

Ceres, Vesta, and Pallas: Protoplanets, Not Asteroids

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Objects in our solar system are currently thought to have formed by condensation and accumulation from the gas and dust nebula, out of which the Sun first arose. Dust grains accreted to form objects of approximately one-kilometer in size, which in turn accreted to form objects of about 1000 kilometers in size. Some of these objects grew to become the planets, and formed a core, mantle, and crust layers through radioactive heating, which melted some or all of the material, and subsequent differentiation. The development of large planets caused gravity perturbations, rearranging the remaining debris and halting the accretion.

Inside five astronomical units (AU, where one AU is the mean distance of the Earth from the Sun), only the terrestrial planets remain, except for the Asteroid Belt, which is shepherded by Jupiter's gravity. The asteroid belt mostly contains many small objects that show signs of heating and melting and are probably left over from the mutual destruction of intermediate-sized objects in the accretion chain. These fragments are what are generally thought of when one speaks of asteroids. However, a few of the intermediate, approximately 1000-kilometer-sized objects in the asteroid belt seem to be intact: Vesta, Ceres, and Pallas. This article points out that, although these objects also have been classified as asteroids, they instead appear to be small planets, or protoplanets. Their existence today helps confirm this general theory of planet formation, and provides evidence for the study of the terrestrial planet formation process.

Evidence for Ceres' Differentiation

Vesta, Ceres, and Pallas orbit in a similar area of the solar system, between 2.36 and 2.77 AU, and are of similar size, between about 500 kilometers (Vesta, Pallas) and 1000 kilometers (Ceres) in diameter. Yet they are very different in nature. Their bulk densities are vastly different: Ceres at 2100 kilograms per cubic meter (kg/m^3), Pallas at 2710 kg/m^3 , and at Vesta 3440 kg/m^3 .

Ceres' potential for rewarding exploration was not widely recognized until recently. Its relatively low bulk density, requiring significant water content, and telescopic observations showing some hydroxide-bearing surface materials [Lebofsky *et al.*, 1978] should have been clues that Ceres deserved greater attention. That greater attention was triggered in part when a recent thermal evolution model [McCord and Sotin, 2005] indi-

cated that Ceres might be highly evolved and differentiated, retaining most of its original water, including some still in liquid state (Figure 1).

According to the model, even when only long-lived radioactive heating on Ceres was considered, the ice would have melted and separated from the silicate rock. This process quickly produced a silicate core and a liquid mantle, while retaining a thin frozen surface. The melting and freezing of water, the exothermic mineralization of the silicates caused by the circulating warm water, and the differentiation itself produced expansion and shrinking, making Ceres an active object at times during this process.

As the radionuclide heating waned, Ceres cooled and the liquid water froze inward from the outer layers, except perhaps for a layer of water near the warm silicate core boundary that may exist today. Due to the high water content and its large latent heat and convection in the liquid and solid water, the silicates in Ceres cannot be made to melt even if short-lived radioactive nuclides (aluminum-26 (^{26}Al) mostly) are considered, because the large latent heat of the water absorbs energy and the convection in the water removes heat.

This differentiated model predicts a hydrostatic shape for the spinning Ceres (9.075-hour period) that, if observed, would be further evidence for a differentiated Ceres. After the model was completed, the shape of Ceres was observed using the Hubble Space Telescope Advanced Camera for Surveys (HST-ACS) [Thomas *et al.*, 2005]. The measured limb shape indicated Ceres is an oblate spheroid, with axes of 487.3 ± 1.8 by 454.7 ± 1.6 kilometers. A smooth, oblate spheroid is indicative of a hydrostatically controlled shape. The difference in long and short axes is inconsistent with a homogeneous body and instead requires a central concentration of mass. This differentiated state, and even the observed difference in polar and equatorial axes (32.6 kilometers), are predicted in the modeling study of McCord and Sotin [2005] (32 kilometers for a protoplanet with a silicate core of serpentine density), a rare agreement between theory and observation.

