partially soluble organic compounds (*13–16*). A partially soluble aerosol component adds solute to the aqueous phase as the droplet grows, decreasing the critical supersaturation of the particle. Many of these organic compounds are surface active (see the figure) (*8*); if, in addition, surface tension is lowered as the substance dissolves, the critical supersaturation is further lowered, and the number of particles that can activate increases even more. In general, the lowering of surface tension associated with a dissolving substance has a stronger effect on cloud properties than the fact that the substance itself is only partially soluble, given that most water-soluble organic compounds are surface active.

As predicted by Köhler some 80 years ago, droplet activation places an upper limit on the supersaturation of water vapor that can be reached in the atmosphere. Given sufficient solute or enough depression of surface tension, or a combination of the two, the supersaturation in a given situation will decrease. At high aerosol and soluble trace gas concentrations and for low cooling rates, strict activation is not necessary for formation of a visible cloud; indeed, a continuum exists from ambient aerosol to wetter and wetter particles to unactivated clouds to activated ones. What is seen as "cloud" can, in reality, be a collection of droplets ranging from fully activated to unactivated.

By affecting cloud optical properties, these chemical phenomena may lead to nonnegligible global negative forcing (*17*) and may be as important regionally as the Twomey effect itself. To assess the importance of the indirect climatic effect of aerosols, one seeks a robust connection between cloud droplet population and a prognostic variable from global aerosol models. How that link might depend upon chemical cloud activation effects, including variations in aerosol chemical composition, solute water solubility, solute surface tension lowering, and condensation of trace gases, remains to be determined. Lack of global data on these activation effects poses additional uncertainty beyond that already recognized by the Intergovernmental Panel on Climate Change (*1*), making the largest uncertainty in estimating climate forcing even larger.

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PERSPECTIVES: PLANETARY SCIENCE

Life Without Photosynthesis

Christopher F. Chyba and Kevin P. Hand

Recent planetary exploration has shown that oceans of liquid water appear to be common in our solar system. Galileo spacecraft measurements of induced magnetic fields suggest that Jupiter's large icy moons—Europa, Ganymede, and Callisto—all harbor salty oceans beneath the surface ice (*1*). This is exciting news for extraterrestrial biology because life as we know it requires liquid water.

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But life also requires energy. Life that does not harvest sunlight directly obtains that energy from chemical disequilibrium in the environment. On Earth, photosynthesis, coupled with organic carbon burial, has produced oxidizing surface conditions that provide chemical disequilibria for biology to exploit. Sunlight cannot, however, penetrate kilometers of ice. The chemical energy available in the form of disequilibrium concentrations of redox reactants is therefore substantially less, raising the specter of entropic death for subsurface oceans—be they within icy satellites or on an earlier "snowball Earth" (*2*). All is not lost, however, because nonphotosynthetic sources of molecular oxygen (O_2) and other oxidants are available even to subsurface oceans. Here we estimate these for Europa (see the figure).

Europa's surface is continuously bombarded with charged particles accelerated in Jupiter's magnetic field. They produce H_2O_2, O_2, and other oxidants at Europa's surface (*3*), as well as hydrogen, which mostly escapes into space. The radiation products are mixed to a depth of 1 m through impact "gardening" (the slow overturning of Europa's surface by meteorite impacts) (*4*). Spectral observations of H_2O_2 only probe the upper ~0.1 mm of the surface, where some H_2O_2 is destroyed photolytically (*3*). These observations therefore give a lower limit to H_2O_2 concentrations in the upper meter.

It is not known whether the top of Europa's ice shell mixes with the ocean on geological time scales. If it does, and if H_2O_2 production is not limited by the quantity of H_2O available in the upper meter of Europa's surface (*4*), up to ~10^{12} mol year^{-1} equivalent O_2 (*5*) could reach Europa's ocean (*3*, *4*). A lower limit may be estimated by assuming that the H_2O_2 concentration observed at Europa's surface holds throughout the upper 1 m of gardening depth (*4*). In this case, ~10^9 mol year^{-1} equivalent O_2 could mix into the ocean. These limits straddle Earth's abiotic source of O_2 (7×10^9 mol year^{-1}) owing to photolysis of water vapor and loss of H_2 to space (*6*).

