THE INTERNAL STRUCTURE OF CALLISTO. C. Thomas[1] and R. C. Ghail[2]. [1]: Planetary Science Research Group, Planetary Science Research Group, Environmental Science Dept., Institute of Environmental and Natural Sciences, Lancaster University, Lancaster LA1 4YQ, England. [2]: T. H. Huxley School, Imperial College, London SW7 2BP, England. E-mail: constantine.thomas@lancaster.ac.uk

Introduction: Recently, the Galileo orbiter has provided very useful gravitational data from close flybys of Io, Europa, Ganymede and Callisto that provide several important constraints to their possible internal structures. We present a new model for the internal structure of Callisto based on gravity data.

Existing models: Callisto is an enigma. Its surface is tectonically inert, but Galileo detected the signature of a magnetic field on one of its flybys of the satellite [1]. This could only be explained if a liquid salty water layer existed a few hundred kilometres below Callisto's surface, and a magnetic field was being induced by the jovian field.

Anderson *et al.* (1998a) explored some models of Callisto's interior [3], but unfortunately this was prior to the discovery of the water layer. It is therefore difficult to incorporate such a layer into their models, which made no provision for such a situation. They proposed that Callisto, with a moment of inertia factor of 0.358 ± 0.004 (determined from the C10 flyby), consists of a rock/metal core taking up 25% of the satellite's radius, a 1450 km thick mixed rock-ice mantle, and a 350 km thick pure ice crust.

A more accurate report on the interior structure and physical parameters of Callisto has recently been presented by Anderson *et al.* (2001) [4]. Callisto's moment of inertia C/MR^2 is refined to 0.3549 ± 0.0042 - too small for Callisto to be completely undifferentiated, but too large for it to have separated completely into a rock core, water mantle, and ice crust. They present a range of two- and three-layer models for Callisto's interior - their three-layer models consist of an ice layer nearest the surface with a density range between 900 and 1500 kg m^{-3}, a rock/ice middle layer with density between 2300 and 3500 kg m^{-3}, and a rock or metal core of density 3550, 5150 or 8000 kg m^{-3}. Their rock core models yield the most realistic results, and are similar to those presented in [3]. but they still do not account for the existence of a water layer within the satellite, as determined by magnetometer measurements [2]. As such their models remain incomplete.

The ONIONSKIN moment of inertia model: We have constructed our own model for the interior structures of Callisto. This model is called 'ONIONSKIN' because it calculates moment of inertia of a satellite based on many thin concentric shells, not unlike the skin of an onion. We take the observed values of radius, mass, density, and moment of inertia factor C/MR^2, and construct a satellite made of layers of different types of (appropriate) material, such as ice I, ice III, rock, iron and/or iron sulphide (N.B. 'layer' refers to a distinct type of material - 'shell' refers to a radius increment used to calculate moment-of-inertia). We also attempt to account for self-compression of this material due to the mass of the overlying material. The size of the layers is determined by the percentage mass of the satellite which they represent and their uncompressed density - both of which can be changed dynamically - although whereas the percentage mass of a layer is very flexible, the uncompressed density of a material is fixed once the material is chosen. However, mixtures of different material (e.g. a rock/ice mixture) can have a wide range of densities so this becomes an important variable in these cases.

The moment of inertia factor C/MR^2 is determined by dividing the satellite into 10000 equally spaced shells from core to surface. The moment of inertia of each of these shells is calculated and then summed to determine the moment of inertia for the whole satellite in the model. By manipulating the percentage mass and type of material comprising each physical layer, it is possible to construct a model - or a range of models - that have values that lie within the derived error-bars for the satellite's radius, mass, density, and moment of inertia factor and thus are realistic.

There are three important *caveats* to be aware of with the ONIONSKIN model: first, the compressed density at the base of a layer is used to determine the moments of inertia of *all* the appropriate shells within that layer - no attempt is made to model the density range across the shells between the top and base of the layer.

Second, the ONIONSKIN model is a purely physical model constrained primarily by moment of inertia, radius, density and mass - no chemical or thermal modelling is carried out as part of the model verification. However, care is taken to assume reasonable densities for materials comprising the layers and to find appropriate physical parameters (e.g. bulk moduli to determine self-compressibility), and obviously certain results requiring layer densities that are too high or low to be realistic are ruled out straight away.

