the body is in hydrostatic equilibrium. The latter parameter is computed after the Radau–Darwin approximation (see equations in Castillo-Rogez, 2006).

It is important here to use the exact, not approximated, equation for the rotational parameter, as Ceres is a rapid rotator:

$$q = \frac{a^3\omega^2}{GM} \quad (2)$$

where a is the equatorial radius, ω is the spin rate, M is Ceres' mass, and G is the universal constant of gravity.

A frequent error is to use the mean radius in Eq. (2) instead of the equatorial radius for rapid rotators like Ceres. This can result in calculated radii errors by up to 3 km. To test the accuracy of our approach we compute the fluid Love number and shape data for the models considered by Thomas et al. (2005) and compare our results with their Fig. 1. We find differences of less than 500 m. Our method is not as accurate as the method used by these authors, which is to compute McLaurin spheroids. However the accuracy of our approach is three times better than the current uncertainty for the shape measurements (which is about 1.7 km), and should be sufficient for the issues addressed in the present paper.

4.2. Results

We consider a range of models from little to extensive hydrothermal cooling of the core. In one endmember model the entire core is made of hydrated silicate. This is possible if the silicate was completely hydrated as part of the differentiation process, and if the temperature in the core never became warm enough for the hydrated silicate to dehydrate. Low temperatures could be due to: (1) hydrothermal cooling, (2) transfer (leaching) of some of the main heat sources to the ocean. We also consider models with the core made of dry, formerly hydrated silicate, overlaid by a 20- to 30-km thick hydrated silicate layer, based on the models presented in Figs. 2 and 3.

We compute the difference between the equatorial and the polar radius for models made up of the layers listed in Table 5. Results are plotted in Fig. 4 and compared against shape measurements by Thomas et al. (2005). The parameter that plays the main effect on the calculation of $(a - c)$ is the thickness of the hydrated silicate layer. This is due to the contrasts in density among this material, the dry silicate phase, and the hydrosphere. This is also the parameter that holds much information on the global history of the satellite.

For the models considered based on Table 5, the difference $(a - c)$ ranges from 28 km in the presence of a metallic core and up to near 35 km if the core is entirely composed of hydrated silicate. In Fig. 4, the model results distribute over a relatively narrow band whose slope is a function of the hydrated silicate layer thickness. The current uncertainty on the shape data limits our conclusions, and future measurements, especially from Dawn, with an accuracy better than 0.5 km would be extremely helpful for better exploiting Fig. 4. The shape data are more consistent with an object whose core is composed of hydrated silicate over more than half and maybe its entire radius. The addition of a metallic core in the models decreases the moment of inertia toward the lower bound of the range for a–c determined by Thomas et al. (2005), and closer to the measurement by Millis et al. (1989). If we assume that the hydrosphere shelters a layer made of brines with a relatively high density (i.e., 1300 kg/m^3), then we can resolve more finely the thickness of the hydrated silicate layer, around 200 km. On the other hand the Carry et al. (2008) shape determination (not represented in Fig. 4) is more consistent with Ceres' core being fully hydrated (Zolotov, 2009). Actually the upper bound of the uncertainty range obtained from those observations, of the order of 37 km, is not consistent with any model for the range of parameters considered in Table 5.

Table 5
Parameter space ranged for computing Ceres' shape.

Material	Thickness range (km)	Density range (kg/m^3)
Ice	0–70	931
Brine + clathrates	0–50	1000–1300
Hydrated silicate	20–340	2500–2700
Dry silicate	0–320	3270–3510
Metallic core	0–100 km radius	5500

We look forward to better measurements in the future, especially from the Dawn Mission. For example, if $(a - c)$ is between 29 and 32.5 km, assuming an accuracy better than 0.5 km, then it will be possible to constrain the thickness of the hydrated silicate layer, with an accuracy better than 100 km.

5. Implications

We have considered a series of models of Ceres as a function of assumptions on initial conditions and internal processes. Internal evolution models all agree that Ceres should be differentiated, which is confirmed by shape data. These data indicate that Ceres' core is rather enriched in hydrated silicate but includes an inner core made of dry silicate (dehydrated or never hydrated). Constraining Ceres' current internal structure has important implications for better understanding its evolution. We address prospective observations by the *Dawn* mission that will help constrain the character of Ceres' interior.

