



Water, heat, bombardment: The evolution and current state of (2) Pallas

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ABSTRACT

Using recent constraints on the shape and density of (2) Pallas, we model the thermal evolution of the body as a function of possible formation scenarios that differ in the time of formation and composition assumed for the protoplanet. We develop possible evolution scenarios for Pallas and compare these to available observations. Our models imply two distinct types of end states: those with a hydrosphere and silicate core, and those where the body is dominated by hydrated silicates. We show that for an initial ice-rock mixture with density 2400 kg/m³, Pallas is likely to differentiate and form a rocky core and icy shell. If Pallas accreted from material with lower initial ice content, our models indicate that Pallas's interior is dominated by hydrated silicates, possibly with a core of anhydrous silicates.

We also investigate the possibility that Pallas's initial density was similar to Ceres', i.e., that it formed from an ice-rock mixture of density 2100 kg/m³. This implies that the object lost a significant fraction of its hydrosphere as a consequence of thermal oscillations and impacts, a distinct possibility given its density, evidence for impact excavation and current orbital parameters. Its blue spectral slope and observed surface variation may also be evidence for such a process (e.g. Jewitt, D.C. [2002]. *Astron. J.* 123, 1039–1049; Schmidt, B.E. et al. [2009]. *Science* 326, 275–279; Yang, B., Jewitt, D. [2010]. *Astron. J.* 140, 692–698). If Pallas still contains a thin layer of water ice, then that layer corresponds to the bottom of a former icy shell, and as such, could be enriched in non-ice materials such as organics. We evaluate the likelihood of each scenario and show the general magnitude of water loss processes for Pallas. Given a balance of observational and theoretical constraints, we favor a water-rich accretion for Pallas that implies that Pallas has lost a significant fraction of its initial water content through exogenic processes since its internal evolution ceased. We also discuss implications of this work to other hydrated asteroids.

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1. Introduction

Accretional models suggest that planetesimals throughout the asteroid belt grew rapidly to several hundred km within the first few million years of the Solar System (e.g. Weidenschilling and Cuzzi, 2006; Morbidelli et al., 2009) making it probable that even the potentially water-rich C-class asteroids formed large and accreted a significant quantity of short-lived radionuclides. However, the low densities of C-class bodies (e.g., Britt et al., 2002), and the evidence for hydrated minerals at their surfaces are strong indications that they did not achieve temperatures high enough to produce near-surface silicate melting as has occurred on Vesta (e.g. Jones et al., 1990; Ghosh and McSween, 1998; Rivkin et al., 2002, 2003). Instead, water likely acted as a moderator of the amount of heating undergone by these objects (Grimm and McSween, 1989).

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As the second largest main belt asteroid, Pallas is potentially one of only a few protoplanets surviving intact since the early Solar System (McCord et al., 2006; Schmidt et al., 2009). Ceres's mean radius is ~476 km (Thomas et al., 2005), Pallas's is ~272 km (Schmidt et al., 2009), and Vesta is near 265 km in radius (Thomas et al., 1997). Pallas's density is intermediate between Ceres's density 2077 kg/m³ (Thomas et al., 2005) that may indicate an ice-rich composition, and Vesta's anhydrous rock-metal interior at 3480 kg/m³ (Thomas et al., 1997; Konopliv et al., 2006). Pallas is also characterized by peculiar orbital properties, having one of the largest eccentricities and inclinations in the asteroid belt; its path happens to cross Vesta's and Ceres's orbits, though it spends most of its orbit in the regime of the C-type asteroids beyond 2.5 AU. These features raise the question of Pallas's relationship to these asteroids. Recent detailed observations by the Hubble Space Telescope (HST) (Table 1, Schmidt et al., 2009) and Keck (Carry et al., 2010) have yielded constraints on Pallas's physical and surface properties, which can then support the development of thermal evolution models aimed to better understand Pallas's current physical state.

Table 1
Physical parameters of Pallas.

Size ^a (radii, upper limit)	291 (± 9) $\times$ 278 (± 9) $\times$ 250 (± 9) km	Schmidt et al. (2009)
(Lower limit)	276 (± 4) $\times$ 258 (± 3) $\times$ 238 (± 3)	Carry et al. (2010)
Mass ^a	2.04 (± 0.06) $\times 10^{20}$ kg	Konopliv et al. (2006)
Density (lower limit)	2400 (± 250) kg/m ³	
(Upper limit)	2870 (± 120) kg/m ³	

^a See Schmidt et al. (2009) for a discussion.

1.1. Free water in Pallas?

Indirect constraints on Pallas can be inferred from observations of other C-type asteroids, assuming a common origin for these objects. Recently, water ice was discovered on the surface of C-type Asteroid 24 Themis (Rivkin and Emery, 2010; Campins et al., 2010), the 198 km largest remnant of a presumably 400-km asteroid broken up in a massive collision (e.g. Castillo-Rogez and Schmidt, 2010) well as 65 Cybele (Licandro et al., 2008). The discovery of ice on the surface of an asteroid is provocative in that it definitively establishes the existence of water within the asteroid belt today and in the past. Thus, it is more convincing than ever that ice and water has been involved in the evolution of Themis and other C-class asteroids.

