IS GLOBAL EXPANSION OF GANYMEDE STILL REQUIRED GIVEN NEW THERMAL EVIDENCE FROM CALLISTO?

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Summary: Showman et al. [1, 2] have recently provided a detailed model of the internal evolution of Ganymede that takes into account the highly differentiated nature of the satellite and the presence of a dense core [3] and intrinsic magnetic field [4], and couples this with the orbital evolution of the Galilean satellites as modelled by [5]. However, the more recent discovery of an induced magnetic field around Callisto [6] may have significant implications for the evolution of the crust of Ganymede and explanations for its current configuration.

Magnetic Field Observations: Callisto was observed on the C3 and C9 fly-bys of the Galileo orbiter at opposite phases of the variation of the background (Jovian) magnetic field. Intrinsic ferromagnetic dipolar field models, in which the magnetic field is generated by convection within a convecting metallic core, were found not to agree with the perturbations that were observed. Instead, it was found that they could best be modelled as being generated by a dipolar magnetic field induced in a conducting sub-surface layer beaneath Callisto's crust. Further evidence that the field was induced was the fact that the dipole moments detected were anti-parallel on opposite sides of Jupiter. This layer was interpreted to be a globally extensive, electrically conducting ocean of salty water at least 10 km in depth, assuming a salinity similar to that of the oceans of Earth [6]. However, to correlate with the apparently geologically quiescent surface of Callisto, the uppermost part of an 'ocean' would have to be located deep below the surface, most likely probably several tens of kilometres.

An sub-surface ocean was confirmed for Europa later in the Galileo mission when an induced magnetic field was observed there during the E4 and E14 fly-bys [6]. Although the exact depth of such a liquid layer has not yet been determined, it is likely that it does lie close to the surface based on geological evidence.

Unlike both the other satellites described here, a magnetic field with the signature of an intrinsic (internally generated) dipole was unambiguously detected at Ganymede by Galileo [4, 7]. This field must be generated by an internal 'dynamo' in a convecting, conducting (i.e. molten metallic) core.

Ganymede Orbital Evolution: Ganymede is part of a complex orbital resonance peculiar to the Jovian system. In this resonance, the ratios of the mean motions (i.e. the mean orbital angular velocities) of the Ganymede-Europa and Europa-Io pairs are both almost exactly 2:1; in other words, when Ganymede completes one orbit around Jupiter, Europa completes two, and Io completes four. In addition, the conjunctions between the satellites within each pair drift, and there is a 1:1 relation between the rates of motion of the Io-Europa and Europa-Ganymede conjunctions - this is known as the Laplace Resonance. This orbital configuration allows the secular transfer of energy and angular momentum from Io to Europa to Ganymede, and the tidal dissipation within these bodies that results significantly affects the surface and interiors of these satellites [1]. Indeed, it is the tidal dissipation within Io that results in the extensive volcanic activity observed on its surface today [8] and it has been suggested [9] that this also provides the heat source for the ocean beneath Europa's surface.

Showman et al. [1, 2] propose that the Io-Europa-Ganymede system passed through one or more Laplace-Like Resonances (LLRs) before settling into the current one; these served to pump the eccentricity of Ganymede, potentially resulting in extensive and rapid tidal heating that mostly affecting its outer icy layers. In their models, Ganymede is captured into an LLR very soon after its formation and complete differentiation into a metallic core, rocky mantle, and icy crust consisting of Ice I at and below the surface, underlain by high pressure (HP) ice phases such as Ice III, Ice V, and Ice VI.

Showman et al. [2] predict that global thermal runaways would occur if the internal thermal profile was within a particular temperature range when Ganymede entered the LLR - if the interior was too hot or cold, runaways would not occur at all. Large runaways cause an increase in internal temperature of between 50 and 100 K which results in the melting of most of the Ice I layer and more importantly of the HP ices deeper below the surface. As the dense HP ices melt, they expand more than the melting Ice I contracts and cause a net 'global expansion'. Such an expansion was first proposed by [10] to explain the formation of the Bright Terrain that covers ~ 50 % of Ganymede's surface. Such a scenario is presented as an alternative to previous hypotheses proposing that the global expansion occurred due to the volume change that resulted in the freezing to Ice I of a water ocean within Ganymede [11].

