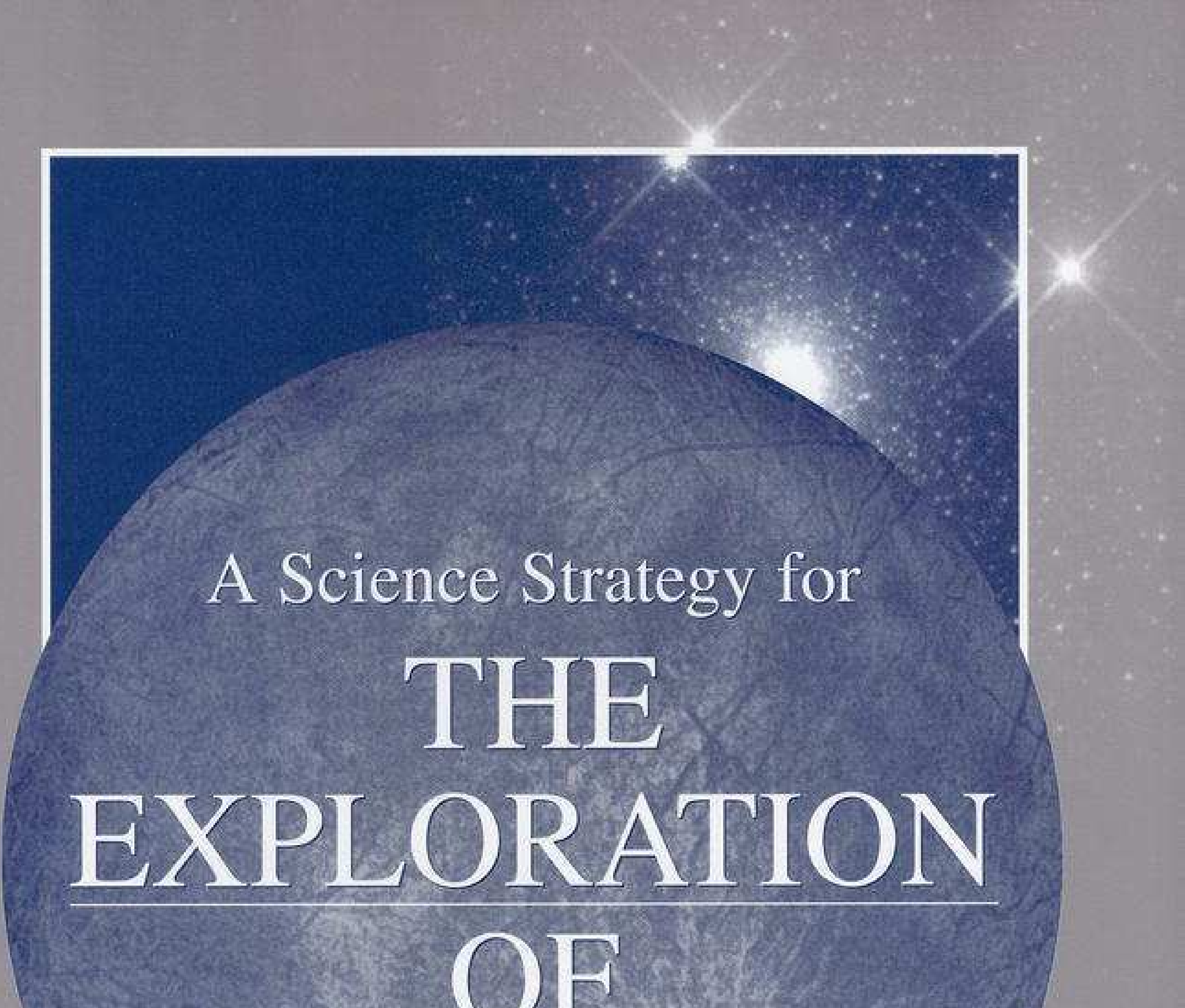

A Science Strategy for THE EXPLORATION OF EUROPA

SPACE STUDIES BOARD

NATIONAL RESEARCH COUNCIL

A Science Strategy for the Exploration of Europa

Committee on Planetary and Lunar Exploration
Space Studies Board
Commission on Physical Sciences, Mathematics, and Applications
National Research Council

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Foreword

Terrestrial studies of life in extreme environments now show that Earth is teeming with microorganisms. Nearly every locale that contains two ingredients, liquid water and some form of energy, appears to host a variety of microbes living happily under conditions that just a few years ago would have seemed impossibly inhospitable. There is also increasing evidence that life emerged very early on Earth, almost as soon as the planet stopped being punished by the deadly rain of debris coursing through the young solar system.