5.1. An ocean inside Ceres today?

In our models and those of McCord and Sotin (2005), it seems highly likely that there was extensive liquid water inside Ceres during its evolution. The current presence of liquid water in icy objects such as Europa or Enceladus is considered as likely. It seems reasonable to consider that this is also the case for Ceres. This object is smaller than Europa, but bigger than Enceladus. While Ceres does not benefit from tidal heating as a means to maintain warm temperatures at depth over the long run, its warm surface temperature helps to create warm internal temperatures in this object today, at least locally (i.e., equal or greater than 180 K at the equator instead of 80 K at Europa).

Based on meteoritic compositions, thermodynamical models, surface composition, and the presence of hydrated silicate making

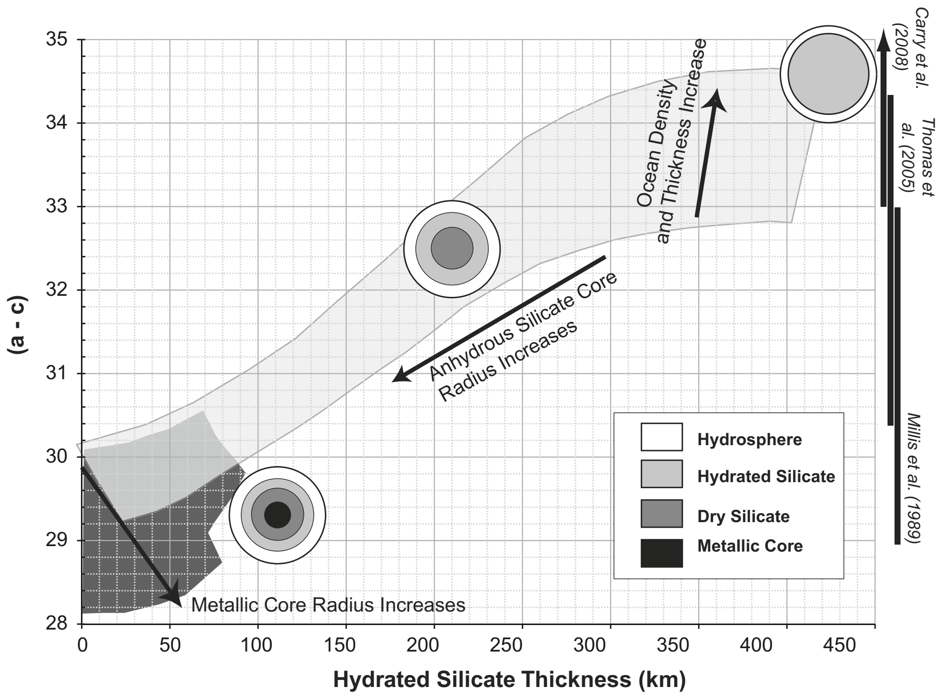

Fig. 4. Difference between the equatorial and the polar radii of models systematically built after the parameters listed in Table 5.

up at least part of the core (constrained by shape data) there is much reason to believe that Ceres' ocean could have been enriched at least to some extent in many anti-freezing chemical species.

In the extreme case that Ceres' internal temperature is in equilibrium with its surface temperature, e.g., at least ~180 K at the equator and if the silicate phase did not undergo significant hydration (i.e., little transfer of major elements from the silicate to the ocean), then an ocean can be preserved in Ceres today only if ammonia accreted and concentrated in a liquid layer as the satellite froze. At the other extreme, if after differentiation the ocean was enriched in various chemical species concentrated at the base of the hydrosphere, as well as long-lived radioisotopes, then it is likely that a significant liquid layer exists today even without the presence of ammonia. Observation of terrestrial analogs in isolated areas (Antarctica, Wynn-Williams et al., 2001), show that hypersaline solutions have a freezing point depressed by up to 80 °C with respect to the water ice melting point.