However, Showman et al. admit that there are problems with this scenario, the most important of which being that if there is even the normal carbonaceous chondrite abundance of radioisotopes in the rocky interior of Ganymede then the internal temperature would be too high to allow such large runaways to occur in the first place. Instead, Ganymede comes into the LLR with a warm interior and already possesses a thick ocean of liquid water between a thin Ice I surface crust and possibly a remnant Ice VI layer overlying the rocky mantle. In this case, presence of the ocean means that the eccentricity is not pumped to a high enough value within the LLR to generate sufficient tidal dissipation to have a significant effect on the satellite other than to stabilise the temperature to a level warm enough to maintain the ocean. The ocean therefore remains until the LLR is disrupted, whereupon it cools and eventually freezes ~ 1 Ga later.

It therefore appears that large runaways may be impossible given a realistic radionuclide distribution within Ganymede. There are uncertainties, particularly in the determination of Q (the tidal dissipation factor) and the assumed properties of the ice, that may allow large runaways to occur within this model, however. If they do occur, some degree of global expansion is likely which could satisfy the requirement that the Bright Terrain on the surface of Ganymede formed as a result of such an event.

It could be argued that the formation of an ocean before entry into the LLR would result in global expansion through the melting of HP ices at the base of the primordial ice crust. However, the high heat flow caused by accretional and radioisotope heating at such an early stage in Ganymede's history may well preclude the freezing of any liquid water to form the HP ices at the base of the ocean in the first place. Even if it were possible, the resulting expansion and fracturing caused by the melting of any HP ice would not be recorded in the crust visible today because that would not have formed. The boundaries of the Bright Terrain belts on Ganymede are sharp, and Bright Terrain is much less cratered and cuts through more ancient, heavily cratered Dark Terrain blocks [12]. It is therefore apparent that the Bright Terrain cannot be associated with the early differentiation of the satellite and so must have formed later in Ganymede's history. Dissipation resulting from passage through a Laplace-Like Resonance is a viable candidate for a phenomenon that could result in the generation of Bright Terrain, although the reasoning shown below throws doubt on the possibility that the Bright Terrain could have resulted from global expansion.

Callisto's Ocean: The recent discovery of an ocean layer within Callisto may create severe problems for any global expansion hypotheses for Ganymede. Callisto has never been involved in any orbital resonances throughout its entire history. Callisto's heavily cratered, primordial surface shows very little (if any) sign of tectonic activity even in high resolution Galileo images, indicating that it has not suffered any tidal heating pulses that could have created changes in its interior that would affect its surface, such as those proposed for Ganymede [e.g. 13]. However, a conducting liquid layer - most likely a salty H_2O ocean - still exists deep within the satellite's interior today. The existence of this ocean is troublesome indeed, since it must be maintained by some hitherto unrecognised heat source.

The internal structure model for Callisto of Anderson et al. [14] proposed that a clean ice layer would extend from the surface to a depth of ~ 350 km in a partially-differentiated three-layer model of the satellite which at the time seemed reasonable. However, Anderson et al. [14] admit that the amount of ice-rock separation they calculate may be a lower limit. If Callisto actually has a strong elastic lithosphere and is not in hydrostatic equilibrium (a fact that remains ambiguous and may be confirmed or denied in the close Callisto fly-bys scheduled later in GEM), the calculated moment of inertia (0.359) would be an overestimate and Callisto would therefore be more strongly differentiated. Such a deviation from hydrostatic equilibrium could arise from a tidal bulge caused by an internal water layer, although the satellite's distance from Jupiter and the depth of the ocean within it may result in too small a tidal bulge to cause such a significant enough deviation. Nevertheless, since the data from which Anderson et al.'s internal structure model [14] are derived is based on only one reliable dataset (the C10 fly-by), it would be prudent to remember that the equilibrium treatment is still an assumption at this stage, and that the possibility remains that Callisto may actually be more differentiated than currently appreciated.

Given this possibility, coupled with the recent confirmation of an ocean layer on Callisto [6], it is possible that the model of Anderson et al. [14] now requires extensive modification. The presence of the ocean would imply that there is no intimate mixture of rock and ice between a rock/metal core and ice crust as proposed by [14]. Instead, there would be sufficient radiogenic heating to allow more complete ice-rock separation early in Callisto's history. Assuming the radioisotopes are concentrated in the silicate component of the satellite, this ocean would most likely be located at the base of the ice crust nearest the heat source that created it.

