Energy for microbial life on Europa

A radiation-driven ecosystem on Jupiter's moon is not beyond the bounds of possibility.

The planet Jupiter's moon Europa may harbour a subsurface water ocean[1-3], but estimates of the available free energy have not been encouraging for supporting life[1,4,5]. Here I show that disequilibrium chemistry in the ocean's ice cover, driven by charged particles accelerated in Jupiter's magnetosphere, should produce enough organic and oxidant molecules to fuel a substantial Europan biosphere. Microbial life could exist in concentrations detectable by surface landers able to filter meltwater from Europa's ice.

Europa's putative ocean lies beneath an ice layer too thick to permit photosynthesis[1]. Hydrothermal vents may or may not exist. As terrestrial hydrothermal ecology depends largely on transported surface oxidants, it has been suggested that these are unlikely to exist on Europa[5]. Some chemoautotrophic metabolism might occur, for example in methanogenesis from H_2 reacting with outgassed CO_2. But if carbon is outgassed on Europa as methane[5], then most metabolic pathways operating on Earth may be denied to organisms inhabiting an ice-covered ocean on Europa[5]. I suggest instead that a radiation-driven ecosystem could exist, and calculate the lower limits on its biomass by reference to terrestrial analogues.

A 4.25-mm spectral feature may be due to CO_2 in Europa's ice layer[6]. Oxidants and organics should both be produced in H_2O/CO_2 ices through radiation chemistry[7-9] and be retained in the ice matrix above normal sublimation temperatures by hydrogen bonding[7,8]. Substantial radiation production extends down to about 1 mm (for a density, r, of about 1 g cm^{-3}) (ref. 8), or to about 1 cm for r 0.1 g cm^{-3}. Sputtering removes 1 mm (r 1 g cm^{-3}) from the surface in roughly 5,000 yr (ref. 9). As the surface sputters away, the irradiated layer maintains a steady-state depth of 1 mm.

Charged-particle interactions with water should produce molecular oxygen, hydrogen peroxide and several other oxidants in comparable abundance[7]. Hydrogen peroxide has been detected[10] on Europa at concentrations of 0.13% by number relative to H_2O. This concentration should hold throughout the top 1 mm, giving a column density of about 42×10^{18} H_2O_2 molecules cm^{-2}.

Cratering does not alter this model. The Europan crust appears to recycle on a 10^7-yr timescale[11]. Over 10^7 yr, the turnover depth due to impacts is expected to be 1–10 cm (ref. 12), which will be sputtered away in only about 10^5 yr.

Spectroscopy of Jupiter's moon Callisto suggests that CO_2 is present at ' 0.5 wt%.

Europa's 4.25-mm spectral feature is ' 10% of continuum globally, compared to a band strength of ' 25% for Callisto[6]. Assuming a linear relationship between CO_2 concentrations and band strength for this unsaturated band suggests that CO_2 is present in Europan ice at ' 0.2 wt% (T. McCord, personal communication). CO_2 in the upper 1 mm of Europa's surface will experience ' 30 eV AMU^{-1}, integrating the flux[7] of 32×10^{13} eV cm^{-2} s^{-1} over 5,000 yr.

Radiation should drive cycling among CO_2, CO and organics in the ice[7-9]. Organic groups may have been observed[6]. Laboratory irradiation of H_2O/CO_2 ices produces a dose-dependent CO/CO_2 ratio that is independent of the H_2O/CO_2 ratio[13]. Relative organic production may be calculated by comparing G values (molecules produced per 100 eV) for CO to those for organics[7]. At 30 eV AMU^{-1}, CO/CO_2 0.3 (ref. 13). Formaldehyde and other simple organic species are produced as well. $G(CO)/G(HCHO)$ 9 (ref. 7), so HCHO should be ' 32×10^{-5} by number in the upper 1 mm, corresponding to a column density, h, of about 82×10^{16} molecules cm^{-2}.

