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PLANETARY SCIENCE:

Enhanced: Life Without Photosynthesis

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Recent planetary exploration has shown that oceans of liquid water appear to be common in our solar system [HN1]. Galileo spacecraft [HN2] measurements of induced magnetic fields suggest that Jupiter's large icy moons--Europa, Ganymede, and Callisto [HN3]--all harbor salty oceans beneath the surface ice [HN4] (1). This is exciting news for extraterrestrial biology [HN5] because life as we know it requires liquid water.

But life also requires energy. Life that does not harvest sunlight directly obtains that energy from chemical disequilibrium in the environment. On Earth, photosynthesis [HN6], 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 [HN7] is therefore substantially less, raising the specter of entropic death for subsurface oceans--be they within icy satellites or on an earlier "snowball Earth" [HN8] (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 [HN9] (see the figure).

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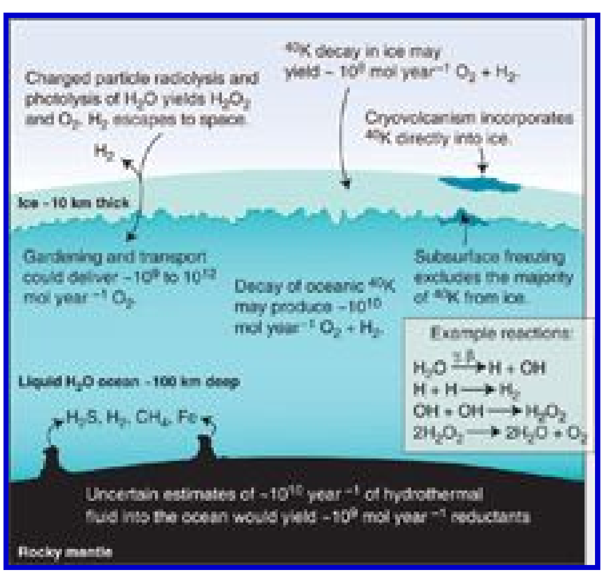

Can there be life in Europa's ocean? Photosynthesis is nearly impossible, but radiation processing of Europa's ice and liquid water might nevertheless provide chemical disequilibrium for life in Europa's ocean. ^{40}K decay via g or b emission decomposes H_2O and leads to O_2 and H_2 production.

Europa's surface is continuously bombarded with charged particles accelerated in Jupiter's magnetic field [HN10]. 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 x 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 [HN11] live at concentrations as low as 20 to 40 mM (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 formation. 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 [HN12] (11). For this case, Kargel [HN13] *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 [HN14] (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 [HN15] (13) implies that potassium is about 0.3 weight % of the Europan ocean, about 10 times that of Earth's oceans. Currently ^{40}K constitutes about 0.012% of total potassium [HN16] 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 x 10^{-4} weight % K, an average ^{40}K decay energy of 5.7 x 10^{5} eV (16) yields a net internal dose of ~3 x 10^{34} eV $year^{-1}$. This produces an estimated 0.1 to 0.4 H_2O_2 molecules per 100 eV (3), or ~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 ~10^8 to 10^9 g $year^{-1}$ of biomass today, and 10 times more 4200 million years ago.

Radiolysis [HN17] 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 Europan 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.

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.

