COUPLED ORBITAL AND THERMAL EVOLUTION OF GANYMEDE: IMPLICATIONS FOR RESURFACING AND MAGNETIC FIELD GENERATION. M. T. Bland[1] and A. P. Showman[2], [1]University of Arizona (mbland@lpl.arizona.edu), [2]University of Arizona (showman@lpl.arizona.edu).

Overview: Two of Ganymede's most distinctive features, its young, disrupted surface and its intrinsic magnetic field may have resulted from the Galilean satellites' passage through a Laplace-like resonance before they evolved into the current Laplace resonance. Passage through such a resonance could have increased Ganymede's eccentricity, generating tidal heating within the ice shell and silicate mantle. Heating the ice produces the melt and global expansion necessary for resurfacing the satellite, while heating the silicates thermodynamically buffers cooling of the metallic core, delaying onset of magnetic field generation until the current epoch.

To test this hypothesis we numerically model the coupled thermal and orbital evolution of Ganymede as the Galilean system progresses through one or more Laplace-like resonances.

Background: One of Ganymede's most striking features is the dichotomy of its surface terrains, with one-third of the surface consisting of ancient, heavily cratered terrain and the rest consisting of young, tectonically deformed terrain [1, 2]. These observations indicate that Ganymede has had a tumultuous history wherein large swaths of heavily cratered terrain were resurfaced. Such resurfacing requires significant internal heating of the satellite to produce both near surface melt and global expansion. However, the source of the required heating remains unclear.

One possible source is tidal heating. Ganymede is currently in a Laplace resonance with Europa and Io. However, this resonance does not pump Ganymede's eccentricity and the current rate of tidal heating is negligible. Malhotra 1991 [3] and Showman and Malhotra 1997 [4] showed, however, that the Galilean satellites may have passed through one or more Laplace-like resonances before evolving into the current Laplace resonance. These Laplace-like resonance do force Ganymede's eccentricity and can therefore lead to internal heating of the satellite as tidal dissipation attempts to circularize the orbit. Showman et al. 1997 [5] explored the effects of tidal heating on the ice mantle of Ganymede and found that, under certain conditions, it can lead to thermal runaway and melting, helping to explain the extensive resurfacing of the satellite. While this work indicated that the likelihood of thermal runaway was small, improved understanding of the internal structure of Ganymede and the nature of convection in variable-viscosity materials (e.g. ice and rock) warrants a reassessment of the applicability of the tidal heating mechanism to Ganymede's resurfacing.

Ancient tidal heating of Ganymede's silicate mantle may also allow the formation of a modern-day intrinsic magnetic field. In contrast to other large satellites (e.g. Europa and Callisto [6], or Titan [7] that show no evidence of an intrinsic magnetic field, a strong (~750 nT) intrinsic field has been observed at Ganymede [8]. Ganymede therefore joins a short list of solid bodies (Mercury and Earth) with detectable magnetic fields.

The simplest explanation for Ganymede's magnetic field is dynamo action within its metallic core, requiring vigorous motions within the conducting fluid [9]. However, because the metallic core is highly conductive, core heat can be rapidly removed without thermal convection occurring. Thus a thermally driven magnetic field cannot be produced by a core cooling slowly over the age of the solar system.

The addition of tidal heating, however, provides an alternative cooling scenario. Because the rate of core cooling is slave to the mantle temperature, tidal heating of the silicate mantle can thermodynamically buffer the core. In such a scenario, core cooling would be delayed until the rate of tidal dissipation is reduced. The silicate mantle and metallic core would then cool rapidly, triggering thermal and compositional convection within the metallic core and magnetic field production.

In light of these considerations we suggest that Ganymede may have undergone the following series of events. Passage through a Laplace-like resonance pumped the satellite's eccentricity causing tidal heating that was dissipated in Ganymede's ice shell and silicate mantle. Dissipation in the ice shell led to thermal runaway and melting [5], ultimately causing the cryovolcanic and tectonic resurfacing that produced the grooved terrain. Simultaneously, tidal heating of the silicate mantle effectively insulated the core, preventing it from cooling. As the Galilean satellites evolved out of the Laplace-like resonance the period in which Ganymede was tidally heated ended. The removal of tidal dissipation in the silicate mantle triggered the onset of core cooling via thermal and compositional convection, and the generation of Ganymede's observed magnetic field.