Were there no sinks, 10^{12} mol year^{-1} equivalent O_2 could produce a ~20 mM oceanic O_2 concentration over the estimated ~50-million-year resurfacing time scale of Europa's crust (*3*). Some deep-ocean macrofauna on Earth live at concentrations as low as 20 to 40 μM (*4*). These considerations suggest that if suitable carbon compounds were available in the ocean, substantial biomass production—10^{10} to 10^{14} g year^{-1}, depending on O_2 production and microbial growth efficiencies—could be achieved (*4*, *7*).

On Earth, photosynthesis produces about 10^{16} mol year^{-1} O_2, but this is nearly balanced by the sinks of respiration and decay (*6*). What sinks might be present on Europa? Hydrothermal activity levels have been estimated based on calculations of internal heating. According to these highly uncertain estimates, ~10^{10} liters year^{-1} of hydrothermal fluid may be generated at Europan hydrothermal vents (*8–10*). If reductants such as H_2S, H_2, CH_4, and Fe are present in this fluid at concentrations of around 50 mM (*9*), about 10^9 mol year^{-1} of reductants would enter the ocean from this source. O_2 input could at least match this potential sink, suggesting that Europa's ocean could have become oxidizing over time.

It is unknown how much carbon Europa may have incorporated at the time of its for-

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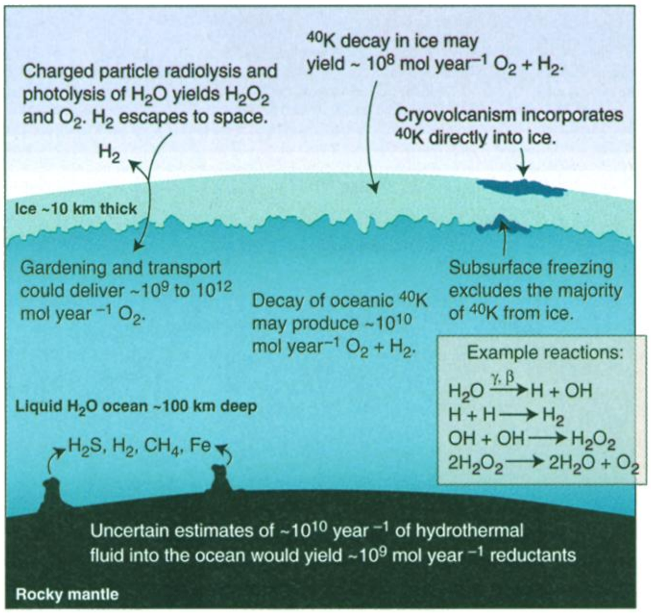
mation. Leading models contradict one another. Some suggest that Europa's formation within the jovian subnebula resulted in a composition strongly depleted in carbon. More popular current models treat Europa's composition as that of a carbon-rich carbonaceous chondrite meteorite (*11*). For this case, Kargel *et al.* estimate that about 10^{20} mol of highly soluble organic carbon could initially have been available on Europa, although much of this would be sequestered in solid phases (*11*). If so, the potential organic carbon sink for dissolved O_2 could be low enough to permit an oxidizing ocean to exist.

The above estimates of oxidant concentrations in Europa's ocean are uncertain because it is not known whether oxidants produced at the surface ever reach the ocean. Other nonsurface sources may also provide O_2 to the ocean. Examples are the radiolytic production of O_2 caused by the decay of ^{40}K in Europa's ice shell, and in its ocean. But they require assumptions to be made about Europa's composition.

