POLAR WANDER ON GANYMEDE: A POSSIBLE SOLUTION TO THE APEX-ANTAPEX CRATERING CONUNDRUM.

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Introduction: The observed leading-trailing hemisphere asymmetry in crater density on Ganymede is far weaker than that predicted by cratering models. We explore polar wander of a floating ice shell as a possible explanation. Due to the latitude dependence of absorbed solar radiation, the surface temperature at the poles is much less than that at the equator. We calculate the resulting ice thickness variations, assuming a conductive, elastic floating ice shell in equilibrium with interior radiogenic heat production. We find pole-equator thickness differences of up to 15 km at 4 Ga and 85 km at the present time. Through their effect on the principal moments of inertia, these thickness variations may cause the shell to become unstable with respect to the rotation axis. We find that the degree-2 thickness variations are sufficient to destabilize the shell for any reasonable value of the relevant parameters. We investigate the possibility of ductile flow in the shell reducing the thickness variations. We find strong thickness variations can be maintained until the onset of convection, which should have occurred when the shell was 30–55 km thick (~1-to-2.5 Ga for monotonically declining radiogenic heat flow).

The Conundrum: Dynamical simulations show that impact cratering occurs preferentially on the leading hemisphere of a synchronously orbiting satellite. Thus, the apex (the center of the leading hemisphere) should show a significantly higher crater density than the antapex (the center of the trailing hemisphere). For Ganymede in particular, cratering models predict an apex-antapex disparity on Ganymede of ~15–40 times. However, the observed crater density at the apex of Ganymede is only ~4 times that at the antapex [e.g., 1,2]. Several mechanisms have been proposed to explain this phenomenon: (1) the surface may be saturated or nearly saturated with craters; (2) a large fraction of the craters may have been made by planetocentric debris or some other unknown source, rather than heliocentric comets; and (3) the ice shell may have rotated nonsynchronously during geologic time [1–3].

In this work, we explore a form of nonsynchronous rotation: polar wander due to thickness variations in the ice shell. This idea has previously been studied for Europa by Ojakangas and Stevenson [4,5], but only potential reorientation due to the impact basin distribution has been considered for Ganymede [6]. Both of the above groups concluded that polar wander by these mechanisms was indeed possible.

A necessary condition for reorientation (of the sort considered here) to occur is that the ice shell be decoupled from the interior of the satellite by an ocean. Galileo magnetometer results suggest the presence of a liquid ocean on Ganymede at the present time [7,8], and it is likely to have existed for much or all of solar system history [8,9]. Polar wander may occur when large variations in ice shell thickness cause the shell to become unstable with respect to its principal moment of inertia (MOI) directions, resulting in inertial interchange polar wander in which the poles exchange positions with apex and antapex. Following the method of [4,5], we estimate thickness variations of Ganymede's cooling ice shell throughout its history and their effect on Ganymede's ice shell MOI. We then investigate the potential for ductile flow in the shell to counteract this by reducing the thickness variations.

Results: Using a model of a conductive, cooling viscoelastic ice shell, we can establish conditions necessary for the reorientation of Ganymede's ice shell. We neglect tidal heating to first order, because for Ganymede tidal heating is far smaller than radiogenic heating today (and throughout most of the past in dynamical models of the Laplace resonance [10]). The thickness variations produced in Ganymede's ice shell by the pole-equator temperature contrast (15–85 km, Fig. 1) should be sufficient to destabilize the shell any point during the its history. As the shell thickens, however, the time scale of viscous flow in shell decreases, eventually resulting in the relaxation of thickness variations when surface heat flows drop below ~6–11 mW m^{-2}.

As the ice shell thickens, it also becomes less stable against solid state convection. Models of grain size evolution in an ice shell suggest that the minimum thickness at which convection is possible (for a Ganymede equatorial surface temperature) would be in the range 30–55 km [11] — corresponding to a heat flux of ~7–15 mW m^{-2}. Convection would bring warm ice from the base of the shell region to the cold lid, producing an adiabatic temperature gradient. This would 1) facilitate relaxation of thickness variations, and 2) reduce the pole-equator temperature contrast responsible for creating the thickness variations. As a result,

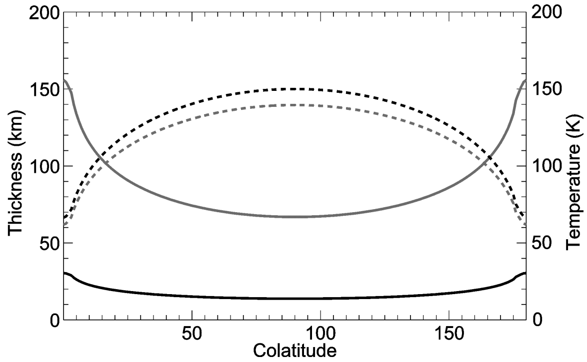

Fig. 1. Temperature (dashed) and ice shell thickness (solid) on Ganymede 4 Gyr ago (black) and today (grey). Local conductive radiogenic steady-state is assumed, but the thickness is only realistic when heat flows are high and ice thicknesses low, which prevents convection and limits viscous relaxation at the base of the shell.

polar wander would be unlikely to occur once the shell had thickened sufficiently to allow convection, which would be expected to occur between 1–2.5 Ga, for a monotonically declining, radiogenic steady state heat flow.

By the same token, the dynamics of polar wander are beyond the scope here — but are nevertheless crucial to the question of whether the shell will reorient. In a viscoelastic ice shell, the torque produced by the unstable MOI configuration must overcome the internal dissipation of the shell (both viscous and frictional) in order for polar wander to occur. The process is very sensitive to the viscosity variation with depth in the shell and is therefore difficult to accurately model. The work of [5] has shown that polar wander is dynamically difficult to achieve on Europa in the absence of 1) a significant low-conductivity regolith, which would greatly reduce the viscosity of ice near the surface, or 2) surface fractures, possibly lubricated by melt water, which extend to a depth where the ice behaves viscously on polar wander time scales. These requirements should also hold here, although the greater thickness variations of Ganymede's ice shell should facilitate the process.

In sum, we argue that polar wander is likely to have occurred early in Ganymede's history, when the satellite's ice shell was thin This would also have been concurrent with the heavy bombardment of what are now recognized as Ganymede's ancient cratered terrains (plausibly due to a heavy cometary flux during a Nice-model-like Solar System rearrangement). Ganymede's shell would need to be thinner than ~55 km; realistically, it would probably need to be substantially thinner in order to overcome the resistance of the shell. An episode of strong tidal heating, such as that proposed by [10], might also have produced the necessary conditions (including thinning and weakening the lithosphere); however, the ice thickness distribution would differ in detail from that discussed here.

A single episode of inertial interchange polar wander (90° of rotation) would not by itself fully erase any apex-antapex crater density differences on Ganymede, but if repeated (or if a continuous process) would be able to do so. If such reorientation(s) did occur, the current modest apex-antapex disparity in crater density on Ganymede must have developed since the last episode of polar wander. Logically, similar arguments might be applied to other icy satellites that possess internal oceans and which in principle had thin ice shells very early in their histories (e.g., Callisto). For other satellites, the lack of a pronounced apex-antapex cratering asymmetry may be due to one of the other causes given above. Is there any real doubt that Rhea, for example, is not saturated with craters (essentially) everywhere?

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