In addition to the warm surface temperature and ocean composition, several processes not included in our modeling could play a significant role in increasing the hydrospheric temperature and maintaining a liquid layer: (1) transfer of the long-lived radioisotopes from the core to the hydrosphere as a result of hydrothermal activity; (2) heat storing capacity of the hydrates and other species accumulating at the base of the hydrosphere; (3) heat transfer enhancement from the core to the ocean driven by the mineralization of highly conductive hydroxides at the surface of the core, as suggested by Fortes et al. (2007) in the case of Titan.

How the decay of the radioisotopes of these species affect the long-term evolution of the hydrosphere needs to be modeled. Uranium has little solubility in water except in the presence of carbonates (e.g., Bailey and Ragnarsdottir, 1994). Outside its stability regime and will tend to adsorb on clay minerals or precipitate in association with dolomite (e.g., Adams, 1959). Potassium is more soluble (see Dreibus et al., 2008, for experimental measurements) but precipitates chloride and/or carbonates in supersaturated solutions. We expect the radioactive heat decay of soluble ^{40}K to play little role in heating the ocean because the heat would be quickly dissipated by hydrothermal convection. However, the evaporates and oxides of these radiogenic elements would accumulate at the base of the ocean. Modeling heat transfer through such a layer is complex because it requires understanding the stability of the hydrates against convection and this is beyond the scope of this article.

In summary, significant hydration of the silicate during differentiation, which seems likely from our models, would result in the juxtaposition of several phenomena described above, with uncertain results, given our current understanding. Finally, decrease of the surface temperature toward the poles might limit the extension of liquid water inside Ceres to the low-latitudes.

5.2. Endogenic activity

Contrary to the assumption by Thomas et al. (2005) it seems unlikely from our work that Ceres should be heavily cratered. In addition to the original crust being gravitationally unstable and large dimensional changes occurring at several stages of evolution, Ceres' endogenic activity, as described above, suggests likely endogenic activity in the past and the potential for ongoing activity involving thermal and compositional diapirism. If Ceres underwent extensive hydrothermal activity in its early history, as our models predict and as has been proposed for Europa (e.g., Kargel et al., 2000; McKinnon and Zolensky, 2003), then geological activity in such a body is extensive and complex (cf. Prieto-Ballesteros and Kargel, 2005). Endogenic activity involving salts is thought to be involved in Europa's recent resurfacing and geological activity (Spaun and Head, 2001; Zolotov et al., 2004) and clathrates are thought to play a role in the geological activity observed at Enceladus (e.g., Fortes, 2007). However the mechanisms driving cryovolcanism in such conditions have not been properly modeled so far.

It may be of interest to compare Ceres and Dione in terms of available heat as these two objects share similar physical properties. While Dione is expected to have a rock mass fraction slightly lower than Ceres (~0.5 vs. 0.75), that icy satellite is thought to be differentiated (e.g., Schubert and Anderson, 2006). Endogenic activity in that satellites could have been promoted by tidal heating; on the other hand, Ceres has benefited from a surface temperature equal at least to 160 K for most of its history, and the potential concentration of long-lived radioisotope heating at the base of its icy shell could play the role of a long-term heat source.

Ceres' relatively thin hydrosphere, compared to Europe, is an advantage for coupling endogenic activity in the hydrosphere to the surface. Limb imaging of Ceres by *HST* showed no relief higher than 5 km, which is the indication of lithospheric relaxation down to the spatial resolution of those observations, of the order of 60 km (Thomas et al., 2005). We expect Ceres to have undergone extensive or complete, multiple resurfacing, due to its extensive thermal activity and have preserved only a few recent craters. Ceres's surface could have extensive mineral evidence of its internal activity. Also the relatively warm surface temperature should have resulted in the relaxation of the largest craters.

5.3. Observations by the dawn mission

We address some key observations expected from the *Dawn* mission that would greatly increase our understanding of Ceres' interior. The *Dawn* spacecraft is equipped with the capability to perform detailed mapping of the surface with a camera, imaging spectrometer (VIR), gamma ray-neutron detector (GRaND) (Russell et al., 2006, 2007a,b).