These findings have greatly expanded the horizons of potential habitats for life in the solar system and beyond. Whereas the prior assumption of life as a fragile and extremely rare occurrence put the focus on Mars, the only other planet that might once have had earthlike conditions, the new view of life as relatively robust, if not unstoppable, brings several other bodies into contention.

Jupiter's moon Europa is foremost among the new candidates for harboring past or present life forms. Europa's smooth crust of fractured water ice suggests a subsurface ocean that might provide just the conditions that can host life on Earth. Discovered by Galileo and studied for the past few years by the spacecraft that bears his name, Europa is now considered "one of the places in our solar system with the greatest potential for the existence of life" (see p. 3 in the Executive Summary).

This study assesses our current knowledge of Europa and outlines a strategy for multiyear investigations that would lead to definitive understanding of this moon and its possible biota. COMPLEX concludes that Europa should have a priority for future investigation equal to that accorded to Mars. And as has already been stressed in the strategy for martian investigations, the report underlines the need for a systematic approach to obtaining a global view of Euorpa science, rather than attempting a rapid and possibly poorly conceived rush to detect life. Such a course will not be easy—the intense radiation environment around Jupiter's moon is just one of the many technical challenges. But the reward in understanding this remarkable object and in pursuing the possibility for discovery of extraterrestrial life will be substantial.

Claude R. Canizares, *Chair*
Space Studies Board

Preface

Over the last few decades the Space Studies Board and its standing discipline committees have devised a series of long-term scientific strategies for NASA's various space science programs. Priorities for the exploration of the solar system, for example, are contained in the report *An Integrated Strategy for the Planetary Sciences: 1995-2010* (National Academy Press, Washington, D.C., 1994). One of the highest priorities identified in that report is the continued exploration of Jupiter and its system of satellites, rings, and complex plasma environment.

Since that report was written, the ongoing Galileo mission has greatly expanded our knowledge of the jovian system and has, in particular, revealed much new information about the galilean satellite Europa. This new information, especially that relating to Europa's exobiological potential, has prompted NASA to identify Europa as a priority object in the future exploration of the outer solar system. As a result, the Space Studies Board charged its Committee on Planetary and Lunar Exploration (COMPLEX) to conduct a study to accomplish the following objectives:

- Review and synthesize the current status of knowledge about Europa in view of the results from the Galileo mission.
- Identify opportunities for Earth-based studies and technology development both to prepare for a program of exploration of Europa and to maximize the scientific connection in the Earth and life sciences of spaceflight missions to Europa.
- Recommend a strategy for the further exploration of Europa, to include:

    1. Global mapping of the topography, geology, and composition of Europa's crust to understand its present state and the history of its evolution;
    2. Measurements and/or tests that would allow the determination of the presence or absence of liquid water under or within the surface ice crust, and mapping of the thickness and internal structure of the crust;
    3. Determining its interior structure, including the size and composition of a core, the possible nature of geological processes at the water- or ice-rock interface, and whether any dynamic processes are continuing at the present;
    4. The means of determining the extent of organic chemical evolution on or under the surface of Europa; and

5. Should liquid water be present, the means of determining the potential for or existence of organic chemical evolution and/or biological activity within that ocean.

- Coordination of planning and science-community participation with federal agencies, such as NASA, the National Science Foundation's Polar Programs and Ocean Sciences organizations, the National Oceanic and Atmospheric Administration, the Office of Naval Research, and others for Europa exploration and Earth-based preparations.

