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Alternative Energy Sources Could Support Life on Europa

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Energy pervades the Solar System in a variety of forms, including electromagnetic and particle radiation, magnetism, heat, kinetic motion, and gravitational interactions. Life on Earth is sustained by the conversion of light and chemical energy into proton gradients across membranes that drive the phosphorylation of high-energy intermediate metabolites. While the use of light and reduced chemical bonds as energy sources is not surprising on Earth, where the intensity of light is strong and an oxidizing atmosphere favors energy-yielding chemical reactions, any naturally occurring energy gradient that generates charge separation across boundary layers could theoretically yield the free energy needed to sustain life. Using specific, plausible examples from Jupiter's ice covered satellite, Europa, we propose that alternative energy sources could sustain life where neither light nor an oxidizing atmosphere are available.

Energy Sources on Europa

Estimating the chances of life elsewhere in our Solar System includes the challenge of envisioning a specific, feasible energy capture mechanism. Europa now appears to be one of the most likely places in the Solar System for harboring extraterrestrial life. The presence of a liquid-water ocean 100 km deep or more beneath an icy crust on Europa is now widely assumed. While chemoautotrophy is a possibility on Europa, the lack of abundant oxygen beneath the icy crust means that oxidation-reduction cycles unlike those on Earth would have to be postulated. Photoautotrophy does not appear to be a viable energy capture mechanism for Europa because of the low amounts of light that pass through the icy surface layer several kilometers thick. Photoautotrophy that is solely based on light emitted from black smokers and flange pools, which may exist on Europa, appears unlikely. Nevertheless, the presence of subsurface liquid water and a rich selection of other energy sources make life beneath Europa's icy crust a viable scenario.

Europa most likely possesses a metallic core that provides internal heat through radioactive decay. Endogenic heat flow to the icy surface is indicated by the observation of systematic post-sunset temperature variation with latitude: northern latitudes are warmer than equivalent southern latitudes and there is a temperature minimum along the equator. Convection currents in the Europan ocean are likely to be generated from thermal differentials between the ice-covered surface and the geothermally heated ocean floor. Such currents may also be generated within tidal channels either on the ocean floor or in the ice ceiling due to Jupiter's strong gravitational attraction, which is in alternating synchrony or opposition to the other Jovian satellites. Thus both thermal energy and the kinetic energy of convection currents could be harvested by living systems on Europa. In addition, Jupiter's magnetic field, through which Europa makes a complete circuit every 85.2 hours, provides an additional potential energy source.

Life Based on Thermal Energy

Thermotrophic life forms may be conceivable that use thermal gradients, possibly in conjunction with the high heat capacity of water (about 4 kJ/kg*K). If we assume a cell mass of 10^{-15} g comparable to the cell mass of microbes on Earth, and further assume that one tenth of the body mass is a vacuole of water within the cell membrane from which the thermotroph could extract energy via the Carnot cycle, 89 eV of usable energy could theoretically be obtained by a temperature change from 20^{o}C to 19^{o}C. This amount of energy is substantially greater than the 2 eV that can be extracted via photoautrophy (per one photon) or chemoautotrophy (from oxidizing one molecule of hydrogen to water). For a cell as large as the giant pantropical alga, *Valonia macrophysa*, containing a water vacuole of approximately 10 g, the potential energy yield could be close to 1 Joule. A plausible energy-harvesting mechanism would be the presence of membrane macromolecules that catalyze high-energy metabolites through temperature-dependent conformational changes.

Life Based on Magnetic Energy

Magnetic fields theoretically can be used to create charge separation and extractable free energy. The physical process may be either based on the principle of the Lorentz force, the movement of a charge within a magnetic field, or by induction of a periodically changing magnetic field. Jupiter's magnetic field of about 450 nT near Europa is most likely too small when using a cell with a diameter in the micrometer range to create a sufficient amount of energy from the Lorentz force. On the other hand, the constraints of a weak magnetic field could be overcome by a meter-long hair cell clinging to a substrate while Europa is moving through Jupiter's dipolar magnetic field. Charge separation of many orders of magnitude larger than across a microscopic cell would occur. The organism could contain magnetite pigments that would orient themselves to the external magnetic field to optimize the harvest of magnetic energy. Alternatively, organisms of microbial dimensions could also be envisaged that would cling to strips of inanimate conducting material and harvest energy from the magnetically induced electron flow in their substrates.

Life Based on Kinetic Energy

Directly harvesting the kinetic energy of convection cells or tidal currents on Europa's ocean floor or ice ceiling would be another way to sustain life in the absence of light and oxygen. Organisms containing hair cells much like ciliated bacteria or protozoa could adhere to a substrate at the ocean bottom or on the underside of the ice ceiling, where they are exposed to currents of moving water that can bend their hair cells. The cells may enclose protein-like macromolecules that induce an electrical polarity across the membrane through a Donnan equilibrium mechanism. The hair cells could be surrounded by Na^+ channels whose permeability is proportional to deflection of the hair, with properties like those of sensory hair cells in the vestibular membrane of vertebrates. By bending the hair cells, the convection currents could lead to the opening of Na^+ channels, allowing Na^+ to flow into the cell passively down its concentration gradient. This thermodynamically favored process could be coupled to the direct formation of high-energy phosphate bonds or to a H^+ transporter across another internal membrane, by analogy with mitochondrial membranes. A steady convection current with a velocity in the cm/s range would certainly be able to power such a system, and the minimum energy needed may be extremely low. Since this system works essentially like a battery that is charged over time, all that is needed is a minimal energy source and enough time to charge the system high enough to form energy-storing chemical compounds.

Analogy to Earth and General Implications

While these postulated energy sources for life on Europa are admittedly speculative, they don't lack for analogs on Earth. Living cells are well known that are sensitive to heat, touch, stretch, convection of air and fluids, gravity, and pressure. Sensitivity to magnetic fields, as in magnetotactic bacteria, is also a well-established mechanism. Theoretically, enough energy can be supplied by all of these postulated processes to generate H^+ gradients across membranes or to power phosphorylation reactions directly.

While the argument given here has focused on Europa as an example, it can be generalized to any planetary ecosystem where energy gradients are available. In particular, collaborative strategies for extracting energy from different types of energy gradients may be a common occurrence on other worlds, because they provide the means for naturally cycling chemical compounds in a manner specific to a given planetary ecosystem. Organisms may have evolved as chemoautotrophs near hydrothermal vents as on Earth, as thermoautotrophs close to hydrothermal areas, as magnetotrophs near suitable magnetic fields, and as kinetotrophs in colder areas on the bottom of an ocean where convection or tidal currents are present. The possibility of life on other worlds would be enhanced by ecosystem differentiation of living environments, each with its own optimal energy source. On worlds such as these, nutrient cycling or even collaborative strategies as far-reaching as symbiosis could evolve.

While speculative, these scenarios are based on reasonable physical, chemical, biological and geological assumptions. Energy-yielding processes that could be conducive for life but that are different from those on Earth need to be considered in the search for life on other worlds. Theoretical possibilities such as those proposed here have the benefit of posing specific follow-up questions such as: What would be the minimum energy required to establish a proton pump? Which type of energy is most suitable to be tapped on other specific planets and moons? What are the likely energy-capture mechanisms for specific sources of energy on other worlds? Developing a good understanding of the theoretical possibilities of life will better guide us to the best search parameters and tools for detecting it.

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