GANYMEDE'S ORBITAL AND THERMAL EVOLUTION AND ITS EFFECT ON MAGNETIC FIELD GENERATION. M. T. Bland[1], A. P. Showman[2], and G. Tobie[3], [1]University of Arizona (mbland@lpl.arizona.edu), [2]University of Arizona (showman@lpl.arizona.edu), [3]CNRS/University of Nantes (Gabriel.Tobie@univ-nantes.fr).

Overview: Ganymede is unique among the icy satellites in the solar system in that it has an intrinsic magnetic field [1], while similar satellites (e.g. Europa, Callisto, Titan) do not. This observation suggests that Ganymede's magnetic field results from the unique orbital history of the satellite, which may have included passage through one or more Laplace-like resonances before settling into its current orbital configuration [2,3]. We propose that passage through such a resonance generated tidal heating within Ganymede's silicate mantle. This heating buffered cooling of the metallic core, causing it to warm. When Ganymede escaped the resonance, tidal heating diminished and the core began cooling rapidly, driving thermal convection and production of the currently observed magnetic field.

Here we present preliminary modeling of the coupled orbital-thermal history of Ganymede that seeks to determine the feasibility of this scenario for generating Ganymede's magnetic field.

Background: One of the great surprises of the Galileo mission was the discovery of a strong (750 nT) magnetic field at Ganymede [1]. In contrast, intrinsic magnetic fields have *not* been observed at other large satellites such as Europa and Callisto [4] or Titan [5] (observations at Io provide no conclusive evidence of an intrinsic field there either [6]). Ganymede therefore joins a short list of solid bodies (Mercury and Earth) with detectable intrinsic magnetic fields. Understanding why Ganymede has a magnetic field is therefore important to our understanding of both icy satellites and solid bodies in general.

The simplest explanation for Ganymede's magnetic field is dynamo action within its metallic core, requiring vigorous motions within the conducting fluid [7]. These fluid motions must be caused by thermally and/or compositionally driven convection as the core cools. However, problems arise with this simple dynamo scenario. Because the metallic core is highly conductive, core heat can be rapidly removed without thermal convection occurring. Estimates of the cooling rate required for thermal convection to "turn on" are 300-400 K/Ga [8], higher than can easily be achieved with the gradual decline in radiogenic heating. Growth of a solid inner core can promote compositional convection and thus lessen the cooling rate required for core convection. However, even in this case maintaining vigorous convection over the age of the solar system is difficult when the sole source of cooling is the decline of radiogenic heating. Thus, Ganymede's relatively small core should have sufficiently cooled to the point where fluid motions are not currently sustained and no magnetic field is present [9]. A successful mechanism for generating Ganymede's magnetic field ideally must not only overcome this difficulty but must also explain why Ganymede alone of the large icy satellites has an intrinsic magnetic field.

One possible explanation that meets these criteria is that the production of Ganymede's magnetic field is accommodated by the unique orbital-thermal history of the satellite. 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 [2] and Showman and Malhotra [3] showed, however, that Ganymede may have passed through one or more eccentricity pumping, Laplace-like resonances as it evolved into the current Laplace resonance. The forcing of Ganymede's eccentricity by these resonances can lead to internal heating of the satellite as tidal dissipation attempts to circularize the orbit. Showman et al. [10] explored the effects of such 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. This clearly illustrates the importance of the orbital-thermal history in understanding the satellite's observed features.

Dissipation of tidal energy occurs not only in the ice shell but also in the silicate mantle [11]. Because the thermodynamics of the core are slave to the mantle temperature, tidal heating in the mantle can buffer core cooling. Such a scenario was explored for Io by Wienbruch and Spohn 1995 [12] who found that the large degree of tidal heating of Io's silicate mantle prevented core convection and generation of a magnetic field. If Io's tidal heating was removed, however, it is likely that the core would rapidly cool by convection, producing a strong magnetic field.

Prompted by the above considerations, we suggest that Ganymede may have undergone the following series of events. Passage through a Laplace-like resonance pumped Ganymede's orbital eccentricity causing tidal heating that was dissipated in the ice shell and silicate mantle. Dissipation in the ice shell lead to thermal runaway and melting [10], ultimately causing extensive resurfacing. Simultaneously, tidal heating of the silicate mantle effectively insulated the core, preventing it from cooling. As Ganymede's orbit evolved out of the eccentricity pumping Laplace-like resonance and into the current Laplace resonance the period of tidal heating ended. While removal of tidal dissipation in the ice shell led to the end of resurfacing, the removal of tidal dissipation in the silicate mantle led to the beginning of the core dynamo, as rapid cooling via thermal and compositional convection generated Ganymede's observed magnetic field. Thus, two of Ganymede's most distinctive features, its disrupted surface and its substantial magnetic field, are elegantly explained by a single event: passage through the Laplace-like resonance.

While it is tempting to compare Io's current state to Ganymede's state during passage through a Laplace-like resonance (Ganymede is structurally similar to Io with the addition of ~900 km of ice), it should be noted that passage through even the strongest Laplace-like resonance produces an order of magnitude less tidal heating in Ganymede than is currently observed for Io [3, 13]. It is therefore essential to elucidate the conditions under which dissipation of tidal energy in Ganymede's silicate mantle is strong enough to delay cooling of the metallic core.

Modeling Approach: We follow the basic conceptual approach of Showman et al. [10], who coupled the orbital model of Malhotra [2] to a thermal model for Ganymede's interior. The orbital model is a generalization of the Yoder and Peale (1981) [14] 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 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 either convection or conduction depending on the rate of cooling. Both radiogenic heating of the mantle and latent heating of the liquid core due to inner core growth are included. The model also includes the effects of partial melt in the ice and silicate layer (if such melting occurs). Such melt can have a strong impact on viscosity and hence tidal dissipation within the satellite, but is excluded from many previous models. Furthermore, the presence of near surface melt has significant implications for the cryovolcanic resurfacing of Ganymede [15].

Coupling between the orbital and thermal models occurs via the tidal dissipation, which depends upon both the orbital eccentricities of the satellites and their physical and thermal structure. By assuming an initial thermal structure, the Q/k (where Q is the tidal dissipation function and k is the second degree tidal love number) of Ganymede can be calculated. This value is used as input into the orbital model, which calculates the evolution of the dynamical variables and the subsequent rate of tidal heating. We use the model of Tobie et al. [11] to determine how this tidal heating is radially distributed throughout the satellite interior. Using the rate of tidal heating in each layer determined by this model as input into the thermal model described above, we calculate a new thermal structure for Ganymede. This allows calculation of a new Q/k value for Ganymede which is again fed into the orbital model and the whole system propagates in time. Thus the entire orbital-thermal evolution of Ganymede can be determined. In addition to the coupled orbital-thermal experiments described above, we will also explore Ganymede's thermal evolution in the absence of tidal heating to provide a baseline for comparison with tidally heated cases.

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