This project was formally initiated in December 1997. Presentations relating to it, however, began somewhat earlier and were conducted in the context of COMPLEX's standing oversight of NASA's planetary exploration programs and during the definition and development of the charge for this study. An initial outline of this report was completed at COMPLEX's February 1998 meeting, and a complete draft was assembled at COMPLEX's June 1998 summer-study meeting. The text was approved by the Space Studies Board in November 1998, sent to external reviewers in December 1998, and extensively updated in the spring and summer of 1999.

Although many COMPLEX members past and present worked on this report, the bulk of the task of assembling their many individual contributions was performed by Bruce Jakosky with the assistance of Wendy Calvin, Ronald Greeley, Larry Haskin, Kenneth Jezek, Michael Mendillo, and Gerald Schubert.

The work of the writing team was made easier thanks to the contributions made by Charles Barnes (Jet Propulsion Laboratory), Jay Bergstrahl (NASA Headquarters), Michael Brown (California Institute of Technology), Frank Carsey (Jet Propulsion Laboratory), Christopher Chyba (SETI Institute), James Cutts (Jet Propulsion Laboratory), Paul Geissler (University of Arizona), Robert Johnson (University of Virginia), Torrence Johnson (Jet Propulsion Laboratory), Krishan Khurana (University of California, Los Angeles), Arthur Lane (Jet Propulsion Laboratory), Christopher McKay (Ames Research Center), William O'Neil (Jet Propulsion Laboratory), Michael Purdy (National Science Foundation), Laurence Soderblom (U.S. Geological Survey), Richard Terrile (Jet Propulsion Laboratory), and Charles Yoder (Jet Propulsion Laboratory).

This report has been reviewed by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's (NRC's) Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the authors and the NRC in making the published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The contents of the review comments and draft manuscripts remain confidential to protect the integrity of the deliberative process. COMPLEX thanks reviewers John A. Baross (University of Washington), Radford Byerly (Congressional Science Committee staff, retired), Marshall H. Cohen (California Institute of Technology), Stanton Peale (University of California, Santa Barbara), Jeffrey B. Plescia (U.S. Geological Survey), and Raymond J. Walker (University of California, Los Angeles) for many constructive comments and suggestions. Responsibility for the final content of this report rests solely with the authoring committee and the NRC.

Contents

Executive Summary

Since its discovery in 1610, Europa—one of Jupiter's four large moons—has been an object of interest to astronomers and planetary scientists. Much of this interest stems from observations made by NASA's Voyager and Galileo spacecraft and from Earth-based telescopes indicating that Europa's surface is quite young, with very little evidence of cratering, and made principally of water ice.

More recently, theoretical models of the jovian system and Europa have suggested that tidal heating may have resulted in the existence of liquid water, and perhaps an ocean, beneath Europa's surface. NASA's ongoing Galileo mission has profoundly expanded our understanding of Europa and the dynamics of the jovian system, and may allow us to constrain theoretical models of Europa's subsurface structure.

Meanwhile, since the time of the Voyagers, there has been a revolution in our understanding of the limits of life on Earth. Life has been detected thriving in environments previously thought to be untenable—around hydrothermal vent systems on the seafloor, deep underground in basaltic rocks, and within polar ice. Elsewhere in the solar system, including on Europa, environments thought to be compatible with life as we know it on Earth are now considered possible, or even probable. Spacecraft missions are being planned that may be capable of proving their existence.

Against this background, the Space Studies Board charged its Committee on Planetary and Lunar Exploration (COMPLEX) to perform a comprehensive study to assess current knowledge about Europa, outline a strategy for future spacecraft missions to Europa, and identify opportunities for complementary Earth-based studies of Europa. (See the preface for a full statement of the charge.)

CURRENT UNDERSTANDING

Perhaps the most exciting aspect of Europa revealed by recent studies is the possible existence of liquid water beneath a surface covering of ice. Although no unique evidence for such an ocean exists yet, very intriguing indications have been seen from spacecraft.