In addition, the first surface albedo maps of Ceres at three wavelengths were calculated and analyzed [Li *et al.*, 2006] using the same HST-ACS data set. These maps reveal 11 surface reflectance (albedo) and color features ranging in scale from 40 to 350 kilometers. This variety, although of smaller range than for some other asteroids and icy satellites, could indicate a very active and varied surface in the past during which some of the materials were mixed with the object's mantle. A strong absorption band (30% of the continuum reflectance) centered at about

280 nanometers is noticed for the first time but has not yet been identified, indicating further the exciting nature of Ceres.

Vesta: A Dry Protoplanet With an Iron Core

Vesta's state and history were discussed by Keil [2002], who also considers Vesta a protoplanet because it is differentiated with an intact internal structure. The mystery of Vesta was first revealed [McCord *et al.*, 1970] by telescope spectroscopy, which showed that Vesta's surface contained a low-calcium form of the mineral pyroxene and had a similar composition of certain basaltic achondrite meteorites. This implies that Vesta melted and differentiated and that there is a connection between Vesta and this type of meteorite [McCord *et al.*, 1970]. This discovery and connection started an extensive study of this object, based partly on the detailed chemistry of basaltic achondrite meteorites, to work out the evolution of Vesta.

Vesta apparently either accreted from drier small objects than did Ceres or lost its water early in its formation. Without the moderating effect of the water that Ceres contained, Vesta's silicates melted and differentiated quickly, and it now has an iron core, silicate mantle, and a basaltic surface. Vesta could be thought of as the smallest terrestrial planet, very different from its largest sister, Ceres, which seems more like the evolved icy Galilean satellites of Jupiter. Hubble Space Telescope imagery (Figure 3) [Zellner and Thomas, 1997] shows a giant crater near Vesta's south pole that probably excavated deep into the mantle and perhaps exposed some of the iron core material.

McCord and Sotin [2005], in their thermal modeling study, pointed out that Ceres' bulk density implied much water still exists within Ceres, whereas Vesta has the density of basaltic rock and could not contain much, if any, water in any form. They noted that if the smaller objects (~1 kilometer) from which

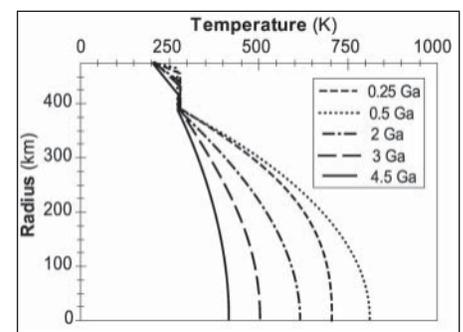


Fig. 1. Temperature as a function of depth below the surface for Ceres with time after accretion, melting of ice, and differentiation, according to models by McCord and Sotin [2005]. Water melts early after accretion and a silicate core forms with a liquid mantle and solid crust. The liquid water then slowly freezes from the surface layer, downward, with perhaps some liquid water remaining today at the core boundary.

Ceres is thought to have formed accreted early enough, they could contain enough short-lived radioactivity (^{26}Al) and create enough heat to boil off their water, leaving dry material to form the larger objects. These dry objects would then not have the moderating influence of water and would thus grow much hotter, perhaps melting the silicates, as is now seen in Vesta. In this way, they pointed out, the dichotomy between Vesta and Ceres can be explained. Only a few hundred thousand years' difference in accretion of the smaller objects that formed the protoplanets could account for this very different evolution cycle.

Pallas and Future Research

Pallas apparently is an intermediate object between Ceres and Vesta and is still mostly unknown. It is about the same size as Vesta, but spectroscopy shows its surface composition to be more similar to that of Ceres. It is denser than Ceres and therefore had less water when it was formed or at least retained less water during evolution, but it is much less dense than Vesta and cannot be made from pure silicate material.

