EVOLUTION OF LARGE, WATER-RICH PLANETESIMALS: IMPLICATIONS FOR THE VARIETY OF C-TYPE ASTEROIDS.

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Introduction: In the absence of tidal heating and with little accretional heat, the evolution of large water-rich asteroids is a function of their initial composition and temperature. The latter depends on the location of formation (in the inner or outer solar system) and most importantly on the timing and duration of accretion, which determines the amount of short-lived radioisotopes available for early internal activity. New accretional models suggest that planetesimals grew rapidly throughout the asteroid belt to several hundred km[1], making it probable that even the water-rich C-class asteroids accreted a volume of short-lived radionuclides significant. Discovery of Ceres' low density and likely differentiation into a core and icy shell [2], Pallas' relatively low density, nearly equilibrium shape and surface variation [3], ice on the surface of 24 Themis [4,5] and the active nature of several main belt comets (MBCs) [6], implies that some large asteroids:

1) contained large quantities of water,
2) can shelter evolved hydrospheres, and
3) can differentiate, forming nested layers of radially-varying composition.

Motivated by these considerations, we modeled the evolution of some of the largest C-class asteroids, focusing on constraining evolution scenarios for 2 Pallas (572 km diameter), the Themis family parent body (400 km diameter). We evaluate the role of composition, and thus location of formation, and time of formation. We use our results to illuminate possible genetic relationships between C-class asteroids.

Models: We assume that the asteroids accreted instantaneously at a given time after the formation of calcium aluminum inclusions (CAIs). We assume a mean chondritic composition for the rock component and content in radioisotopes. Our software tracks the evolution of the radius, porosity, temperature and density profiles from accretion until present time.

Time of formation. Carbonaceous chondrite parent bodies are believed to have been the object of intense hydrothermal activity, explained as a consequence of ^{26}Al decay. It thus makes sense to consider that large wet asteroids could have formed early enough to benefit from short-lived radioisotope decay. We varied the time of formation from 2 myr to 10 myr after CAIs. Specifying a density of 2100 kg/m^3 (comparable to that of Ceres), for the class of objects about the size of Pallas, little evolution can proceed for times of formation past 5 My after CAIs, i.e., after ^{26}Al decay heat peak. For bodies in the ~500 km size range, total differentiation occurs for times of formation of 2-4 Myr after CAIs. In this case, water ice melts and separates from the silicate, leading to a stratified interior. In the denser cases, the body can also incur small amounts of silicate dehydration at depth. The extent of silicate serpentinization is a function of a number of parameters that are not properly constrained. Thus we consider a range of possible situations, from 50% to 100% of hydrated silicates in the core. During hydrothermal circulation, major elements may be leached from the silicate phase and end up as impurities in the icy shell. This shell may remain liquid for several tens of My. As it freezes, supersaturated brines enriched in impurities, including organics, may concentrate at the base of the ocean.

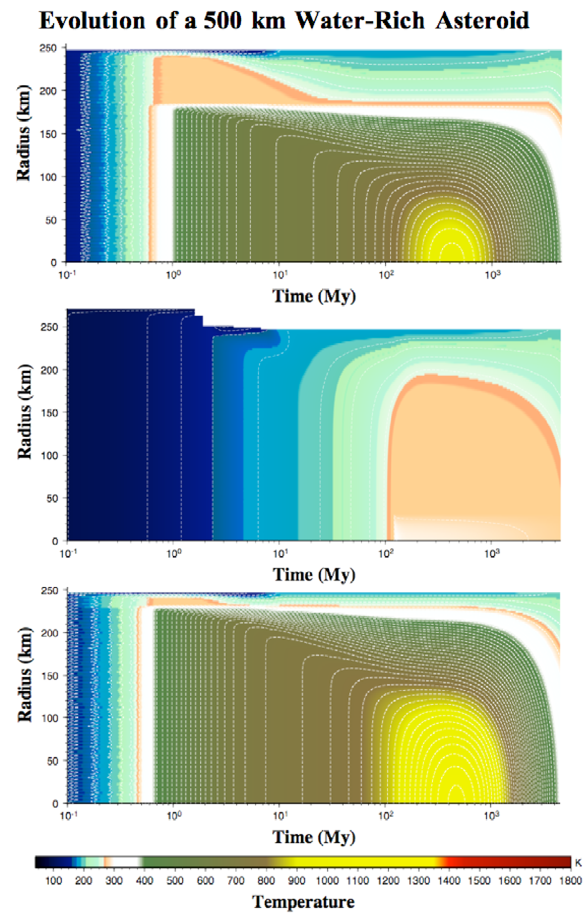

Figure 1: Models of the evolution of a 500km water-rich asteroid: a) for an initial density of 2100 kg/m^3 and time of formation (TOF) 3 Myr after CAIs, b) same as (a) but for TOF 5 Myr after CAIs, and c) same as (a) but for an initial density of 2500 kg/m^3.