Europa's reflectance characteristics indicate that its surface is almost-pure water ice. Local- and global-scale ice tectonics dominates the geology, with a very large number of cracks criss-crossing Europa's surface. Seen at kilometer-scale resolution from the Galileo spacecraft, large "rafts" of ice appear to have broken up and moved with respect to each other; the appearance is similar to that of sea ice on Earth. Contaminants have been detected within the ice, including sulfur dioxide (SO_2) frost, hydrogen peroxide (H_2O_2), and a variety of salts. The salts, in particular, may provide additional evidence for a global ocean, as they are easily dissolved in and transported by water. The presence of hydrogen peroxide suggests that Europa's surface chemistry is dominated by radiolysis.

Gravity measurements obtained from the tracking of Galileo indicate that Europa's interior is differentiated. The outermost layer is predominantly water and/or water ice and is perhaps 100 km thick. Below the water exists a "rocky" interior, which also has differentiated into a dense core and a less-dense mantle; these are thought to be analogous to the iron core and silicate mantle of the terrestrial planets. Europa's magnetic "signature" indicates the presence of a conducting layer near the satellite's surface, most likely owing to water containing dissolved salts.

Europa also has a thin atmosphere, likely composed primarily of materials ejected from its surface. To date, molecular oxygen and atomic sodium have been identified, although other species are expected to exist. These species are thought to have been emplaced into the atmosphere as a result of the collisions of highly energetic particles from the jovian magnetosphere; some of the sodium, however, may come from Io, where it is ejected by similar processes. The gases reside in an extended atmosphere until they are ionized by solar ultraviolet light or magnetospheric electrons and picked up by Jupiter's magnetic field.

As a result of the likely existence of liquid water, at least on a transient or intermittent basis, Europa has the potential for life to exist below its surface. The other requirements for life—access to the biogenic elements and to a source of energy—are present at the water-rock boundary at the bottom of the water layer. While no evidence for life exists, the potential for life makes Europa an exciting target for additional exploration following the completion of the Galileo mission.

OUTSTANDING QUESTIONS AND ISSUES

At our current level of understanding, then, the outstanding questions and issues to be addressed for Europa include the following:

- Is there liquid water on Europa today, or was there liquid water in the geologically recent past?
- Are the ice rafts seen in Galileo's images of Europa the result of movement atop liquid water or through a warm, soft (but not necessarily melted) ice?
- What is the composition of the deep interior of Europa, below the water/ice layer?
- What is the composition of the non-ice component of the surface materials (such as the salts)?
- What is the nature of the ice-tectonic processes that have affected the surface?
- What is the composition of the atmosphere and of the ionosphere?
- What are the characteristics of the surface radiation environment and what are the implications for organic/biotic chemistry?
- What is the abundance of geochemical sources of energy that could support life?

KEY MEASUREMENTS

The outstanding questions and issues for Europa can be addressed through a series of spacecraft missions that, together, can contribute to an integrated understanding of the nature of Europa, the possibility that liquid water exists there, and the potential for life. In particular, important measurements will include:

- **Measuring Europa's global topography and gravity, and determining how Europa's shape changes as it orbits Jupiter;**
- **Characterizing Europa's geology and surface composition on a global scale;**
- **Mapping the thickness of Europa's ice shell and determining the interior structure;**
- **Distinguishing between any intrinsic europan magnetic field and induction and/or plasma effects; and**
- **Sampling the geochemical environment of Europa's surface and possible ocean.**

CONCLUSIONS AND RECOMMENDATIONS

Priority Status of Europa Exploration

With the likelihood that it has vast quantities of liquid water beneath its icy surface, Europa is one of the places in our solar system with the greatest potential for the existence of life. Along with Mars, it appears to possess all of the environmental conditions necessary to support the origin and the continued existence of biota. As a result, finding evidence that might indicate whether life had existed on either Mars or Europa would help us to understand whether our theories for the origin of life on Earth are correct and would help us to understand whether life might be widespread outside our solar system.