References and Notes

1. M. G. Kivelson *et al.*, *Science* **289**, 1340 (2000).
2. E. J. Gaidos, K. H. Nealson, J. L. Kirschvink, *Science* **284**, 1631 (1999).
3. J. F. Cooper *et al.*, *Icarus* **149**, 133 (2001) [ADS] [Icarus].
4. C. F. **Chyba**, C. B. Phillips, *Proc. Natl. Acad. Sci. U.S.A.* **98**, 801 (2001) [PNAS].
5. Both O_2 and H_2O_2 are produced, the latter 10 times more efficiently than the former. H_2O_2 will decompose into O_2 once mixed into the Europan ocean with a half-life of less than 10 years (4), so we treat either O_2 or H_2O_2 mixed into the ocean as "equivalent" O_2.
6. J. C. G. Walker, *Evolution of the Atmosphere* (Macmillan, New York, 1977), p. 93.
7. This lower limit is about 10^3 times greater than that in (4), because there we took as the sole available reductant HCHO produced by radiolysis of CO_2 in the upper meter of Europa's ice shell. In contrast, here we assume that only the oxidants are limiting for biological energy production.
8. B. M. Jakosky, E. L. Shock, *J. Geophys. Res.* **103**, 19359 (1998) [ADS].
9. T. M. McCollom, *J. Geophys. Res.* **104**, 30729 (1999) [ADS].
10. If these estimates are correct, only a fraction of Europa's ocean would have passed through hydrothermal systems over Europa's history, whereas Earth's entire ocean passes through its vents every 50 million years.
11. J. S. Kargel *et al.*, *Icarus* **148**, 226 (2000) [ADS] [Icarus].
12. T. B. McCord *et al.*, *J. Geophys. Res.* **104**, 11827 (1999) [ADS].
13. K. Fredriksson, J. F. Kerridge, *Meteoritics* **23**, 35 (1988) [ADS].
14. Models for imperfect extraction of salts from carbonaceous meteorites (20) suggest K concentrations in Europa's ocean ranging from 0.001 to 0.5 times those found here on the basis of (11).
15. J. C. Moore, A. P. Reid, J. Kipfstuhl, *J. Geophys. Res.* **99**, 5171 (1994) [ADS].
16. I. G. Draganic *et al.*, *Precambrian Res.* **52**, 337 (1991) [GEOREF].
17. D. S. Colburn, R. T. Reynolds, *Icarus* **63**, 39 (1985) [ADS].
18. Our preliminary work suggests that these $v \times B$ currents could be significantly higher than predicted in (17), because of higher conductivities in Europa's ice owing to its salt content and, possibly, warm diapirs. These results will be published elsewhere.

19. K. H. Nealson, *J. Geophys. Res.* **102**, 23675 (1997) [ADS].
20. M. Yu. Zolotov and E. L. Shock, *Lunar Planet. Sci.* **XXXI**, abstract 1580 (CD-ROM, 2000) [ADS] [fulltext].
21. Supported in part by the NASA exobiology program and a Presidential Early Career Award for scientists and engineers.

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HyperNotes

Related Resources on the World Wide Web

General Hypernotes

The Academic Press Dictionary of Science and Technology is made available on the Web by its publisher Harcourt.

The xrefer Web site makes available definitions from scientific and other specialized dictionaries.

The NASA Astrophysics Data System makes available abstracts of astronomy and astrophysics journal articles, an archive of articles from some journals, and other resources.

AstroWeb, maintained by the international AstroWeb Consortium, provides a database of links to astronomical Internet resources. A section on planetary astronomy is included.

The Google Directory provides links to Internet resources related to the solar system and exobiology.

The Planetary Society offers a collection of Internet links and a collection of news articles about Jupiter.

The Lunar and Planetary Institute offers a collection of Internet resources, as well as images of the satellites of the outer planets.

Space.com provides news coverage of topics on the solar system and astrobiology.

Astrobiology Web, a resource provided by SpaceRef.com, offers links to news and Internet resources related to astrobiology.

Exploring the Planets from the National Air and Space Museum (NASM) includes a presentation on Jupiter and its moons.

C. Hamilton's Views of the Solar System offers a presentation on Jupiter and its satellites. A glossary is also provided.

Bill Arnett's Nine Planets is a multimedia tour of the solar system made available by SEDS (Students for the Exploration and Development of Space) at the Lunar and Planetary Laboratory, University of Arizona. A glossary is included. Presentations, with lists of Internet resources, on Jupiter and Europa are included.