Organics and oxidants in Europa's crust are biologically relevant only if they reach the ocean. Crustal recycling mechanisms are unclear[2,3]. Chaos regions may form by melt-through[3]. If resurfacing were primarily due to melt-through, about 12×10^{12} g HCHO, comparable amounts of other organics, and ' 72×10^{13} g H_2O_2 would mix into the ocean every 10^7 yr. The H_2O_2 in solution would decompose into H_2O and O_2 with a half-life of ' 10 yr.

A putative microbial ecology on Europa could therefore be powered by the reaction HCHO & $O_2 \rightarrow H_2O + CO_2$. The terrestrial soil bacterium *Hyphomicrobium* can live on HCHO as its sole carbon source[14]. Terrestrial methanotrophs obtain their energy by first oxidizing CH_4 to HCHO, then to HCOO$^-$ and HCO$_3^-$. Oxidation of HCHO in these organisms yields an energy e4 4.7 eV per molecule[14]. The chemical energy available by melting the upper 1 mm of Europa's crust into the ocean is therefore he 42×10^{17} eV cm^{-2}. If 10% of available chemical energy were used for biosynthesis, a typical terrestrial efficiency, w, for microbial biomass (dry weight) production is w 22×10^{-21} g eV^{-1} (ref. 4). Biomass production on Europa would then be hew 82×10^{-4} g cm^{-2}. Taking the dry mass of an aquatic cell[15] to be 22×10^{-14} g, this would give 42×10^{10} cells cm^{-2}.

If Europa's crust is recycled into the ocean over 10^7 yr, net Europan cell synthesis is dN/dt 12×10^{21} cells yr^{-1}, where N is the number of cells. The steady-state biomass is given by the product of dN/dt and the biological turnover time t. Adopting a turnover time appropriate for Earth's deep biosphere[15], t 12×10^3 yr, N ' 12×10^{24} cells, or ' 22×10^{10} g. If biomass were not limited by energy, but instead by carbon available from HCHO alone, N would be roughly 10^3 times smaller.

Radiation products might instead mix into Europa's ocean in sudden localized melting events analogous to Conamara chaos[3]. The mixing timescale can be estimated by comparing the energy flux from Europa's silicate/metal interior[1] to that required to melt the final 1 mm of ice: the required timescale is about 0.1 yr (probably an upper limit as melting events may involve larger-than-average local heat fluxes).

For an event of Conamara's area[3], about 10^4 km^2, a microbial mass M hew 2×10^4 km^2 82×10^{10} g, or 42×10^{24} cells could bloom over ' 0.1 yr, which is more than could be supported in steady state. This is ' 10^{-4} of the Earth's oceanic prokaryotic population[15]. Microbial blooms could occur wherever Europa's surface communicated with its ocean — at chaos regions or along active cracks, for example. Any coloration or spectral features of such blooms after radiation processing could be explored by comparison with terrestrial analogues[5].

Europan microbes would lie dormant and drift between melt-through or cracking events. There are at least ten chaos regions of ' 10^4 km^2, or at least one of ' 10^5 km^2 (ref. 3), and perhaps thousands of small melt-through events on Europa's surface[3]. If so, they probably occur frequently.

For an ocean about 100 km deep[1-3], average cell densities could be as high as 1 cell cm^{-3}. If this water erupted to the
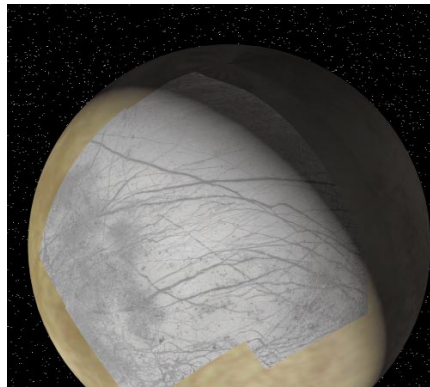

Figure 1 Jupiter's moon Europa is covered in ice, beneath which there may lie an ocean. Calculations suggest that, even without photosynthesis or hydrothermal vents, it could support life.

surface and froze, instruments being developed by NASA (P. Grunthaner, personal communication) could detect signs of life in ‵ 10 litres of melted and filtered surface ice. Ice from melt-through blooms may contain more cells, reducing melting requirements.

