IMPACT GARDENING RATES ON EUROPA: COMPARISON WITH SPUTTERING. Cynthia B. Phillips and Christopher F. Chyba, Center for the Study of Life in the Universe, SETI Institute, 2035 Landings Drive, Mountain View CA 94043. phillips@seti.org

Introduction: A biosphere on Europa would require available liquid water, appropriate biogenic elements, and sufficient free energy sources [1]. Charged-particle interactions with materials at Europa's surface can produce useful oxidants such as molecular oxygen and hydrogen peroxide. Irradiation of carbon-containing materials at the surface of Europa should also produce simple organics [1-5]. These oxidants and organics, if transported downward through the ice shell to a liquid water layer, could provide a significant amount of energy to sustain a biosphere. However, irradiation also destroys such materials if they remain exposed on Europa's surface [6]. Sputtering erosion and surface mixing through impact gardening act to change the preservation depth.

If sputtering dominates over gardening, then material is created and destroyed at Europa's surface much faster than it can be buried and preserved by gardening. However, if gardening dominates, this means that irradiation products can be buried beneath the surface by gardening, where they are protected from further radiation processing. We are investigating models of gardening on Europa's surface to determine which regime is most appropriate.

Three Sputtering Regimes vs. Gardening: An initial survey of this problem by Chyba [2,3] used an estimate of sputtering at the Europan surface [7] of 0.2 $\mu m\ yr^{-1}$, and a gardening estimate [6], based on a lunar analogy, of 1-10 cm over a mean Europan surface age of ~10 Myr [8,9]. This resulted in the loss of oxidants and organic molecules through sputtering before they were gardened down to depths at which they would be protected against further radiation processing or sputtering loss. For this case, Chyba [2,3] took the relevant radiation-processed depth at Europa's surface to be ~1 mm, the stopping depth of incident electrons [10,11,4].

However, subsequent estimates [4] suggested that the sputtering rate at Europa was more than an order of magnitude lower, ~0.02 $\mu m\ yr^{-1}$, and that the gardening depth over 10^7 yr was ~1.3 m, rather than 1-10 cm. In this case, oxidants and organics created by irradiation of Europa's surface would be efficiently buried by gardening, and therefore protected. The sputtering rate at Europa is now fairly well constrained, but better estimates of the gardening rate may be possible given surveys of the impactor population in the Jovian system. Our work attempts a new estimate of the gardening rate, and compares that to previous estimates of gardening and sputtering.

New Gardening Estimate: The analysis of Cooper *et al.* [4] of gardening rates on Europa relies heavily on a regolith depth estimate from studies of Voyager images of Ganymede [12]. It also uses a mass flux for small particles from studies of planetary rings [13]. We are currently attempting to update the gardening rate for Europa using the impactor populations in the outer solar system summarized by Zahnle *et al.* [8,9] combined with lunar regolith growth studies of Shoemaker *et al.* [14,15] and Gault [16] as summarized in Melosh [17].

Zahnle *et al.* [8] give cumulative crater distributions for Europa in the typical form: $N_{cum}(>D) = c\,D^{-b}$, where N is the cumulative number area density of craters of diameter equal to or greater than D, c is a constant, and b is the exponent in the power law. Using this distribution, we can calculate the fraction f_c of the total area covered by craters with diameters between some value D and the maximum value (we actually integrate up to infinity). Paralleling the Melosh [17] treatment of Shoemaker [14], we can say that:

$$f_c(D,\infty) = -\frac{\pi}{4}\int_D^{\infty} D^2 \frac{dN_{cum}}{dD}\,dD = \frac{\pi bc}{4(b-2)}\left(\frac{1}{D^{b-2}}\right)$$

The overturn time [15,17] is given by $t_{ovr} = t_{surf} / f_c$. Thus:

$$t_{ovr} = t_{surf}\,\frac{4(b-2)}{\pi bc}\,D^{b-2}$$

We then need to substitute appropriate values. We have adopted b=2.93, from [12]. This value comes from lunar studies for craters below 1 km in diameter, but is also consistent with fragmentation cascade studies done for small objects [8]. We also scale to Europa from a value for c from [12] for km-sized craters on Ganymede. They give $c=10^{1.69}\ m^{0.93}$, which we scale up by a factor of 2 to account for an impactor flux at Europa twice that at Ganymede, as given by [8]. This value must also then be scaled down by a factor of 100 to account for our assumption that the surface of Europa is 1% as old as the surface of Ganymede. This scale value may be linearly adjusted if different ages are adopted for the two satellite surfaces, but this is consistent with a 10 Myr surface age of Europa and a 1 Gyr surface age for Ganymede. Thus c becomes 0.98 $m^{0.93}$. For the value of D we have taken 4d, where d is the overturn depth. This assumes that the surface of Europa is saturated with craters of size D, which have broken up the surface to a depth d=D/4. When we insert these values, we obtain $t_{ovr} = 1.5\ t_{surf}\ d^{0.93}$ (with d in units of meters).