Windows to the Universe provides information on Jupiter and Jupiter's moons and rings.

Astronomy Notes is a Web textbook by N. Strobel, Physical Science Department, Bakersfield College, CA.

J. Schombert, Department of Physics, University of Oregon, provides lecture notes for a course on the formation and evolution of the solar system; a presentation on the Galilean satellites is included. A glossary of physics and astronomy is provided.

The Astronomica Web site makes available the textbook *Astronomy: The Cosmic Journey* by W. Hartmann and C. Impey, Department of Astronomy, University of Arizona. A chapter on Jupiter, Saturn, and their moons is included.

S. Daunt, Department of Astronomy and Physics, University of Tennessee, makes available lecture notes for a Web-based course on the solar system.

J. Morgenthaler, Department of Physics, University of Wisconsin, offers lecture notes for an astronomy course on the exploration of the solar system. Lecture notes on the Galilean satellites and life in the solar system are included.

The Atmospheric Physics Laboratory at the Department of Physics and Astronomy, University College London, makes available lecture notes by A. D. Aylward for a course on solar system science. Included is a presentation on icy satellites.

J. Frogel, Department of Astronomy, Ohio State University, offers lecture notes for a course on solar system astronomy. Lecture notes on the Jovian planets are included.

The 30 January 2001 issue of the *Proceedings of the National Academy of Sciences* had a special feature section on astrobiology that included a perspective by C. **Chyba** and C. Phillips titled "Possible ecosystems and the search for life on Europa."

The 4 June 1999 issue of *Science* had a Perspective by E. Gaidos, K. Nealson, and J. Kirschvink titled "Life in ice-covered oceans" (2).

A Science Strategy for the Exploration of Europa is a 1999 report of the Space Studies Board of the National Academy of Sciences.

Numbered Hypernotes

1. Archival material from Water in the Solar System, an online educators' workshop presented by the College of Exploration and the Educational Outreach Program of NASA's Jet Propulsion Laboratory (JPL), includes background information about water on Earth, the Moon, Mars, and Europa. Space.com provides a 17 September 1999 article titled by G. Clark titled "Spacecraft search for solar-system's oases."

2. JPL provides a Galileo mission Web site; an overview of the mission and its history and a presentation on the moons and rings of Jupiter with sections on Europa, Ganymede, and Callisto are provided. The February 2000 issue of *Scientific American* had an article by T. Johnson titled "The Galileo mission to Jupiter and its moons." The Network Cybernetics Corporation provides a directory of Internet resources related to the Galileo space probe.

3. A. Hsui, Department of Geology, University of Illinois, makes available a presentation on Jupiter and its moons prepared for a course on the geology of the planets. NASA's Solar System Exploration Web site provides information on Jupiter, Europa, Ganymede, and Callisto. The 1 October 1999 issue of *Science* had a Review by A. Showman and R. Malhotra titled "The Galilean satellites." M. Kivelson, Department of Earth and Space Sciences and Institute of Geophysics and Planetary Physics, University of California, Los Angeles, makes available a lecture presentation titled "Galilean moons of Jupiter: Exploration of remote worlds." R. Nowack, Department of Earth and Atmospheric Sciences, Purdue University, offers lecture notes on Jupiter and the Galilean moons for a course on the planets. B. Ryden, Department of Astronomy, Ohio State University, offers lecture notes on the moons of Jupiter for a course on solar system astronomy.