These calculations indicate that a particular radiation-driven ecosystem is plausible, quantifiable using our current knowledge of Europa: others are possible. Neither photosynthesis nor hydrothermal vents need be postulated. But only direct exploration will reveal whether life on Europa actually exists.

Christopher F. Chyba
*SETI Institute, 2035 Landings Drive, Mountain View, California 94043, USA, and Department of Geological and Environmental Sciences, Stanford University, Stanford, California 94035, USA
e-mail: chyba@seti.org*

1. Reynolds, R. T., Squyres, S. W., Colburn, D. S. & McKay, C. P. *Icarus* **56**, 246–254 (1983).
2. Pappalardo, R. T. *et al. J. Geophys. Res.* **104**, 24015–24055 (1999).
3. Greenberg, R. *et al. Icarus* **141**, 263–286 (1999).
4. Jakosky, B. M. & Shock, E. L. *J. Geophys. Res.* **103**, 19359–19364 (1998).
5. Gaidos, E. J. *et al. Science* **284**, 1631–1633 (1999).
6. McCord, T. B. *et al. J. Geophys. Res.* **103**, 8603–8626 (1998).
7. Delitsky, M. L. & Lane, A. L. *J. Geophys. Res.* **102**, 16385–16390 (1997).
8. Delitsky, M. L. & Lane, A. L. *J. Geophys. Res.* **103**, 31391–31403 (1998).
9. Johnson, R. E. in *Solar System Ices* (eds Schmitt, B. *et al.*) 303–334 (Kluwer, Dordrecht, 1998).
10. Carlson, R. W. *et al. Science* **283**, 2062–2064 (1999).
11. Zahnle, K., Dones, L. & Levison, H. F. *Icarus* **136**, 202–222 (1998).
12. Varnes, E. S. & Jakosky, B. M. in *Lunar Planet. Sci.* abstr. 1082 (Lunar and Planetary Institute, Houston, 1999) (CD-ROM).
13. Brucato, J. R., Palumbo, M. E. & Strazzulla, G. *Icarus* **125**, 135–144 (1997).
14. Madigan, M. T. *et al. Brock Biology of Microorganisms* (Prentice Hall, Upper Saddle River, New Jersey, 1997).
15. Whitman, W. B., Coleman, D. C. & Wiebe, W. J. *Proc. Natl Acad. Sci. USA* **95**, 6578–6583 (1998).

Physiology

A function for guttural pouches in the horse

Athletic animals must keep their brains cool during exertion because this organ can be damaged irreversibly by hyperthermia. But how horses do this has remained a mystery, as they don't appear to have thermoregulatory derivices like those found in other animals. They do, however, have a unique anatomical arrangement of their internal carotid arteries, which supply blood to the brain: these are enveloped by a pair of air-filled guttural pouches. Here we show that horses use their guttural pouches to cool these important arteries during exercise, keeping the brain from overheating.

The guttural pouches are auditory-tube diverticula that contain about 300–500 ml of air. They are found in odd-toed hoofed animals, hyraxes[1], some bats and a South American forest mouse[2], and are susceptible to potentially life-threatening diseases from bacterial and fungal infections.

Their anatomical association with the upper respiratory tract suggests that the horse's guttural pouches might function during selective brain-cooling to maintain blood carried by the internal carotid arteries (ICA) at a temperature below the core temperature during hyperthermia. Inflowing arterial temperature has the greatest effect on the brain above 40 °C (ref. 3). Other selective brain-cooling devices include the carotid rete mirabile, which horses do not have, and a mechanism for direct cooling between the brain and cranial venous sinuses[3].

Selective brain-cooling in horses is all but abolished by a tracheostomy[4]. The blood to the horse's brain is supplied mainly by the ICA, but also by the occipital and vertebral arteries[5]. The extracranial portion of the ICA is enveloped by the thin (45–200 mm) mucous membrane of the guttural pouch's medial compartment (Fig. 1).