Estimates of the salt content of Europa's ocean are based on the leaching expected from a carbonaceous chondrite meteorite. These models are broadly consistent with Galileo spectroscopy of infrared features on Europa often attributed to magnesium or sodium sulfates (*12*). One such model (*11*) predicts that 29 weight % of Europan ocean water is $MgSO_4$. The ratio of water-soluble K_2SO_4 to $MgSO_4$ in the Orgueil meteorite (*13*) implies that potassium is about 0.3 weight % of the European ocean, about 10 times that of Earth's oceans. Currently ^{40}K constitutes about 0.012% of total potassium on Earth, and presumably on Europa; this fraction would have been 10 times higher 4200 million years ago, early in Europa's history (*14*).

What is the potassium concentration expected in Europa's ice? If the ice was formed primarily as a result of eruptive events onto the surface, the overall concentration would be that of the ocean. If the ice instead formed primarily by freezing onto the bottom layer, analogous to terrestrial marine ice, the potassium concentration in the ice would be much lower owing to exclusion from the ice matrix during freezing. Terrestrial ice cores suggest that marine ice may contain ~ 0.1% the K concentration in seawater (*15*). For a 10-km-thick ice shell containing 3×10^{-4} weight % K, an average ^{40}K decay energy of 5.7×10^5 eV (*16*) yields a net internal dose of $\sim 3 \times 10^{34}$ eV year^{-1}. This produces an estimated 0.1 to 0.4 H_2O_2 molecules per 100 eV (*3*), or $\sim 10^7$ to 10^8 mol year^{-1} equivalent O_2. Even if the uppermost meter of Europa's ice never reaches the ocean, recycling of the bulk of the ice shell—difficult to avoid under most geological models—will provide this oxygen flux to the ocean, along with any hydrogen that fails to escape to space. Recombination of this H_2 and O_2 by microorganisms in Europa's oceans could produce $\sim 10^8$ to 10^9 g year^{-1} of biomass today, and 10 times more 4200 million years ago.

Radiolysis should also produce O_2 and H_2 directly in Europa's ocean. A careful treatment of the problem must model reactions in solution among radiolytically produced H, OH, H_3O^+, and electrons, together with whatever solutes are present. Draganic *et al.* (*16*) have modeled this for Earth's ocean 3800 million years ago, and find that about 10^{10} mol O_2 year^{-1} were produced. Most salts are not in European abundances, however, nor is there an ice cover. In the absence of a more appropriate model, we extrapolate this model to Europa by simply scaling the ^{40}K abundance and assuming that the ocean is 100 km deep, with twice the mass of Earth's oceans. This yields about 10^{10} mol O_2 year^{-1} today, supporting perhaps 10^{10} to 10^{12} g year^{-1} biomass, and 10 times more 4200 million years ago.



Can there be life in Europa's ocean? Photosynthesis is nearly impossible, but radiation processing of Europa's ice and liquid water might nevertheless provide chemical disequilibrium for life in Europa's ocean. ^{40}K decay via γ or β emission decomposes H_2O and leads to O_2 and H_2 production.

Comparable amounts of H_2 would also be produced, and unlike in Earth's open ocean, the H_2 is not free to diffuse away. H_2 is not strongly reactive, however, so that the O_2 concentration may nonetheless begin to build. This may be aided by electrical currents expected in Europa's conducting ocean as a result of its velocity of 104 km s^{-1} relative to Jupiter's magnetic field. These currents, strongly limited by Europa's nearly insulating ice cover, are likely too low for significant electrolysis (*17*), but radiolytically produced H^+ and other ions in Europa's ocean should nevertheless migrate, leading to a partial segregation of hydrogen and oxygen between the antijovian and subjovian hemispheres (*18*). If so, then a hemispheric oxygen gradient might persist through geological time, reminiscent of those found in lakes or seas (*19*) on Earth where photosynthesis reigns. Such gradients could greatly enhance the prospects for life in the seas of Europa.

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