Thus, **COMPLEX concludes that Europa is an exciting object for additional study following the completion of the Galileo mission. It offers the potential for major new discoveries in planetary geology and geophysics, planetary atmospheres, and, possibly, studies of extraterrestrial life. In light of these possibilities and the equal priority given to the exploration of Mars and the Jupiter system by COMPLEX's *Integrated Strategy,*[1] COMPLEX feels justified in assigning the future exploration of Europa a priority equal to that for the future exploration of Mars. This equality must, however, be tempered by the uncertainty as to whether liquid water is actually present and the technological challenges posed by the exploration of Europa.**

The two highest-priority overall science goals identified by COMPLEX for exploration of Europa reflect the emphasis on the potential for life as a major driver in Europa's exploration:

1. Determining whether liquid water has existed in substantial amounts subsequent to the period of planetary formation and differentiation, whether it exists now, and whether any liquid water that is present is globally or locally distributed; and
2. Understanding the chemical evolution that has occurred within the liquid-water environment and the potential for an origin of life and for its possible continuation on Europa.

The Need for a Systematic Program of Exploration

COMPLEX recognizes the frustration that will inevitably result from following a well-conceived strategy for conducting a thorough and detailed investigation of the potential for life on Europa that likely will take one or two decades to carry out. With the excitement today about searching for life elsewhere, it is tempting to advocate a spacecraft mission that will immediately search for europan life or return samples of surface ice to Earth for such analyses. However, the history of space exploration suggests that a phased approach, in which the results of one mission provide the scientific foundation for the next incremental advance, is more productive in the long term.

We need only look to the history of the search for life on Mars to see the wisdom of an incremental approach. Although the Viking missions seemed very well conceived in 1970, they look naive today in the light of current understanding of the martian environment, and of the diversity of life on Earth and its ability to survive in extreme conditions. As a result, Viking did not sample the most appropriate environments in its search for extant life on Mars. The results from the Viking biology experiments, though, have provided a remarkable foundation for understanding of martian geochemistry that is playing a key role in knowing how and where to look for life on Mars today.

In a similar vein, the absence of identifiable surface environments that might support life or contain evidence of life on Europa and our complete lack of understanding of the chemical environment of the icy surface layer, the liquid water layer that may or may not underlie it, and the rocky interior of Europa suggest that a detailed exploration of the satellite will provide the best opportunity to answer these exciting questions. In other words, understanding the history of the satellite and the potential for life requires a detailed investigation into the geochemistry of the surface and subsurface ice or water, and of possible organic molecules or biological activity. Measurements of the atmosphere, ionosphere, the rocky interior, and the ice- or water-rock interface will also be important.

Therefore, **COMPLEX recommends that Europa be explored within the framework of a well-conceived and planned strategy designed to create a scientific base of information that is sufficient to provide a global context for interpreting data pertaining to the possible presence of life on Europa.** A comprehensive understanding of the geology, geochemistry, and geophysics of Europa, and of the nature of its atmosphere, is not strictly necessary in order to determine if liquid water is present. Knowledge of these is necessary, however, to assess the potential for life, to determine whether life is present, and to understand the chemical evolution of Europa.

COMPLEX concludes that, should it turn out that liquid water is not present on Europa and has not been present in geologically recent times, the strong evidence for comparatively recent or ongoing geologic activity still makes it an appropriate target for exploration. However, the priority accorded Europa in the solar system exploration program and the sequence of exploration activities would have to be reassessed at that time.

Europa and the Search for Life in the Solar System

The search for extinct or extant life on Mars, and the geophysical and geochemical analyses that are a fundamental part of the search, will provide substantial new insights into the environments in which life might exist and the precursor and resulting molecules that might obtain. Similarly, the search for life in extreme environments on Earth is providing key new insights into the potential for life elsewhere in the universe. In both cases, the new results need to be integrated into the ongoing Europa program to ensure a solid basis for investigation and analysis.

Thus, **COMPLEX recommends that the search for evidence of present or past life on Europa, or for evidence of chemical evolution that has the potential to lead to life, should be coordinated with other aspects of the search for possible abodes of life in the solar system.**

Elements of a Comprehensive Exploration Program

A comprehensive exploration of Europa that can address the major scientific goals will require a combination of spacecraft missions, ground-based telescopic observations, technology development, and supporting research and analysis. The scientific priorities for exploring Europa should proceed from the global to the local scale in searching for liquid water, determining the composition of the surface and near-surface ice, and exploring any pockets of liquid or oceans that may be discovered. The set of subsequent spacecraft missions to Europa that follows from this, then, likely should proceed from a polar orbiter, to landed experiments, to subsurface devices that can penetrate to depths necessary to reach liquid water. COMPLEX recognizes that implementation of such an ambitious sequence of spacecraft, with each being able to take advantage of results from the earlier missions, may require decades.