We measured the temperature of air from the guttural pouch as well as of blood from the ICA in four horses by using fine thermocouples (response times, 0.1 and 0.002–0.04 s) surgically implanted on the ICA at three sites corresponding to sites before, midway and beyond the guttural pouch, respectively (trifur, mid and f. lacerum) (Fig. 1a). At rest, trifur was significantly cooler than rectal temperature and mid (trifur, 0.565 0.02 °C less than rectal; mid, 0.25 0.03 °C more than trifur; results are combined mean5 standard error).

It has been reported that a horse's common carotid arteries are cooled[6], presumably by heat loss from the pulmonary circulation and the proximity of the arteries to the trachea and skin. When the horse is resting, mid blood is warmed and f. lacerum blood cooled. Other surrounding tissues, notably the salivary glands and neck muscles, which are at core temperature, influence the warming of mid blood. Adjacent to f. lacerum is the extracranial ventral petrosal venous sinus, which is cooler than the resting core temperature[4].

During trotting and cantering, the temperature at trifur rises, whereas that at mid and f. lacerum increases little by comparison (Fig. 1b–d). After prolonged cantering, the temperatures of guttural-pouch air and f. lacerum are similar. The rectal temperature differs from that of the ICA throughout, probably because of the lag phase between the horse's rectum and core[4].

Guttural-pouch air temperature varied little with exercise (37.65 0.03 °C at rest, 37.55 0.05 °C trotting and 37.65 0.08 °C cantering), as did rectal temperature (38.35 0.01 °C at rest, 38.45 0.04 °C trotting and 38.75 0.1 °C cantering). Environmental air temperatures (and relative humidity) were 18.55 3.5 °C (465 5%) at rest, 18.35 3.0 °C (455 4%) trotting and 18.15 2.7 °C (475 5%) cantering. Exercise trials without the guttural-pouch temperature probe followed the same significant trends of cooling of the ICA.

Cool air in the guttural pouch would drive heat transfer from the passing ICA, and this is the only structure in this area
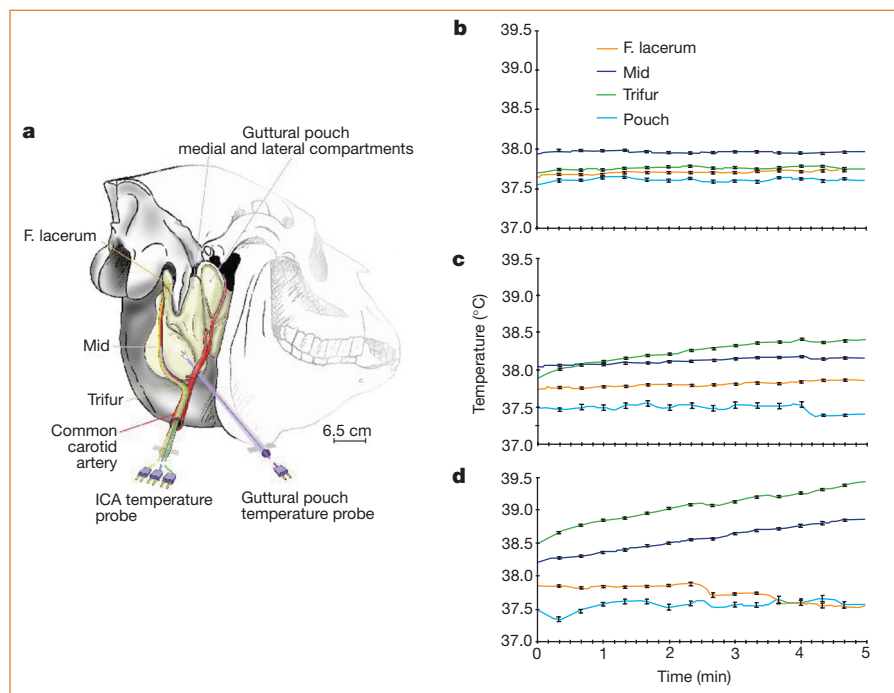

Figure 1 Guttural pouches act to cool the horses' brain. **a,** The arrangement of guttural pouches and internal carotid arteries (ICA) in the skull, and the position of the temperature probes used to measure blood temperature. **b–d,** Combined averaged temperatures (5 s.e.) for two trials in all four horses: **b,** at rest; **c,** trotting; **d,** cantering.