DYNAMICS OF HYDROTHERMAL PLUMES ON EUROPA: IMPLICATIONS FOR CHAOS FORMATION.

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Introduction

The apparent existence of a substantial liquid water layer beneath Europa's icy crust [1, 2, 3] affects the transfer of energy from the tidally-heated rocky interior to the surface ice layer. Better understanding of the characteristic length, time, and velocity scales of flow in the liquid water layer can improve our understanding of the processes that reshape Europa's surface.

Of those processes, debate is especially intense regarding the formation mechanism for chaotic terrain. The "melt-through" model proposes that chaos regions and/or lenticulae are formed when hydrothermal plumes rising from localized seafloor heat sources melt away the overlying ice layer [4, 5, 6]. Thomson & Delaney [5] (T&D, hereafter) suggest that the ocean currents at the top of the plume might drive the apparent drift of large ice blocks in chaos regions [7]. But do hydrothermal plumes have the right size, heat flux, and velocities to be compatible with the melt-through hypothesis?

Plumes in an Unstratified Fluid: Scaling Laws

Unlike Earth's oceans, Europa's liquid layer is heated entirely from below. As the heating at the bottom attempts to place warm, light water beneath cold, dense water, turbulent convective mixing will erase any mean vertical density gradient. Thus, Europa's ocean should, on the whole, be unstratified.

The ambient stratification of the ocean strongly influences the behavior of buoyant plumes rising through it. In an unstratified system, the dominant buoyancy contrast which drives fluid motion is between the plume fluid and its surroundings. In a stratified system, the dominant buoyancy contrast is between the top and bottom of the ambient fluid. In an earlier description of hydrothermal plumes on Europa, T&D assumed a "weakly-stratified" system, by which they meant that that the ambient stratification was too weak to impede the ascent of plume fluid, and yet was strong enough to control fluid motion. This formulation is inconsistent: it requires that the plume's buoyancy anomaly be both greater and less than the buoyancy contrast within the ambient fluid.

We have performed a detailed scaling analysis of the ascent of a buoyant plume, released from a small source region into an unstratified fluid in a rotating reference frame. Our analysis is informed by laboratory and numerical simulations of this phenomenon [8,9]. In agreement with T&D, we find that the width of the ascending plume is restricted by Coriolis effects. The narrow plume rises until it reaches the lower surface of the ice layer: at this point, it is forced to spread outward. Coriolis effects cause rotational currents to develop in the spreading plume. The baroclinic instability process causes the plume to break up into discrete eddies once it reaches a width r_D, the so-called "radius of deformation". r_D describes both the limiting size of the plume and the size of the eddies that break off from it.

While the qualitative description is similar, our assertion that the ambient fluid is unstratified leads to a quantitative description of the plumes that is very different from that of T&D. The velocity and temperature of plume fluid, the radius of deformation, and other key variables depend on different parameters in our analysis than in T&D's.

We find that a single dimensionless parameter governs the behavior and structure of the plume. This is the "natural Rossby number":

$$Ro^* \equiv (Bf^{-3})^{1/4}/H.$$

Here, B is the flux of buoyancy from the seafloor source (B is proportional to the source's heat output), H is the depth of the ocean, and $f \equiv 2\Omega\sin(\theta)$ is the Coriolis parameter (Ω is planetary rotation rate, θ is latitude.) The natural Rossby number measures the importance of Coriolis effects on the plume. If $Ro^* \ll 1$, the plume fluid takes many days to rise from the bottom of the ocean to the top, and the plume dynamics is dominated by Coriolis effects. If $Ro^* \gg 1$, the plume is less affected by rotation.

We assume that Europa's ocean is between 50 and 140 km deep, and consider a range of possible plume heat outputs between 0.1 and 100 GW. Despite the wide range, the weak $1/4$-power dependence of Ro^* on B means that Ro^*varies only by a factor of 6, between 1/10 and 1/60.

A series of dynamical and dimensional-consistency arguments leads to a set of scaling laws that express the diameter of the fully-developed plume, the rotational velocity and buoyancy anomaly of the plume fluid, and other parameters in terms of Ro^* (Table 1). However, a constant of order unity remains unknown in each of these expressions (the k's in Table 1), which must be determined empirically.

Parameter	Scaling Law
Plume diameter	$k_{lc}\sqrt{Ro^*}H$
Buoyancy anomaly	$k_b Ro^* H f^2$
Swirl velocity	$k_v\sqrt{Ro^*}Hf$
Eddy formation time	$k_\tau (Ro^*)^{-2} f^{-1}$

Table 1: Scaling laws for buoyant plumes in an unstratified fluid, when $Ro^* \ll 1$.