For a surface age of 10 Myr for Europa, we find that the surface is overturned once to a depth of 0.67 meters. It takes about 1.7 Myr to overturn the surface once to a depth of 0.1 meters. Over a surface age of 10 Myr, the surface is mixed once to a depth of about 0.67 meters, 10 times to a depth of about 5 cm, and 100 times to a depth of about 5 millimeters.

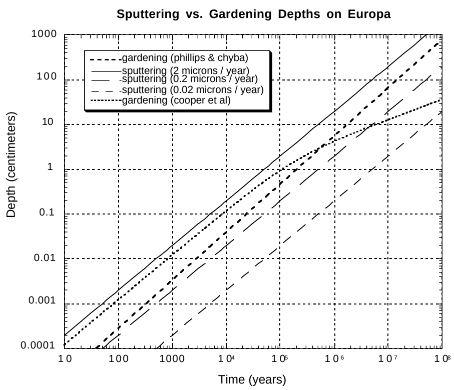

Figure 1: Sputtering vs. Gardening Depths on Europa

Comparison of regimes: Figure 1 shows a preliminary comparison of sputtering vs. gardening rates for Europa's surface. The values plotted here are the time it takes for a single overturn down to a particular depth. The curved line shows the gardening rate from [4] derived from estimates of the interplanetary mass flux at Jupiter. The three straight lines show three different sputtering erosion rates, spanning the range of numbers in the literature [7,18]. The dark dashed line is the new gardening rate we have developed, which is quite similar to the estimate from [4].

For the sputtering rate 2 μm yr^{-1}, sputtering dominates over gardening, so material is removed from Europa's surface before it has a chance to be buried and preserved. However, for the current best-estimate 0.02 μm yr^{-1} case [4], gardening seems to be the dominant process over Europa's entire surface age, and material may be buried faster than most of it can be removed through sputtering.

For a mean surface age of ~10^7 yr [8,9], Cooper *et al.* [4] suggested that gardening should extend to a depth of 1.3 m. Our new gardening rate suggests that the gardening depth over 10^7 years is about 0.67 meters. The radiation products produced over this timescale will be mixed through this layer. Thus, for reasonable values of the sputtering rate, gardening dominates over sputtering at all time scales, increasing with longer times. Radiation products created at the surface will be mixed throughout this layer, and thus can be preserved for potential integration into a subsurface water layer where they might fuel a biosphere [1,5].

Comparisons with crater counts: Our new gardening results predict that the surface of Europa has been mixed at least once down to a depth of about 0.67 meters over a timescale of 10 Myr. Since D=4d, a depth of 0.67 meters implies that the surface of Europa is "saturated" with craters about 2.7 meters in diameter. The highest resolution Galileo images of Europa include a few images at resolutions of 6 to 9 meters per pixel. While these images are not of sufficiently high resolution to image these small 2.7-meter craters, we should be able to see craters in the 20 to 100-meter diameter range. These high resolution images show very few small craters in this size range.

However, is this a contradiction? With the power law crater distribution and a -2.93 slope, we would expect that there would be about $4x10^4$ times as many small 2.7-meter craters as there would be larger 100-meter craters. New work by Bierhaus *et al.* [19] suggests that a -4 slope may be more appropriate for small craters on Europa (which may primarily be secondaries); in this case, there would be about $2x10^6$ times as many small 2.7-meter craters as larger 100-meter craters. Thus with either a -2.93 slope or a -4 slope, there could be thousands of small craters below the limit of resolution of the highest-resolution Galileo images, but very few or no craters in the detectable size ranges. We are currently reexamining our gardening rates to consider the steeper -4 cratering distribution.

We can also estimate the number of small craters expected by extrapolating down from the Zahnle *et al.* [8] cratering distribution for Europa. In this case, using their slope of -2.2, we get that over a surface age of 10 Myr, a single 10-meter-per-pixel Galileo image (covering 64 km^2) should have 1 or 2 100 meter craters, and about 5000 smaller 2.7-meter craters. Again, the existence of many small craters below the limit of resolution does not seem implausible, given the fact that the Zahnle *et al.* [8] cratering studies were for much larger (10-km) craters, and it is likely that the small crater distribution has a much steeper slope [19].

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