Ice-silicate composition. We also test the effect of the dry rock mass fraction on the geophysical evolution of these bodies. More silicate material implies more radioisotope heating and less water to regulate hydrothermal heat transfer. Depending on the extent of hydrothermal activity, water may be consumed in serpentinization reactions leading to interiors dominated by a large hydrated silicate core and a thin outer layer enriched in water, hydrates, and organics. Such a model is presented in Figure 1, compared against a model enriched in water ice (i.e., Ceres' density).

Implications for Individual Asteroids: Our models demonstrate possible interior structures of large, C-class asteroids today, as well as the parent bodies of C-class families within the main belt. While it may be possible large objects like Ceres to maintain a global ocean even today [7], it is less likely that smaller asteroids could support liquid water until present.

Pallas. With a size of 565 km and density and 2400-2800 kg/m^3 [2], Pallas can differentiate completely if formed within 4 Myr after CAIs, while it shows little evolution if formed later. In some scenarios with sufficiently early formation, Pallas can not only form an icy shell, but also a silicate core that is largely hydrated, with the possibility of dehydrating the inner core. It is however possible that Pallas might represent the core of a larger body that has had its ice shell stripped by impact, or sublimated as a consequence of the very warm surface temperature undergone by Pallas on its very eccentric and inclined orbit. To further constrain this model, we also model the case where Pallas formed much larger, in the range of 600-800 km diameter, from material with a density of 2100 kg/m^3. Not surprisingly, the end result is similar to that of Ceres [7], with a somewhat less dehydrated core and smaller icy shell.

Themis. The discovery of water ice on the surface of 24 Themis [3], as well as the presence of organic materials [4] are evidence that the Themis family parent body contained a significant amount of water ice. Our models show that Themis can readily differentiate into a silicate core dominated by hydrated material and an icy shell. The density expected for the shell is between 1000 and 1600 kg/m^3 depending upon the ability of circulating water to leach organics, salts and other volatiles from the rock. The predicted density of the silicate core is near 2700 kg/m^3, in agreement with the mean density of 24 Themis, the largest family member and likely core of the parent body. Presumably, the icy and organic-rich surface of 24 Themis is either a remnant from the base of the ice shellor reaccretion of material from the shell vaporized in the break-up. Our models expect that the large binary asteroid 90 Antiope may in fact be comprised of a mix of water ice, rock and hydrated minerals, rather than being rubble piles of rocky material, explaining the asteroids' relaxed shapes and low density. This is consitent with the discovery of ice on 24 Themis and the presence of MBCs in the family.

Implications for the Distribution of C-type bodies in the Main Belt: Recent models [morbi] of the early solar system require an initial distribution of main belt bodies dominated by >100-1000 km bodies established within ~3Myr to explain the current size frequency distribution in the belt, suggesting that asteroids formed both rapidly and large. We find that unless ~500km diameter asteroids formed after about 5Myr, some degree of differentiation and alteration will persist. Formation within 3Myr can establish nested layers of water ice, organics and salts, and silicate with radially varying degrees of alteration and hydration, occasionally establishing a dehydrated component at depth.

The Themis family contains 24 Themis (C-type; core), MBCs (B-type; volatile shell), and a mix of other C-type bodies. Our models are consisten with the diversity of spectral properties among family members as the signature of a differentiated parent body. Pallas is larger than the Themis parent, and probably denser. If it formed at the same time as the Themis parent and Ceres, Pallas could differentiate as well. Since Pallas is a B-type, like the MBCs, centaur Chiron and candidate extinct comet Phaeton, it may be that its surface properties are indicative of water-loss processes. Thus our models suggest that the variety of C-type objects in the main belt may in part be explained by thermal evolution and water-rock reactions achieved by large water-rich bodies.

Future Work: We look to quantify the duration and extent of chemical reactions that may be linked to spectral variability among C-types. We also will quantify the stability of a non-ice layer overlaying the ice shell of these bodies.

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