COMPLEX recommends that a staged series of missions be utilized to explore Europa, with the scientific focus of the first mission being to determine whether liquid water exists at the present epoch or has existed relatively recently. If liquid water is present, the focus of follow-on missions should be to characterize surface materials and to access and study the liquid water.

Priorities for the Initial Europa Mission

COMPLEX recommends that the primary goals for the first Europa mission should be determining whether a global ocean of liquid water exists beneath the icy surface, determining if possible the spatial and geographical extent of liquid water, determining the bulk composition of the surface material, and charac-

terizing the global geologic history and the nature of any ongoing surface and atmospheric processes. These science objectives can best be met by observations from polar or near-polar orbiting spacecraft.

Specific measurement objectives include, in priority order:

1. Obtaining measurements of the time variations of Europa's global topography and gravity field over a period of several tens of orbits of Europa around Jupiter, with a precision and accuracy of ±2 meters to uniquely distinguish between tidal distortions of several meters (expected for a completely solid ice cover) and several tens of meters (expected if a global layer of liquid is present). The results of these efforts will allow a unique conclusion regarding the present-day existence of a global liquid-water layer;
2. Imaging Europa's surface, with resolution of at least 300 m/pixel for global coverage and with higher resolution (< 50 m/pixel) for selected regions, to understand the global geologic history and identify regions where liquid water may be readily accessed;
3. Performing radar sounding of Europa's subsurface structure to a depth of 5 to 10 km, to identify possible regions where liquid water might exist close to the surface. If the ice is less than 5 to 10 km thick, use of ice-penetrating radar may allow determination of the vertical extent of the surface ice layer (and possibly a direct detection of any underlying liquid water), as well as the local structure of the ice;
4. Mapping the near-infrared reflectance spectrum of Europa's surface materials globally at kilometer-scale resolution, supplemented by 300-m resolution in selected areas, and using the results to identify the bulk composition of the surface materials, their abundances, and their spatial distributions. A spectral resolution of 10 to 15 nm will be required;
5. Measuring the magnetic field to a precision of 0.5 nT under a variety of different background conditions (i.e., at different jovian longitudes), combined with coordinated measurements of the plasma environment, to determine whether there is an intrinsic magnetic field and what the properties of either the intrinsic or induced field are. Such measurements may provide important information about the structure of and dynamical processes operating in Europa's deep interior; and
6. Determining the composition and properties of the atmosphere using both in situ and remote-sensing experiments.

Priorities for Follow-on Europa Missions

Following the systematic orbital characterization of Europa, the focus of follow-on missions should shift to studies of the nature of Europa's surface materials and the means to access and study any liquid water present. Therefore, **COMPLEX recommends that:**

- **The science objectives for follow-on experiments designed to elucidate the properties of Europa's surface materials should include in situ determination of the composition of the ice and of any non-ice surface components, including the bulk material, trace elements, isotopes, and mineralogy; analyses of any organic molecules at or near the surface, and identification of endogenic or exogenic sources; determination of the composition and properties of the atmosphere and of any materials sputtered from the surface; and estimation of the absolute ages of surface materials.** These science goals probably can best be met using a landed package of instruments on Europa's surface.
- **If subsurface liquid water is detected and found to be accessible with an instrumented probe, the science objectives of subsequent missions should include determination of the physical and chemical properties of the water, including salinity, acidity, pressure and temperature profiles within the water, abundances and chemical gradients in key redox compounds, and existence and abundances of organic materials; determination of the composition and abundance of suspended particles; exploration of the properties at the water-ice interface; and a search for extant life in the water.**

Earth-based Studies, Technology Development, and Other Issues

Much additional laboratory and theoretical work, together with field studies and associated technical developments, is required in a program designed to pursue the exploration of Europa. As a result, **COMPLEX recommends that:**

