

EUROPEAN CHAOS AND LENTICULAE: A SYNTHESIS OF SIZE, SPACING, AND AREAL DENSITY ANALYSES. N. A. Spaun¹, J. W. Head¹, and R. T. Pappalardo², ¹Brown University, Box 1846, Providence, RI 02912, ²LASP, University of Colorado, Boulder, CO 80309-0392. nspaun@fbiacademy.edu

Introduction: We performed detailed analyses of Europa's near-equatorial region at several longitudes to assess the size, spacing, and surface distribution of micro-chaos lenticulae and chaos in order to determine the properties of the European ice shell. Chaos is defined as large, irregularly shaped regions commonly containing linear-textured blocks of pre-existing terrain and also containing a hummocky matrix material [1]. Micro-chaos lenticulae are smaller features containing a hummocky matrix material similar to that within chaos [2]. Both a "melt-through" model and a diapiric model have been suggested for the origin of chaos and lenticulae. The former entails a very thin European ice shell that is melted locally, exposing the ocean below [3]. In the diapiric model, a brittle ice layer a few km thick is underlain by an icy asthenosphere (> few km) that may or may not be underlain by an ocean [4]. Solid-state convection occurring at the base of an ice layer when the temperature is near the solidus, causes diapirs to rise buoyantly. [2] and [5] show that micro-chaos lenticulae and chaos are consistent with the predictions of a diapirism model. Diapirs may create chaos and the various lenticula types in a possible sequence, including the coalescing of lenticulae to make chaos [2, 5].

We present a synthesis of our size, spacing, and areal density studies of chaos and lenticulae in order to integrate the data and to determine trends that might be related to the physical properties of the European ice shell.

Data: (see Table 1). The smallest feature sizes, spacing distances, and high areal density are observed in the E4DrkMat02, E11Morph01, E6DrkLin01 (lesser areal density), and E15RegMap02. Conamara Chaos only comprises 10% of the surface area of the E6DrkLin01 observation, a much lower percentage than that of the largest chaos features in the above regions, suggesting that surface area density is greatly affected by the presence of large chaos regions. The largest size and spacing distributions are found in the E11RegMap01 and E14Wedges01 regions. Interestingly, the E11RegMap01 region has a very high surface density of micro-chaos lenticulae and chaos (44%) while the E14Wedges01 region has the lowest observed surface density (10%). The E17RegMap01 region has dominantly small features but an intermediate feature spacing and surface area density.

Comparing these results by longitude, we find features containing chaos materials are generally more abundant, smaller, and closer together near 270°W (trailing point), 90°W (leading point), and 330°W. A low surface density of large, far apart features occur near 180°W (anti-Jovian point) and a high surface density of large, far apart features near

240°W, with intermediate characteristics for the in-between region at ~ 210°W. Thus, it is possible that the size and spacing of micro-chaos lenticulae and chaos vary regularly at certain longitudes, however the measurements for E4DrkMat02 (330°W) and E11RegMap01 (240°W) are inconsistent with a regular pattern of varying size and spacing of features. The surface area density of features varies significantly by longitude with no obvious pattern.

Implications: Based on the size, spacing, and surface density results, we suggest that a diapiric model is most consistent with the observations and measurements. In this case, a convecting asthenosphere produces diapirs that create 4 – 8 km surface disruptions spaced 15 – 23 km apart, where greater sizes and spacings may be due to coalescing of lenticulae or sub-surface merging of plume heads. These results suggest that Europa's convecting ductile layer should be ~7 – 10 km thick (approximately half the spacing distance [5]), indicating that Europa's total ice shell thickness, asthenosphere and lithosphere, ≥ 10 km thick. These estimates are consistent with geophysical modeling for Europa's ice shell thickness [6, 7, 8, 9, 10]. The modeling of [6] suggests that plumes can start with diameters less than 4 km in diameter from a depth of only a few tens of kilometers. The measured micro-chaos lenticulae and chaos sizes are likely to be several kilometers greater than the initial plume size, as the plume may spread out while rising [6]. *Comparison to geophysical models.* We compared our results to the global lithospheric thickness and stress models of [11], which suggest that the ice shell may be thickest at the sub- and anti-Jovian points (0° and 180°W) and thinnest at the leading and trailing points, 90°W and 270°W. While it may appear that the results of [12] revise away the proposed pattern of variation found in [11], we instead generally consider that pattern as applying to only the convecting layer. As such, the total ice shell thickness would be constant (per [12]) and the relative thicknesses of the asthenosphere and lithosphere vary according to the model shown in [11]. The intensity of convection is directly related to the cube of convecting layer thickness [5] suggesting: the thicker the convecting layer (i.e., asthenosphere) the greater the convective vigor; thus the greater the size of rising diapirs and the greater the size of convection cells; thus the larger the feature spacing distances. E6DrkLin01, E11Morph01, and E15RegMap02 correspond to areas of minimum shell thickness according to the predictions of [11]; these regions have small features spaced closely together, supporting expectations for the smaller spatial scale of convection cells and diapirs at the trailing and leading points respectively. The E14Wedges01 observation is located at the anti-Jovian point