Orbital tracking will allow accurate measurements of the gravity field leading to the determination of Ceres' internal density distribution. The shape of Ceres will also be accurately determined from imaging. As discussed in Section 4, refining Ceres' shape determination allows an estimate of the size of the hydrated silicate layer in Ceres' core. Accuracy better than 0.5 km would provide strong constraints on the density of the hydrosphere (Fig. 4) and its composition. Coupling between shape and gravity data will allow further constraints on the shell thickness. Gravity data will provide complementary information to the shape and topography data to determine the degree of relaxation of surface features. Also, the two dataset are not sensitive to the same part of the density profile. The gravity data are more sensitivity to the structure at depth (core) while the shape information is more sensitive superficial structure.

Compositional mapping will be crucial in order to constrain Ceres' internal composition, and especially the possibility for past and maybe also current hydrothermal activity. Surface imaging will provide constraints on the geological history of the protoplanet. Whether endogenic activity is ongoing in Ceres bears many implications on the current preservation of liquid at depth. Imaging should also permit surface dating, from crater counts, on global and regional scales, thereby possibly identifying sites of endogenic activity. Combining information provided by the *Dawn* instruments will also allow constraints on the evolution of the lithospheric properties. Models show that Ceres encountered several changes in volume in the course of its evolution. Thermal stress resulting from freezing could also lead to ongoing accumulation of stress in the icy shell, possibly driving ongoing tectonic activity as has been suggested by Nimmo (2004) for Europa. The consequences of such events may be observable by *Dawn*, provided that recent activity did not remove records of past geological history.

Additionally *Dawn* will constrain surface mineralogical and molecular composition from visible-near infrared spectra from 0.35 μm to 5.0 μm from its imaging spectrometer VIR, and elemental composition from GRaND. GraND will especially be able to measure the composition of the surface in major elements and long-lived radioactive elements, such as ^{40}K. The idea of using ^{40}K as a geochronological tracer of geological activity has already been suggested (Kargel, 1989; Engel and Lunine, 1994). The prospect of obtaining such measurements if potassium-bearing compounds are present at the surface of Ceres is quite exciting.

5.4. Ceres as a meteorite parent body

C-type asteroids like Ceres are thought to be related to primitive carbonaceous chondrites (CI- and CM-types). These chondrites are characterized by their enrichment in hydrated minerals (silicates and salts), oxides, sulfides, and organics. Ceres' density is close to the one measured for CI-type of chondrites (Britt and Consolmagno, 2000).

If a body such as Ceres was disrupted as a result of an impact with a large interloper, we expect that it yields different types of small asteroids and future meteorites (Fig. 4): presence of veins with chemistry representative of the outer layer of the core, corresponding to the composition observed for carbonaceous chondrites and foliated, dry, silicate with little salts, organics, or volatiles, that could correspond to metamorphosed Cc rich in dehydrated silicates (e.g., Nakamura, 2005) although the details and consequences of the metamorphism process in terms of mineralogical assemblages and chemistry needs to be further investigated.

It is known from terrestrial analogs that hydrothermal vents are best places for the production of organics molecules (Shock, 1992). The occurrence of such a phenomenon in a small ice-rock body has been studied by Matson et al. (2007) and Glein et al. (2008) in the case of Enceladus. Our modeling also indicates that conditions in Ceres were suitable for hydrothermal geochemistry to take place, which could yield the rich variety of organic and non-organic molecules found in carbonaceous chondrites. For example, if ammonia accreted in Ceres, in hydrothermal context it dissociated into molecular nitrogen, or could react to form ammonium salts, as has been observed by King et al. (1992). The presence of clays provided optimum support for geochemical reactions to take place (e.g., Pearson et al., 2002).

Interestingly, the C-type asteroids that are large enough for porosity to be negligible have a density close to Ceres', i.e., lower than any type of silicate. Thus we can expect they are composed in part of water. This is the case for Hygeia (the fourth largest asteroid in the main asteroid belt) with a density 2.4 g/cm^3 or 324 Bamberga (1.8 g/cm^3). These objects are especially present in the outer belt beyond 2.7 AU.

