Can hydrothermal plumes melt through Europa's ice shell? G. C. Collins[1], J. C. Goodman[2], and R. T. Pierrehumbert[2], [1]Physics and Astronomy Dept., Wheaton College, Norton MA 02766 (gcollins@wheatonma.edu), [2]Dept. of Geosciences, University of Chicago, Chicago IL 60637.

Introduction: The formation mechanism for regions of chaotic terrain on Europa is the subject of much debate. Several models have been proposed to account for these disrupted areas of Europa's surface including melting through the ice shell by a concentrated heat source in the underlying ocean [1,2], coalescence of solid-state diapirs [3], extrusion of warm ice onto the surface [4], and melting within the ice shell [5]. While the melt-through hypothesis is attractive from the standpoint of explaining why chaos areas look, at first glance, like disrupted sea ice, it is more difficult in this model to explain the origin of the concentrated heat source beneath the floating ice shell.

O'Brien *et al.* [6] developed a numerical model of the melt-through process in order to explore the range of energies and timescales necessary to melt through the ice shell. Assuming a 6 km thick conductive ice shell with heat sources of 50-500 GW spread out over a 20-200 km wide area at the base of the shell, O'Brien *et al.* find that melt-through is possible over timescales on the order of 10^2 to 10^4 years, depending on the chosen heat flux. We have investigated these results using a different numerical scheme, and find that total melt-through will not occur under these conditions.

Steady-state energy balance: In order to maintain a certain thickness of conducting ice, the outgoing thermal radiation must balance the incoming solar radiation plus the heat input to the base of the ice shell: $F_{base} + F_{solar} = \sigma T_{surf}^4$. Adding more heat to the base of the ice shell should thin the ice until it reaches a new conductive equilibrium, up to the point that enough heat is added to maintain liquid water at the surface. For example, we can compute the equilibrium ice thickness for conditions similar to the lower standard case of O'Brien *et al.* (50 GW over a 200 km wide patch, or F_{base} = 3.3 W/m^2) using a one-dimensional vertical diffusive balance, ignoring sublimation at the surface (which would carry away more heat), lateral diffusion (since it is 3 orders of magnitude smaller than vertical diffusion in this case), ice flow, and tidal heating (which are small in this case [6]). The equilibrium ice thickness h will be

$$h = [b_1 \log(T_{base}/T_{surf}) + b_0(T_{base} - T_{surf})] / F_{base}$$

where T_{base} = 273 K, $T_{surf} = [(F_{base} + F_{solar}) / \sigma]^{1/4}$, b_1 = 488 W/m, and b_0 = 0.468 W/m/K [7]. This yields an equilibrium ice thickness value of 143 meters for F_{base} = 3.3 W/m^2.

Maintaining liquid water at Europa's surface requires at least 300 W/m^2 of subsurface heating, plus enough energy to overcome heat loss from boiling the water into a vacuum (probably >>100 W/m^2, which is the typical latent heat loss from Earth's polar oceans to the atmosphere). Only the most extreme case considered by O'Brien *et al.* (500 GW over a 20 km wide patch) approaches this heat flux.

Model: Since steady-state energy balance predicts that some ice will remain over all but the most extreme basal heat sources, why does the numerical model of O'Brien *et al.* predict total melt through for cases where over a hundred meters of ice should remain? It is possible that this system could overshoot the equilibrium thickness, if melting is more rapid than thermal gradient equilibration. However, it is also possible that this behavior is an artifact of the model. The numerical model of O'Brien *et al.* [6] is divided into 100 m thick cells, which are either all water or all ice, so their model cannot distinguish between no ice and 50 m of ice. Additionally, the thermal structure of the ice becomes unresolved as the ice becomes only one or two cells thick.

We have constructed a numerical model which solves this problem by increasing its resolution as the ice thins. The model always consists of 20 vertical levels above the bottom of the ice, solving the vertical diffusion of heat and melting of the ice from a basal heat source. In each timestep, the new ice thickness is computed and new gridpoints are interpolated between the new bottom and the top of the ice for the next timestep. Other than this different numerical scheme, all parameters were the same as those used by O'Brien *et al.*, to facilitate comparison of model behavior.

No overshoot of the equilibrium ice thickness occurs in our model. For example, with a basal heat flux of 3.3 W/m^2 (as described in the last section), the ice gradually approaches the equilibrium thickness of 143 m after a period of 20,000 years (fig. 1). The melting timescale is similar to that found by O'Brien *et al.*, but the final thickness of the ice is not. We have experimented with various starting thicknesses and heat fluxes, and tens to hundreds of meters of ice always remain for heat flux values between 1 and 50 W/m^2.