4. Science@NASA provides a 23 October 1998 article titled "Callisto makes a big splash," a 9 September 1999 article titled "Divining Water on Europa," a 10 January 2000 article titled "Surf's up on Europa?", and a 28 August 2000 article titled "New evidence for an alien ocean." Space.com offers a 24 August 2000 article by M. Weinstock titled "Galileo shows signs of ocean on Europa" and an 18 December 2000 article by A. Bridges titled "Ocean lurks deep in Ganymede, Galileo finds." The *Washington Post* had a 17 December 2000 article by K. Sawyer titled "Evidence of liquid found on Jupiter's Ganymede: Largest moon may be a place to look for life." The Planetary Society makes available an article by D. Stevenson titled "How a magnetic field reveals an ocean" that was a sidebar to an article by M. Melton titled "An ocean deep within Ganymede?" The 25 August 2000 issue of *Science* had a Perspective by D. Stevenson titled "Europa's ocean--the case strengthens" and a Report by M. Kivelson *et al*. titled "Galileo magnetometer measurements: A stronger case for a subsurface ocean at Europa" (1). The 5 January 2001 issue had a News of the Week article by R. Kerr titled "Jupiter's two-faced moon, Ganymede, falling into line."

5. The NASA Ames Research Center provides an Astrobiology Web site that presents NASA's astrobiology roadmap and links to news stories. The NASA Astrobiology Institute has as its mission to promote, conduct, and lead integrated multidisciplinary astrobiology research and train young researchers. The 28 April 2000 issue of *Science* had a News Focus article by R. Irion titled "The science of astrobiology takes shape." The 1 October 1999 issue

had a news article by G. Vogel titled "Expanding the habitable zone." Windows to the Universe offers a presentation on NASA's exploration for life. Life on Other Planets in the Solar System is a educational presentation made available by the Regional Educational Service Agency of Wayne County, MI; a section on life on Europa is included. Looking for Life beyond Earth is a special feature (originally published in the January 2001 issue of *Research/Penn*) made available by Space.com in cooperation with the SETI Institute; an article about Europa titled "An ocean in space" is included. The January-February 1999 issue of *Ad Astra* was a special issue on astrobiology that included an article by P. Boston titled "The search for extremophiles on Earth and beyond: What is extreme here may be just business-as-usual elsewhere." The March 1998 Magnificent Cosmos special issue from *Scientific American* had an article by B. Jakosky titled "Searching for life in our solar system." Exobiology and Europa is a presentation by T. Stevens, Department of Biochemistry, University of Cambridge. Is there Life on Europa? is a student Web project prepared for an honors chemistry course taught by M. Dantus, Department of Chemistry, Michigan State University.

6. J. Schombert's glossary provides an introduction to photosynthesis. The online Columbia Encyclopedia, made available by Bartleby.com, provides introductions to photosynthesis and chemosynthesis. Britannica.com provides an *Encyclopædia Britannica* article on photosynthesis. The Center for the Study of Early Events in Photosynthesis at Arizona State University provides an introduction to photosynthesis and links to Internet resources on photosynthesis. The New Millennium Observatory Web site provided by NOAA's Pacific Marine Environmental Laboratory offers a brief presentation on photosynthesis *vs* . chemosynthesis.

7. Britannica.com provides an *Encyclopædia Britannica* article on oxidation-reduction reactions. Purdue University's General Chemistry Help Homepage offers a tutorial on oxidation-reduction reactions.

8. R. Cowan, Department of Geology, University of California, Davis, offers an essay on snowball Earth in the Web supplement for his textbook *History of Life* . *Scientific American* presents a January 2000 article by P. Hoffman and D. Schrag titled "Snowball Earth" and a November 1999 Explore! feature by K. Leutwyler titled "The first ice age." The 6 November 1999 issue of New Scientist had an article by G. Walker titled "Snowball Earth." The 22 August 1998 issue of *Science News* had an article by R. Monastersky titled "Popsicle Earth." The 28 August 1998 issue of *Science* had a report by P. Hoffman *et al* . titled "A Neoproterozoic snowball Earth." The 15 February 2000 issue of the *Proceedings of the National Academy of Sciences* had an article by J. Kirschvink *et al* . titled "Paleoproterozoic snowball Earth: Extreme climatic and geochemical global change and its biological consequences"; the California Institute of Technology issued a 14 February 2000 news release about this research.