The present study did not explore the geophysical consequences of the accretion scenario recently published by Turrini et al. (Turrini, D., Magni, G., Coradini, A., 2009. Probing the history of Solar System through the cratering records on Vesta and Ceres. Available from: <arXiv:0902.3579v1>). That model suggests that Ceres accreted over a timescale of 1 My in several stages: a dominant accretion of rocky planetesimals in the first stage, followed by preferential accretion of icy planetesimals in the later stages. This initial density gradient combined with incremental accretion (i.e., decreasing concentration of ^{26}Al in the rock phase between the beginning and end of accretion, e.g., Ghosh et al., 2003) should result in a very contrasted thermal history of Ceres' interior and outer layers.

6. Conclusions

McCord and Sotin (2005) were the first to study Ceres as an icy object that was subject to differentiation, hydrothermal activity, and that might host a liquid layer today. Our geophysical models are fully consistent with McCord and Sotin (2005) as they predict the differentiation of a rocky core from the volatile phase under almost all circumstances of formation and evolution. In the present study we expanded upon that previous work using new information and exploring the core evolution and hydrosphere evolution. We show here the importance of studying core formation and evolution and suggest that dehydration of part of the core can be achieved for early times of formation. Determining the current state of the core will constrain the evolutionary track. McCord and Sotin (2005) quantified heat transferred by convection assuming pure water ice composition for the volatile phase. For the present study, we chose not to model convection in the ice shell because the chemical consequences of hydrothermal circulation on the geophysical evolution of Ceres need to be quantified for the several possible situations, before detailed convective modeling can make sense.

We show that Ceres' shape, in hydrostatic equilibrium, is very sensitive to the abundance of hydrated silicate in the core. However, available shape data are not consistent enough for further constraining the core structure. The average shape numbers by Thomas et al. (2005) seem to indicate that Ceres' core is probably stratified in an inner core made of dry silicate and an outer layer made of hydrated silicate, which encompasses at least half of the core radius. The lower end of the shape measurements allows the additional presence of a metallic core but our models suggest that, although it is possible, it is unlikely that Ceres differentiated to this extent.

We emphasize the importance of comparisons between Ceres and outer planet satellites and show that Ceres may be the warmest endmember of the group of icy objects found further out in the solar system. The evolution of this class of objects should be considered together.

We expect, that, contrary to current thinking, Ceres has been and could still be undergoing resurfacing and should present a relatively young surface without large vertical relief, with few large craters and perhaps with current hydrothermal activity.

Our models lack important aspects such as convective heat transfer in the hydrosphere and hydrothermal flow and we discuss the implications. We suggest a roadmap of tasks to undertake in order to improve our modeling and understanding of Ceres and also of icy objects in general. A main task is the modeling of the geophysical consequences of hydrothermal chemistry, such as the transfer of major elements, including long-lived radioisotopes, from the core to the ocean. Coupling geochemical and geophysical modeling is crucial in order to understand heat transfer in a complex hydrosphere enriched in salts and radiogenic sources (Castillo-Rogez et al., 2008). Other major tasks include hydrothermal circulation modeling and two-dimensional modeling in order to determine the thermal effect of latitudinal variations in surface temperature. While we based our approach on the current understanding of large meteorite parent body formation, i.e., full accretion within a few My after the production of CAIs in the meteorite belt, it will also be interesting to further investigate the geophysical evolution of Ceres if it formed in the trans-neptunian region on a timescale of several tens to hundreds of My before being ejected toward the inner solar system as has recently been suggested (McKinnon, 2008).

Detailed measurements from orbit by the *Dawn* spacecraft should help immensely in constraining the evolution models. Combined gravity and refined shape measurements should provide strong constraints on Ceres' internal structure and nature of any internal liquid ocean and thus yield constraints on the degree of differentiation and the time of formation. Compositional and thermal mapping will help constraint on the internal chemistry. Imagery of the surface should show evidence of recent and even of current activity.

In general, we conclude that Ceres is a very interesting object in itself, represents a class of objects that played a major role in the development of the inner planets and is a probe to the early formation of solid objects in the Solar System.

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