EUROPA AS AN ANALOGUE OF AN ICE-COVERED PRIMITIVE EARTH

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Without sufficient greenhouse gases in the atmosphere, the early Earth would have become a permanently frozen planet because the young Sun was less luminous than today. Several resolutions to this faint young Sun-frozen Earth paradox have been proposed, with an atmosphere rich in CO_2 being the one generally favored. However, these models assume that there were no mechanisms for melting a once frozen ocean on the Earth. Recently it has been proposed that bolide impacts between about 3.6 and 4.0 billion years ago could have episodically melted an ice covered early ocean (1). Thaw-freeze cycles associated with bolide impacts could have been important for the initiation of abiotic reactions that gave rise to the first living organisms on Earth (1).

Europa offers a potential opportunity to directly investigate the processes that could have important on an ice-covered primitive Earth. An important issue is whether there is sufficient energy available to maintain a partially frozen ocean on Europa. Although on the primitive Earth, heat flow through the oceanic crust would have provided enough heat to maintain a liquid ocean covered by only 300±100 m ice, this heat source would likely not be significant on Europa. Rather the heat would be generated from tidal stresses (2). In order to evaluate the amount of tidal dissipation energy (μ in joules $cm^{-2}\,s^{-1}$) needed to maintain a partial frozen ocean on Europa, the following equation based on a simple one dimensional heat flow model can be used (1):

$$\mu = k\,(1\text{x}10^{-5})\,(T_{\textbf{ocean water}} - T_{\textbf{ice surface}})\,X^{-1}$$

k is the thermal conductivity of ice ($2\text{x}10^{-2}$ joules $s^{-1}\,cm^{-1}\,{}^{o}C^{-1}$) and X is the ice thickness in km. Using $T_{\textbf{ice surface}} = -150^{o}C$, $T_{\textbf{ocean water}} = 0^{o}C$ and X = 1 and 10 km (2), yields $\mu = 3\text{x}10^{-5}$ and $3\text{x}10^{-6}$ joules $cm^{-2}\,s^{-1}$. These calculated values of μ required to generate a liquid ocean covered by ice 1-10 km thick on Europa are probably not unreasonable (2).

Bolide impacts would have temporarily melted part of the ice cover on the Europa ocean. Adopting the value of Sleep et al (3) that 25 % of the impact energy of a large bolide would be globally distributed as thermal energy (the rest of the energy is buried at the impact site or lost to space), we can calculate the size of the object needed to melt an ice layer on a Europa ocean. The diameter ($\mathbf{d_{melt}}$) of an ice melting bolide is given by (1):

$$\mathbf{d_{melt}}\,(cm) = 5.3\text{x}10^{2}\{\mathbf{Q}\ \rho_{\mathbf{ice}}\ \mathbf{H_f}\ X\}^{1/3}\,\{v^2\ \rho_{\mathbf{bolide}}\}^{-1/3} = 9\text{x}10^{4}\,X^{1/3}$$

where **Q** is the ice surface area on Europa ($3\text{x}10^{17}$ cm^2), $\rho_{\mathbf{ice}}$ the density of ice (0.9 g cm^{-3}), $\mathbf{H_f}$ the heat of fusion of ice at 0° C (334 joules g^{-1}), **v** the bolide impact velocity ($1.5\text{x}10^{6}$ cm sec^{-1}), $\rho_{\mathbf{bolide}}$ the bolide density (4 g cm^{-3}) and **X** the ice thickness (cm). If only 10 % of the impact energy was globally distributed as heat, the $\mathbf{d_{melt}}$ values would increase by only 36 %. The bolide diameters would be about 40 % larger if the entire ice layer was at -100°C.

The above equation thus indicates that bolides in the 5-10 km diameter range would have periodically punctured and partly melted 1-10 km of ice cover on a

Europa ocean. Although the Europa ocean surface would have rapidly refrozen because of the low temperatures, these bolide impacts could have seeded the ocean with exogenous organic material. The long-term accumulation of this exogenous organic material, along with important prebiotic reagents such as ammonia, hydrogen cyanide, aldehydes and ketones possibly generated during the impact events themselves, could have generated a rich prebiotic soup in the Europa ocean. Subsequent reactions in the soup may have generated molecules considered important in the steps that led to the origin of life on Earth. Life itself in the form of self-replicating molecules capable of Darwinian evolution may even have developed in an ice-covered Europa ocean. Future exobiology investigations of Europa could be pivotal in our understanding of prebiotic organic chemistry and the processes involved in the origin of life.

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