9. Astronomy Picture of the Day featured Europa images on 16 January 2001, 2 January 2001, 25 August 2000, 14 July 2000, 18 April 2000, and 3 March 1998. NIX (NASA Image eXchange) provides a collection of Europa images. Icepick: the Europa Ocean Explorer project Web site provides a collection of Internet links related to Europa. JPL provides an Europa Orbiter mission Web site. The 6 January 1999 *Stanford Daily* had an article by K. Wu about the proposed Europa orbiter mission titled "Stanford scientists search for extraterrestrial life: Europa, Jupiter's largest moon, may harbor life beneath the ice." The Planetary Science Research Discoveries Web site, maintained by G. J. Taylor and L. Martel, Hawaii Institute of Geophysics and Planetology, University of Hawaii, Manoa, provides a 26 February 2001 feature by Martel titled "The Europa scene in the Voyager-Galileo era." The NASA Astrobiology Institute offers a feature titled "Through thick or thin: Exploring Europa's outer layer of ice." The 15 January 1999 issue of *Science* had a Perspective by C. Chapman titled "Probing Europa's third dimension." The 18 September 1999 issue of *New Scientist* had an article by G. Walker titled "Waterworld" about Europa. *Scientific American* offers an April 1997 exhibit feature titled "Europa: Wet and wild." Space.com provides a 26 January 2000 article by R. Britt titled "Jupiter's deadly radiation could power life on Europa." SpaceDaily makes available an 11 April 2000 article by B. Moomaw titled "Increasing evidence that Europa lives" and an 11 June 1999 article by Moomaw titled "Chemosynthesis may drive Europan life." *Nature* offers an 8 June 2000 Science Update by M. Haw titled "Brief bloom for frozen life on Europa?" about the article by E. Gaidos and F. Nimmo titled "Tectonics and water on Europa" in the 8 June 2000 issue of *Nature* . E. Gaidos, Jet Propulsion Laboratory and Division of Geological and Planetary Sciences, California Institute of Technology, makes available a preprint (in Adobe Acrobat format) of the *Nature* article.

10. The Galileo mission Web site provides introductions to Jupiter's interior and magnetosphere and magnetic field. The Galileo Magnetometer Team provides an overview of the Galileo magnetic field investigation. A section on Jupiter's magnetic field is included in lecture notes on Jupiter for a course on the solar system offered by the Department of Physics and Astronomy, University of Tennessee. NASM's Exploring the Planets offers a presentation on Jupiter's magnetic field, radiation belts, and radio noise. The University of Oregon's Distance Education Program offers lecture notes on Jupiter's magnetic field for a course on solar system geology. C. Russell, Department of Earth and Space Sciences and Institute of Geophysics and Planetary Physics, University of California, Los Angeles, makes available an encyclopedia article titled "Jupiter: Magnetic field and magnetosphere."

11. Science@NASA offers a 13 April 2001 article titled "Life as we *didn't* know it" about an ecosystem that thrives on geothermal energy in complete darkness. The May-June 1996 issue of *Zoogoer* had an article by R. Meadows titled "Life without light: Discoveries from the abyss." The NASA Astrobiology Institute offers a presentation by H. Bortman titled "Twenty thousand leagues under the sea." Life on Other Planets in the Solar System includes a section on life in extremis on Earth. The Geological Society offers a presentation titled "Life in the smoking zone." Into the Abyss, a presentation of NOVA Online, includes a section on life in the abyss. The Discovery Channel offers a presentation about deep-sea vents titled "Where life began: Thriving in the Earth's most extreme environment." NOAA's Arctic Theme Page makes available an article by P. Vogt titled "Vent and seep communities on the Arctic seafloor." J. Schieber, Department of Geology, University of Texas at Arlington, offers a presentation titled "Deep sea vent communities: Did life originate in the abyss?" for a course on Earth systems. L. Ver, Department of Oceanography, University of Hawaii, makes available lecture notes on hydrothermal vents for an oceanography course.