However, there is still the question as to why the ocean remains in a liquid form within Callisto today. As mentioned earlier, tidal heating cannot have sustained the ocean's existence, since Callisto has not been involved in any orbital resonances with the other satellites. Accretional heating and heating from short-lived radioisotopes would only keep an ocean in a liquid state early in Callisto's history and then would cease to be effective. The presence of a large amount of long-lived radio-isotopes (and a correspondingly smaller amount of other heavy elements) in Callisto's silicate component could actively maintain an ocean today, although this is admittedly unlikely unless there was a significantly higher proportion of such isotopes concentrated within the proto-Jovian nebula from which the satellites formed and if this is the case, then there are significant implications for the thermal evolution of the other Galilean satellites. Another possibility is that the ocean is no longer being actively heated (and hence is ancient), but rather is simply not being cooled efficiently, possibly because of highly inefficient heat loss mechanisms within the interior of Callisto.

Clearly, much investigation remains to be done into this topic but the evidence suggests that an ocean has to exist today deep below Callisto's surface. This can only be maintained if there is some previously unrecognised internal heat source within the satellite.

Synthesis and Implications for Ganymede: Ganymede and Callisto have often been considered as 'sister worlds' - they have similar sizes, and bulk compositions and densities - yet they have evolved on very divergent paths: Ganymede's surface is divided into pseudocircular blocks of ancient, heavily cratered Dark Terrain and bands of Bright Terrain with pervasive linear ridges and troughs throughout that obviously formed as a result of some kind of prolonged tectonic activity. In contrast, Callisto's surface shows no indication of any tectonic activity whatsoever, instead bearing the scars of impacts apparently dating back to its formation.

Given the similarities in the size and densities of these satellites, it is likely that Ganymede and Callisto were very similar worlds very early in their histories and that something happened that caused them to evolve on separate paths. The obvious difference is that Ganymede became involved in the Laplace-Like Resonances proposed by Showman et al. [1, 2] and that the tidal dissipation caused by this created the Bright Terrain. Callisto did not become involved in any orbital resonances due to its remoteness from the inner Jovian system and thus it was not subjected to the extensive resurfacing that Ganymede suffered.

Since the two worlds are similar, and assuming the reasoning presented here is valid, it does not seem unreasonable to assume that Ganymede possesses the same mysterious internal heat source that maintains the ocean within Callisto today. If this heat source was active from the formation of both satellites, an ocean would certainly have had to be present within Ganymede before it entered the Laplace-Like Resonance. This extra heat source would most likely completely rule out the possibility of any kind of thermal runaway within Ganymede, and what is more it would act to keep the ocean liquid until today. Thus, not only is the possibility of a global expansion through the melting of high pressure ice phases removed (since they most likely would never have had a chance to form in the first place), but the continued internal heating later in Ganymede's history would offset the cooling and freezing of the ocean (and prevent the global expansion that would result from this) after the satellite leaves the LLR and enters the Laplace Resonance observed today.

It is therefore possible, given the realistic orbital and thermal evolution models of [1, 2, 5] and the reasoning presented here, that global expansion of Ganymede's crust is no longer necessary to explain the Bright Terrain/Dark Terrain dichotomy. Preliminary examination of Galileo images of Ganymede also indicates that the prime reason for invoking global expansion in the first place - the apparent lack of compressional features on Ganymede's surface - may no longer be valid. Evidence for possible compressional features has been observed in the Northern Marius Regio area of Ganymede, imaged during the G8 fly-by (Galileo image c0394517800) and is noted by [15]. Within this area, compression may have occurred to form the axial ridges within Byblus Sulcus, and may also have formed some of the arcuate ridges within Nippur Sulcus in the northern part of the image.

Conclusions: The existence of a liquid ocean within Callisto maintained by a previously unrecognised heat source may have important implications for the internal and surface evolution of Ganymede and the other Galilean satellites. This additional heat source may also be present in Io and Europa unless it is somehow only associated with larger accumulations of ice such as those found in the two outer Galileans. Most significantly though, the similarity of the bulk properties of Callisto and Ganymede makes it likely that the heat source maintaining the ocean in a liquid state in Callisto is also present within Ganymede. If this is so, mechanisms for global expansion of Ganymede proposed to explain the formation of Bright Terrain may no longer be valid since the formation of high pressure ice phases and/or the melting of Ice I would be precluded by the higher heat flow that would instead result in the formation and maintainance of an ocean within Ganymede. It may be possible for Galileo to detect Ganymede's ocean if an induced magnetic field signature can be separated from that of the intenal dynamo.

Initial examination of Galileo images of Ganymede reveals possible compressional features within the Bright Terrain, throwing doubt on the validity of one of the cornerstone arguments for global expansion; that of the apparently complete lack of such features on the surface. If this element of doubt exists, it would be prudent to re-examine the surface of Ganymede in case other compressional features have been mis-identified. Furthermore, mechanisms for the formation of Bright Terrain would have to be re-evaluated if global expansion is no longer an option.

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