Discussion: So far, we have not attempted to precisely estimate the magnitude of local or global heat fluxes on Europa, we have simply been using the values of O'Brien *et al.* to facilitate comparison with their results. However, these values may be unrealistically high. Global heat production on Europa is unknown, but most estimates suggest 750-1500 GW [8], less than the 3000 GW needed to maintain a 6 km thick conductive ice shell. If the equilibrium ice shell is thicker than 6 km, as is suggested by impact crater morphology [9], then the melting timescale will be underestimated by the same factor. A more important factor is the concentration of this heat into localized sources which can be sustained for millennia. On Io, individual long-lived heat sources account for <2% of the global heat output [10].

We think a more realistic melting model would deliver 1 GW (close to a typical terrestrial hydrothermal plume [11]) distributing its heat over a 60 km diameter area [12] to the base of a 20 km thick ice shell. In this case, it would take 750,000 years to locally melt the shell to an equilibrium thickness of 1.3 km. On this timescale nonsynchronous rotation may be important [13], and the ice may never reach the equilibrium thickness.

It is also worth considering whether melting the ice shell to a hundred meters thick can create the observed chaotic terrain. There are two main obstacles to this hypothesis. First, The motion of 'ice rafts' cannot be driven by currents from the hydrothermal plume, as others have suggested [2], because the currents are too weak to push the rafts through even a few meters of ice [12]. The second obstacle is topography: while thinning of the ice shell would produce a pit on the surface, some chaotic matrix is observed to lie atop surrounding terrain [4], while stereo and photoclinometric elevation models show that chaos areas are generally domed above their surroundings [14]. Unless these problems are resolved, and a vast heat source is found on Europa, melt-through of the ice shell to produce chaotic terrain is a less viable model than hypotheses which invoke diapirism and/or partial melting within a thick ice shell.

References: [1] Greenberg *et al.*, *Icarus* 141, 263-286, 1999; [2] Thomson and Delaney, *JGR* 106, 12,335-12,365, 2001; [3] Spaun *et al.*, *LPSC XXX*, #1276; [4] Figueredo *et al.*, *JGR* 107, 10.1029/2001JE001591, 2002; [5] Head and Pappalardo, *JGR* 104, 27,143-27,155, 1999; [6] O'Brien *et al.*, *Icarus* 156, 152-161, 2002; [7] Hobbs, *Ice Physics*, 1974; [8] Pappalardo *et al.*, *JGR* 104, 24,015-24,056, 1999; [9] Schenk, *Nature* 417, 419-421, 2002; [10] Davies *et al.*, *Icarus* 148, 211-225, 2000; [11] Baker and Massoth, *EPSL* 94, 59-73, 1987; Thomson *et al.*, *EPSL* 111, 141-154, 1992; [12] Goodman *et al.*, this conference; [13] Hoppa *et al.*, *Icarus* 137, 341-347, 1999; [14] Schenk and Pappalardo, *LPSC XXXIII*, #2035, 2002.

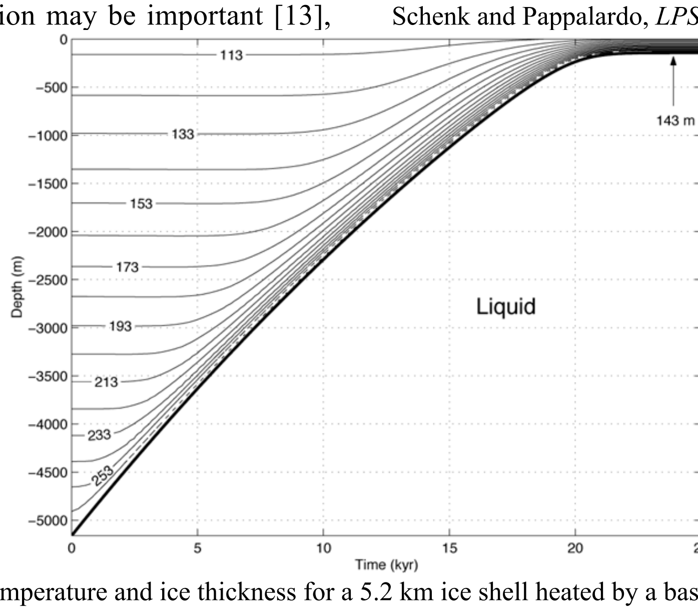

Figure 1: Evolution of temperature and ice thickness for a 5.2 km ice shell heated by a basal heat flux of 3.3 W/m^2.