12. C. Hamilton's Views of the Solar System provides an illustrated introduction to meteoroids and meteorites. N. Strobel's Astronomy Notes includes a section on meteorites. S. Hughes, Geology Department, Idaho State University, provides lecture notes on meteorites and asteroids for a course on planetary geology for teachers. Meteorites and Their Properties is a Web presentation by D. Kring, Lunar and Planetary Laboratory, Department of Planetary Sciences, University of Arizona; a section on the structure and composition of meteorites is included. Carbonaceous chondrite is defined in the Academic Press Dictionary of Science and Technology and in in xrefer's *Dictionary of Earth Sciences* , which also provides a description of meteoritic abundance of elements. Carbonaceous chondrite is defined in xrefer's *Dictionary of Earth Sciences* ; a description of meteoritic abundance of elements is also provided. Meteorites.com offers a presentation on the classification of meteorites with a section on carbonaceous chondrites. New England Meteoritical Services provides an introduction to carbonaceous chondrites.

13. J. Kargel is at the U.S. Geological Survey Flagstaff Field Center. The Lunar and Planetary Institute provides abstracts (in Adobe Acrobat format) of papers on Europa's composition by J. Kargel prepared for the Lunar and Planetary Science Conferences: 1998 conference ("Composition of Europa's crust and ocean"), 1999 conference ("Aqueous chemical evolution and hydration state of Europa's salts"), and 2001 conference ("The system sulfuric acid-magnesium sulfate-water: Europa 's ocean properties related to thermal state").

14. The Planetary Science Research Discoveries Web site offers an article by G. J. Taylor titled "Europa's salty surface." The 22 May 1998 issue of *Science* had a research perspective by J. Kargel titled "The salt of Europa" and a report by T. McCord *et al* . titled "Salts on Europa's surface detected by Galileo's Near Infrared Mapping Spectrometer." Galileo's Near Infrared Mapping Spectrometer (NIMS) Web site provides information about the NIMS observations; a NIMS image of salts on Europa is available. D. Hogenboom, Department of Physics, Lafayette College, Easton, PA, offers a research presentation on sulfate solutions and the Galilean satellites of Jupiter.

15. A Systematic Classification of Meteorites, available on D. Weir's Meteorite Studies Web site, includes information on the Orgueil meteorite. The 27 February 2001 issue of the *Proceedings of the National Academy of Sciences* had an article by P. Ehrenfreund *et al* . titled "Extraterrestrial amino acids in Orgueil and Ivuna: Tracing the parent body of CI type carbonaceous chondrites."

16. Visual Elements, a presentation of the Chemical Society, provides information on potassium. WebElements, maintained by M. Winter, Department of Chemistry, University of Sheffield, UK, provides information about potassium and its isotopes. The WWW Table of Radioactive Isotopes provides information about ^{40}K and other potassium isotopes.

17. Radiolysis is defined in the Academic Press Dictionary of Science and Technology and in xrefer's *Dictionary of Science* . Nu Energy Technologies, Inc. makes available a presentation by B. Perreault titled "The dissociation of water by radiant energy." The Internet Photochemistry & Photobiology Web site makes available a presentation by L. Grossweiner on ionizing radiation that includes a section on the radiation chemistry of water.

18. C. F. **Chyba** is at the Center for the Study of Life in the Universe of the SETI Institute, the Center for International Security and Cooperation (CISAC), Stanford University, and in the Department of Geological and Environmental Sciences, Stanford University.

19. K. P. Hand is at CISAC and the Department of Mechanical Engineering, Stanford University.

This article has been cited by other articles:

- Thomas, D. N., Dieckmann, G. S. (2002). Antarctic Sea Ice--a Habitat for Extremophiles. *Science* 295: 641-644
  [Abstract] [Full Text]

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