Pallas's orbit is inclined to the ecliptic plane by 35.7 degrees, suggesting a strong gravity interaction and perhaps a major collision after formation. Because of this highly inclined orbit and the very large change in velocity needed to reach Pallas by spacecraft, it is likely to be unexplored and thus poorly understood for a long time.

These results are forming the basis for a new and much more complete understanding of this class of objects—which are very different from the fragments normally referred to as asteroids—and indicate that they have undergone planetary processes. Data from these objects could reveal new

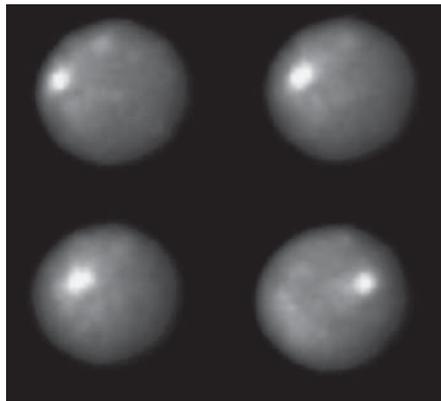


Fig. 2. Brightness images of Ceres at several longitudes from the Hubble Space Telescope Advanced Camera for Surveys [Thomas et al., 2005]. From these images, Thomas et al. calculated the shape of Ceres. Note the several albedo features suggesting some compositional variation on the surface.

insights into the formation and evolution of the solar system.

In 2001, NASA had selected the Dawn mission, which would have visited and investigated Vesta and Ceres starting in 2010. The mission was scheduled for launch in June 2006, but NASA cancelled the project on 2 March.

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Fig. 3. This image of Vesta is derived from a shape model by Zellner and Thomas [1997]. Considerable topography is evident, especially the large crater at the southern pole.

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dition on 23 January drilled to a depth of 3029 meters at Japan's Dome Fuji Station in east Antarctica and recovered ice estimated to be one million years old.

If the age is verified, the ice core will be the oldest ice ever retrieved, 20,000 years older than the one from East Antarctica's Dome C. The core will be dated using ice flow law models, cosmic ray analysis, geomagnetic time markers, and comparisons to ocean sediment cores.

"We wanted to extract the oldest ice in the world," said Hideaki Motoyama, an associate professor at Japan's National Institute of Polar Research (NIPR), who was chief driller for the 2005–2006 austral summer season. "I especially want to know the relationship between greenhouse gases and air temperature between 800,000 and one million years ago." To analyze this, oxygen and hydrogen isotopes, dust size and distribution, pollen, gas bubbles, and other aspects of the core will be studied.

In addition, scientists will use the core to research the climate and environmental impacts of the Brunhes-Matuyama geomag-

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In Brief

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European ice satellite replacement approved

The European Space Agency (ESA) will build and launch a new CryoSat spacecraft to study polar and sea ice, the agency announced on 24 February. The first CryoSat was lost on 8 October 2005 when the rocket and spacecraft fell into the ocean north of Greenland due to problems with the rocket launcher.

At a 23–24 February meeting of the ESA's Earth Observation Programme Board, the agency received permission from its member states for CryoSat-2, which will have the same mission objectives as the satellite it replaces.

CryoSat-2 is expected to be launched in March 2009 for a three-year mission. The satellite will monitor the thickness of ice on land and sea. That information can be used for studying how melting polar ice may affect sea levels and climate change. The design of its main instrument, the synthetic aperture radar/interferometric radar altimeter, will allow detailed measurements of irregular ice features not possible with earlier altimeters.

Volker Liebig, ESA director of Earth Observation Programs, said, "This decision is very important, as the scientific community in Europe and elsewhere is eagerly awaiting resumption of the CryoSat mission."

—SARAH ZIELINSKI, Staff Writer

Ice core could be oldest ever recovered

The Japanese Antarctic Research Expe-