Laboratory Experiments

We have constructed a small-scale model of buoyant plumes in the laboratory to empirically find the k constants in Table 1. Dyed, salty fluid is released from an injector at the surface of a tank of fresh water. The entire apparatus is mounted on a rotating table. The salty fluid sinks, forming a descending turbulent plume (Figure 1) whose behavior (except for the up/down reversal) is identical to that described above. By

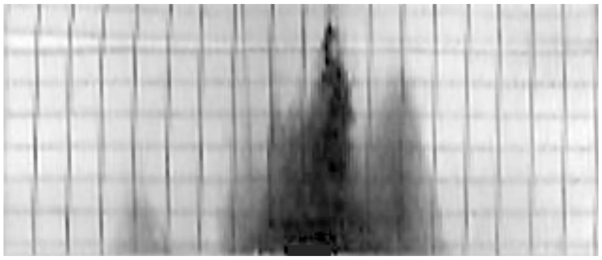

Figure 1: Elevation view of laboratory plume experiment, showing descent and turbulent mixing of dyed saline water into a rotating tank of freshwater. View image upside-down for comparison with buoyant hydrothermal plumes. Note conical shape of central plume, and two conical eddies ejected from plume to left and right. B = 4.27 cm^4 s^{-3}, H = 20 cm, f = 2 s^{-1}; Ro^*= 1/23.

varying the rotation rate of the table and the depth of the tank in a series of experiments, the parameter range $1/60 > Ro^* > 1/10$ can be simulated. Measurements of the dimensions of these plumes show good agreement with the predictions of the scaling laws in Table 1. Having verified the scaling laws, we use these measurements to find best-fit values for the unknown constants.

Dimensions of Europan Plumes

With this information, we may use the scaling laws in Table 1 to predict the diameter of the plumes, the heat flux per unit area supplied to the base of the ice layer, speed of vortical currents in the plume, and temperature anomaly of plume fluid (proportional to buoyancy anomaly). These predictions are given in Table 2. Note that over a range of heat output of 3 orders of magnitude, the plume diameter and current speeds vary by less than a factor of 3. These parameters are proportional to the 1/8th power of the heat or buoyancy flux.

Parameter	Predicted Value
Plume diameter	20 - 50 km
Heat flux (upper bound)	0.1 - 10 W/m^2
Swirl velocity	3 - 8 mm/s
Temperature anomaly	0.2 - 1 mK

Table 2: Predicted dimensions of hydrothermal plumes on Europa. Ocean depths 50-140 km, heat source output 0.1-100 GW.

Discussion

If chaos and/or lenticulae are formed when a hydrothermal plume melts through a patch of ice crust, then the size of the plume must be comparable to the size of the resulting surface feature. Predicted plume diameters of 20-50 km are comparable to the size of the large Conamara chaos feature (∼100 km); note that the warm eddies surrounding the main plume will spread the heating somewhat beyond the diameter of the main plume (see Figure 1). However, the plumes and eddies are much wider than the typical diameters of lenticulae (< 10 km [10]). Thus, lenticulae are probably not the products of melt-through.

By dividing the thermal output of the heat source by the area covered by the plume, one may compute the heat supplied to the base of the ice layer. This is an upper bound, since some heat will be carried away laterally by the warm eddies shed by the plume. Heat fluxes of this magnitude may substantially thin the ice layer, but cannot melt completely through it: this heat flux is balanced by conduction through the ice when between 40 meters and a kilometer of ice remain unmelted [11].

T&D have proposed that the satellite lenticulae surrounding Conamara Chaos are caused by melting induced by warm eddies shed from a central plume underlying the chaos. If an eddy is to create a lenticula, it must remain stationary long enough to melt the ice (∼10,000 yr [6, 11]). However, the currents near the plume (3-8 mm/s) will carry the eddy away from the putative melting site long before significant thinning occurs.

The large ice rafts in Conamara Chaos have moved several kilometers from their pre-chaos positions [7]. There appears to be a clockwise rotational component to this motion, though this result is uncertain [12]. T&D note that the upper part of a hydrothermal plume at Conamara's location would have a clockwise circulation; therefore, they suggest that the rafts might have been pushed into their present position by ocean currents during a melt-through episode.

As we have noted earlier, a melting episode cannot expose open water at Europa's surface: the unmelted matrix material between rafts must be at least 40 m thick. Ice rafts must deform this crust in order to drift. Can ocean currents impart the necessary force? We consider terrestrial sea ice as an analogue for the matrix material. Terrestrial sea ice behaves as a plastic material on large scales: it remains rigid until its yield stress is reached [13]. We find that drag force from an ocean current moving at 3-8 mm/s past an ice raft ∼1 km thick is many orders of magnitude too weak to deform the matrix material. Thus, we must seek another explanation for the motion of ice rafts. Viscous flow of warm ice beneath a brittle surface layer, in the form of either diapirism or flow driven by horizontal hydrostatic pressure gradients, may be a reasonable alternative.

References

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