and has larger sized micro-chaos lenticulae and chaos that are also spaced farther apart, consistent with the predictions for an area of maximum shell thickness such as the anti-Jovian point. We also observe a lower surface density of features containing chaos materials (10%) in the anti-Jovian region, further suggesting that only the largest diapirs are affecting the surface in a zone of maximum shell thickness. The E4DrkMat02 region at 330°W and E17RegMap01 region at 210°W longitude are at zones of intermediate predicted shell thickness and in E17RegMap01 we do observe intermediate characteristics for micro-chaos lenticulae and chaos. However, the E4DrkMat02 region has small sized features containing chaos materials spaced closely together, resembling the leading and trailing point results and unlike those of E17RegMap01. The E11RegMap01 region near 237°W longitude is predicted to be in a zone of thin shell thickness, though not a minimum, yet the local features are large and spaced far apart with a high surface areal density. While it may just be the statistics of small numbers, it is also possible that the shell thickness changes with time before or after convection achieved a steady-state. Therefore, the results are generally consistent with *Ojakangas and Stevenson* [11] model of European ice shell thickness; though observations of some regions differ from the predictions and suggest that another model component may be necessary.

Conclusions: The size and spacing results suggest that Europa’s convecting layer is at least 7 – 10 km thick, possibly up to 18 km, and thus the whole ice shell must be larger than 10 km thick. Our results are generally consistent with a model of asthenospheric thickness variations for Europa [11]. A plausible scenario is that a relatively thin ice shell with a thin lithosphere and asthenosphere was dominated by tectonism and conductively thickened, initiating convection. Solid-state convection within the asthenosphere gave rise to plumes of similar size and spacing. The interaction of these

plumes with the surface could generate a partial melt [9, 13, 14] creating the texture of micro-chaos lenticulae and chaos. Possible local variations in shell thickness, shell composition, or convective vigor might allow the merging of lenticulae to create chaos. A change in convective style could produce larger plumes, which may create some chaos regions such as the E15RegMap02 mitten-shaped chaos feature. Because of the relative youth of lenticulae and chaos and the lack of chaos materials within the background plains [2], a global change in resurfacing style is suggested. With repeated thinning and thickening of the ice shell, through balancing of Europa’s heat budget between tidal heating and heat loss mechanisms, it is also possible that Europa’s surface features occur by episodic processes: global tectonic resurfacing is followed by cryomagmatic resurfacing and then tectonism dominates again, removing evidence of earlier diapirism.

The JIMO mission would permit further tests of these hypotheses. An imaging system would provide images better than 250 m/pxl of much of Europa, allowing an improved global assessment of chaos and lenticulae size, spacing, and areal density. Furthermore, geophysical experiments may be able to test these results by directly evaluating ice shell thickness.

References: [1] Spaun, N. A., et al. (1998), *GRL*, 25, 4277-4280. [2] Spaun, N. A., R. T. Pappalardo, J. W. Head, (2004), Size, Spacing, and Surface Distribution of Chaos and Lenticulae on Europa, *Icarus*, submitted. [3] Greenberg, R., et al. (1998), *Icarus* 135, 64-78. [4] Pappalardo, R.T., and Head, J.W. (2001) *LPSC XXXII*, 1866. [5] Pappalardo, R. T., et al. (1998), *Nature*, 391, 365-368. [6] Rathbun, J. A., et al. (1998), *GRL*, 25, 4157-4160. [7] McKinnon, W. B. (1999), *GRL*, 26, 951-954. [8] Sotin, C. et al. (2002), *GRL*, 29, 10.1029. [9] Turtle, E. P. and E. Pierazzo (2001), *Science*, 294, 1326-1328. [10] Schenk, P. (2002), *Nature*, 417, 419-422. [11] Ojakangas, G. W., and D. Stevenson, (1989), *Icarus*, 81, 220-241. [12] Stevenson, D. L. (2000), *LPSC XXXI*, 1506. [13] Collins, G. C., et al. (2000), *JGR*, 105, 1709-1716. [14] Head, J. W. and R. T. Pappalardo, *JGR*, 104, 27,143-27,155.

Data and Statistics	E4DrkMat02 (6°, 327°) 25 m/pxl	E6DrkLin01 (10°, 271°) 180 m/pxl	E11RegMap01 (11°, 237°) 220 m/pxl	E17RegMap01 (15°, 210°) 225 m/pxl	E14Wedges01 (-10°, 180°) 230 m/pxl	E15RegMap02 (15°, 89°) 230 m/pxl	E11Morphy01 (35°, 87°) 30 m/pxl
<i>Size</i>							
N	18	157	68	352	228	309	17
Min, Max	1, 23.5	1.8, 105.6	3.2, 156.5	2.3, 222.8	3.1, 114.3	1.6, 345.7	1.5, 25.3
Mean	4.8	9.5	13.7	9.5	15	11.3	8.5
Mode	2	5	8	5	7	4	2
Median	3.3	7.2	8.8	6.4	11.2	6.7	8
<i>Spacing</i>							
Min, Max	13.6, 25.2	15, 65.4	23, 78.4	12.1, 91.7	15.2, 86	11.8, 121	16, 27.1
Mean	17.9	26.5	38.1	29.5	37.4	21	20.8
Mode	16.5	24	33	26	31	17	17
Median	16.8	24.3	35.7	27.5	35.2	18.7	20.1
<i>Density</i>							
% lenticulae and chaos	42	24	44	27	10	39	68
% chaos only	27	10	29	15	2	24	22