Third, ONIONSKIN is currently an empirical model - that is, appropriate values must be entered manually into the model and manipulated by hand to converge on the target values. This necessarily limits the investigation of the model's possible 'phase space' to those values that are obvious to the user. It is clear that the results that the model produces are not unique - various combinations and types of materials can produce models that fit within the acceptable 1σ error range. An automated process to work through the phase space and pick out those models that conform to the target values is planned but has not been developed yet, and would be extremely useful in determining the possible internal structures of the satellites.

These problems will be refined in future work, but can be a source of inaccuracy in the current models and should be borne in mind here. Despite these limitations however, ONIONSKIN generally produces results that broadly agree with published models [3, 4], which bodes well for its validity.

Callisto ONIONSKIN model results: Here we present a possible ONIONSKIN model of Callisto's interior that also incorporates a salty water layer. Kivelson *et al.* (1999) propose that such a water layer must be tens of kilometres thick, but also that it must be a tens of kilometres below the surface in order for the detected magneto-convective field to have the correct magnitude. As yet, a mechanism that would form a water layer so close to the surface is not understood. The main problem is that the water layer would be placed entirely within the ice I layer, with no apparent mechanism to allow it to exist there. This problem remains insurmountable at the time of writing. Instead, we continue to focus on physically plausible density and temperature models and disregard this problem. The resulting model is presented in Tables 1 and 2.

It should be noted that this model actually represents a lower bound, since most of the derived model results lie near the lowest error bounds of the target values proposed in [4]. It is possible to reach slightly more "accurate" results (lying more within these error bounds), but it becomes progressively harder to achieve these results. There are several reasons for this. First, the density constraint is very tight and very sensitive to change - increasing the ice/rock mantle or rock core mass by anything more than approximately 1% produces densities that are unacceptably high or low. The radius constraint is similarly tightly restricted. There is also a potential base pressure constraint at the base of the ice III layer if ice V is also present (it is not present in this particular model, however). In effect, this acts to severely limit the range of proportions of the material above and including the ice III layer - the pressure at the base of the ice III *must* be 346 MPa in order to allow it to change phase to ice V. However, this constraint is not considered here, as we assume that the top of the ice/rock mantle lies above the ice III/V phase boundary. This means that the ice III transforms to ice V within the ice/rock mantle (and indeed, the ice V transforms to ice VI, and ice VII towards the rock core), but these phase changes are subsumed into the density of the ice/rock mix.

The ice/rock mantle is assumed to be a layer of constant density (excluding the effects of self compression), consisting of a uniformly mixed 71:29 mixture of ice (with a density of 1300 kg m^{-3}) and rock (with a density of 3500 kg m^{-3}, identical to the core). Such uniform mixing across a large ice/rock mantle is however rather unlikely, since the rock is more likely to be concentrated towards the core. If this happens, the density of the ice/rock mantle should increase with depth - however, attempts to model this layer by dividing it into three layers whose density increases with depth give rise to severe problems in keeping the model constrained to the target radius, density and moment of inertia targets. At this stage, this problem is insurmountable, and is left for future work to rectify.

Table 1: ONIONSKIN model of the internal structure of Callisto with a silicate core (density: 3500 kg m^{-3}).

Layer	% Mass	P/T density (kg m^{-3})	Model radius (km)	Layer Thickness (km)
Ice I	8.05	936	2408.85	133.79
salt water	5.00	1169	2275.06	72.83
Ice III	4.25	1182	2202.23	65.16
Ice/Rock Mantle	72.70	2054	2137.07	1249.62
Rock Core	10.00	3662	887.45	887.45
Totals:	**100**			**2408.85**

Table 2: Callisto silicate core ONIONSKIN model compared with target values for radius, mass, C/MR², and density

	Target Values	**1σ error range**
Radius	2410.3	± 1.50 km
Mass	1.07214 x 10^{23}	± 0.00062 x 10^{23} kg
C/MR²	0.353608	± 0.0042
Density	1834.37	± 3.4 kg m^{-3}
	Model Results	**Error**
Radius	2408.85	- 1.45 km
Mass	1.07214 x 10^{23}	-
C/MR²	0.351551	- 0.002057
Density	1831.18	- 3.19 kg m^{-3}

References: [1] K. K. Khurana *et al.* (1998). *Nature*, **395**, 777-780. [2] M. G. Kivelson *et al.* (1999). *Journal of Geophysical Research - Space Science*, **104**, A3, 4609-4625. [3] J. D. Anderson *et al.*(1998a), *Science*, **280**, 1573-1576. [4] J. D. Anderson *et al.* (2001), *Icarus*, **153**, 157-161.