The Model: We follow the basic conceptual approach of Showman et al. 1997 [5] who coupled the orbital model of Malhotra 1991 [3] to a thermal model for Ganymede's interior. The orbital model is a generalization of the Yoder and Peale 1981 [10] scenario for evolution into the Laplace resonance that allows a more complete dynamical investigation of the orbital histories of the Galilean satellites. This includes capture into one or more Laplace-like resonances that cannot be rigorously explored analytically. The model includes perturbations from Jupiter's gravity field, the mutual perturbations amongst Io, Europa, and Ganymede, and secular perturbations due to Callisto. Forward integration allows determination of the eccentricity, semi-major axis, mean longitude, and longitude of periapse of each satellite.

The thermal model simultaneously solves the energy balance in Ganymede's ice shell, silicate mantle, and liquid Fe/FeS core. Heat transport within the ice and silicate layers occurs via stagnant lid convection, while in the core heat transport is by conduction. Both radiogenic heating of the mantle and latent heating of the liquid core due to inner core growth are included. Ocean formation can also occur if temperatures exceed 251 K in the ice shell.

Coupling between the orbital and thermal models occurs via tidal dissipation, which depends upon both the orbital eccentricities of the satellites and their physical and thermal structure. We use the model of Tobie et al. 2005 [11] to determine how tidal heating is radially distributed throughout the satellite interior. This model provides a more robust calculation of dissipation in a multi-layered viscoelastic body than many previous studies (e.g. [5]).

Preliminary Results: Simulations both with and without tidal heating have been performed. These simulations were initialized with a range of temperatures in the ice shell, silicate mantle, and metallic core that correspond to a cold, intermediate, and hot initial Ganymede. The silicate rheology is controlled by dislocation creep appropriate to wet olivine. The rheology of the ice shell is allowed to transition between diffusion and GBS creep depending on the temperature and convective stresses (cf. [12]). We use the convective scaling of Solomatov and Moresi 2000 [13] to parameterize the convection in each layer.

The Absence of Tidal Heating. Simulations of Ganymede's evolution without tidal heating provide an essential baseline for modeling that includes tidal heating. In these simulations silicate mantle temperatures rise until convective heat transport reaches equilibrium with radiogenic heat production at a temperature of 1700 K. Mantle temperatures then steadily decline with the fall off of radiogenic heating.

Temperatures in the ice shell initially rise rapidly until a temperature of 251 K is reached. At this point an ocean forms at a depth of ~150 km and further heating of the ice shell is buffered. At its maximum extent the ocean remains 50 km below the surface. Subsequent cooling of the ice shell leads to closure of the ocean well before the present epoch.

With a relatively cool mantle above it Ganymede's metallic core initially cools rapidly. As mantle temperatures increase, however, the cooling rate of the core decreases. Once core temperatures become cool enough for iron condensation an inner core begins to form. The rate of inner core formation is initially rapid, but begins to decrease as the sulfur content of the remaining outer core increases and the release of latent heat and gravitational energy reduces the rate of core cooling. Assuming an initial sulfur mass fraction of 10%, approximately 50% of Ganymede's core remains liquid after 4.5 Ga. Cooling rates throughout Ganymede's history are significantly lower than is required for thermal convection.

We note that the timing of these events depends weakly upon the initial thermal structure assumed for the satellite.

The Addition of Tidal Heating. The inclusion of tidal heating profoundly affects Ganymede's thermal history. Preliminary modeling suggests that if passage through a Laplace-like resonance increased Ganymede's eccentricity to at least .01 (~7 times its current value) tidal heating in the ice shell would be strong enough to allow melt to exist within a few kilometers of Ganymede's surface. Such melting would accommodate resurfacing of the satellite. Furthermore, core cooling is prevented while the eccentricity is high, delaying the onset of magnetic field generation. Passage through such a resonance therefore remains a strong candidate for explaining many of Ganymede's unique features.

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