Observations of Ceres suggest indirectly that it contains a large fraction of water ice, and its shape argues for differentiation into a rocky core and icy shell (Thomas et al., 2005; McCord and Sotin, 2005; Castillo-Rogez and McCord, 2010). Most recently Castillo-Rogez (2011) modeled the evolution of Ceres, concluding that a porous hydrated silicate interior is improbable. Thus if Ceres, Pallas and Themis formed contemporaneously at their present locations, it is certain that Pallas too accreted ice. However, contrarily to 24 Themis, it is unlikely that water could remain near the surface of Pallas today, given its prolonged incursions nearer the Sun as a result of its high orbital eccentricity. Its current orbit passes from 2.13 to 3.41 AU, nearing the orbit of Mars and crossing that of Themis (2.71–3.53 AU; Giorgini et al., 1996).

Several other lines of evidence exist for a water-rich past, and possibly present, for Pallas. Its near-IR spectrum possesses a $\sim 3\text{-}\mu\text{m}$ absorption feature that is indicative of hydration, requiring that its surface minerals were processed in the presence of liquid water (Lebofsky, 1979; Larson et al., 1979, 1983). Pallas's surface shows evidence for albedo variation in the UV that is consistent with gradients in either thermal processing or water content of its surface materials (Schmidt et al., 2009). Recent measurements from HST indicate that Pallas's shape is within a few km of the equilibrium oblate spheroid for its rotation rate of 7.8 h suggesting that the body may have once been in hydrostatic equilibrium (Schmidt et al., 2009, Table 1), consistent with early thermal differentiation. However, there is evidence for impact excavation on Pallas down to $\sim 100\text{-km}$ scales (Schmidt et al., 2009; Carry et al., 2010). This is consistent with the fact that Pallas has an impact family. Pallas's ability to sustain some long-wavelength topography indicates that the material presently composing the asteroid is stronger than that making up Ceres, which shows no topography down to $\sim 25\text{ km}$ scales (Thomas et al., 2005). As a result, Pallas's current shape is probably influenced by its early thermal evolution overprinted by late-stage impact excavation.

The largest uncertainty in Pallas's density is due to the wide range of mass estimates; however, after careful analysis of these various inferences, Schmidt et al. (2009) established that Pallas's current density is likely to be between 2400 and 2800 kg/m³, bracketed by their upper limit on its size and the lower limit presented by Carry et al. (2010). These two end member densities are

chosen as the starting points for the modeling to follow since they offer the most reasonable bounds on Pallas's interior composition. Particularly, a density much higher than this range is not only unlikely given the limits of observations, but is also inconsistent with Pallas's surface properties and spectral characteristics, characteristic of the larger C-class (see review in Schmidt et al. (2009)). At its mass, size, shape, and surface temperature, Pallas's density is unlikely to be explained by a high degree of porosity (Britt et al., 2002). For a surface temperature of 230 K (Lim et al., 2005), icy materials relax on a timescale of a few tens of thousand years (Castillo-Rogez et al., 2011). Also Castillo-Rogez (2011) recently demonstrated in the case of Ceres that an assemblage of hydrated minerals is expected to compact as a consequence of long-lived radioisotope decay heat, driven by the creep of organic-rich and hydrated minerals that represent at least 25% of the volume of carbonaceous chondrites. Such a process would also compact silicates within Pallas.

It is thus probable that Pallas's relatively low density is due to the presence of ice or a low-density assemblage of hydrated minerals (e.g. chondritic material). The density is consistent with a volume fraction of water up to 5–30%, depending upon the average density of the silicates. In Fig. 1, we show the possible ranges of material distribution within Pallas given three possible values of its initial density. This figure shows that Pallas's water may be stored in the form of water of hydration, for example in serpentines and hydrated salts, or in an outer shell up to 80 km thick. The thickness of each layer is determined by the extent of hydrothermal activity in the object in the course of its history.

1.2. Accretional and orbital considerations

While Pallas is relatively low-density compared to Vesta, it is higher in density than other C-class asteroids, though it shares observational and orbital similarities with these objects, and particularly Ceres. Thus we pose the question: is Pallas's density representative of its initial composition, or might it reflect an altogether different history? The densities of other large C-type bodies cluster near 2000 kg/m³, including Ceres (Thomas et al., 2005), Hygiea, and the density inferred for the Themis family (see Castillo-Rogez and Schmidt (2010) for discussion). Turrini et al. (2009) suggested that the difference in density between Ceres and Vesta may arise from dynamical interactions between Jupiter and planetesimals in the vicinity of the giant planet. This work suggests more rocky planetesimals were likely to accrete near Vesta and more icy planetesimals at Ceres. Although Pallas's formation in that context has not been modeled, it is possible that it may also have accreted with more rock than Ceres since its orbit reaches 2.1 AU. Recent work has suggested pathways both for growing large planetesimals within the asteroid belt implying accretion of condensates at or near the “ice line” (e.g. Weidenschilling and Cuzzi, 2006; Morbidelli et al., 2009) or for supplying planetesimals to the inner Solar System from up to 13 AU following a major inward and then outward migration of Jupiter (Walsh et al., 2011). The latter may provide a context for explaining the large variations in water content among the asteroids within a relatively confined region of the Solar System, if it can be shown to reproduce other characteristics of the asteroid belt.

Pallas's orbit is much more irregular than many other large asteroids, such as Ceres, with an inclination of $\sim 35^\circ$ and eccentricity of 0.23, similar to that of Pluto. The Tisserand parameter (e.g. Jewitt, 2002) provides a means of distinguishing the orbital population from which a body is derived and the stability of its orbit to perturbations from a particular perturbing body. Pallas's Tisserand parameter relative to Jupiter, is just stable at 3.01 (against, e.g., 3.65 for Ceres), while anything below 3 is considered “cometary.” Near-Earth asteroids having comet-like (< 3) Tisserand values with respect to Jupiter, for example, tend to have low albedos

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