- **A vigorous program of laboratory measurements and supporting theoretical analyses be carried out, to encompass the nature of materials at temperatures, pressures, and irradiation conditions likely to be found on Europa.**
- **NASA support a program of theoretical analysis of the geophysical and geochemical environment at Europa, including the nature of the interior, surface, atmosphere, and magnetospheric interactions.**
- **New large telescopes and instrumentation that are being developed incorporate, from the beginning of the design stages, the ability to observe relatively bright targets moving with respect to the background stars, and that these capabilities be implemented in a timely manner. For new ground- and space-based facilities, a non-sidereal tracking capability with an accuracy analogous to that of the Hubble Space Telescope would be appropriate.**
- **Low-mass, radiation-hardened instruments be developed for use on orbiting and surface spacecraft.**
- **Devices that can penetrate through any surface ice and explore the subsurface ice and possible liquid water ocean on Europa be developed, on a schedule that will allow them to be launched on possible spacecraft missions a decade from now.**
- **Appropriate diagnostic remote tests and instrumentation for determining the physical and chemical properties of a sub-ice ocean and for detecting the presence or potential for life be developed.**
- **NASA continue its collaborative efforts with other government agencies to explore sub-ice freshwater lakes (such as Antarctica's Lake Vostok) and sub-ice-shelf ocean environments as a means of understanding scientific, technological, and operational issues associated with the exploration of isolated environments.**
- **Peer review be used to select Earth-analog programs and investigators to ensure a significant and appropriate level of participation by all of the relevant scientific communities.**
- **NASA, to avoid "reinventing the wheel," should look to other federal agencies to deal with some of the scientific and technological issues and develop mechanisms for cooperating with governments of other countries in exploring Earth analogs.**
- **Appropriate planetary protection measures be determined and implemented on all relevant spacecraft missions.**[*]

REFERENCE

1. Space Studies Board, National Research Council, *An Integrated Strategy for the Planetary Sciences: 1995-2010*, National Academy Press, Washington, D.C., 1994, pages 8 and 191.

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[*] Appropriate planetary protection measures are currently being determined by the Space Studies Board Task Group on the Forward Contamination of Europa.

1

Why Europa?

Europa—one of the four large satellites of Jupiter discovered by Galileo Galilei in 1610 (Figures 1.1 and 1.2)—is among the most intriguing objects in the solar system (Box 1.1). In large part, this interest stems from the possibility that Europa may have substantial amounts of liquid water, possibly as a global-scale ocean buried beneath a surface layer of ice,[1,2] with liquid water being one of the primary requirements for the origin or continued existence of life as we can imagine it. The interest in Europa extends beyond the scientific community, and the idea that a europan ocean might harbor life has become a part of popular culture. This is exemplified by Arthur C. Clarke's science-fiction novel, *2010: Odyssey II,*[3] in which life-harboring Europa is declared off-limits to humans with a mysterious, preemptive warning—"All these world are yours except Europa, attempt no landings there."

Scientific and public interest has intensified as the Galileo spacecraft has revealed remarkable indications of geologically recent or ongoing activity in Europa's atmosphere, on its surface, and within its interior. There is abundant evidence on its icy surface for relatively recent geologic activity, including resurfacing with fresh ice and tectonic movement of the ice. Above the surface is an atmosphere produced mainly by the bombardment of the icy surface by energetic particles interacting with the jovian magnetospheric environment. The average density of Europa suggests that the interior, although not sampled or observed directly, is composed predominantly of a rocky material similar to that of Io or the Moon and has a dense core at its center. The outermost 100 to 200 km, however, consists of a layer composed predominantly of water. Evidence for fairly recent geologic activity at the surface suggests that the combined heating produced by the decay of radiogenic isotopes, tidal flexing associated with its orbit around Jupiter, and resonant interactions with neighboring satellites is substantial.[4]

What makes Europa of special interest, however, is the potential that it may hold for the presence of liquid water within this surface layer and the associated possibility of life. Internal heating may be sufficient to raise temperatures to the melting point of water ice at only a modest depth of a few to tens of kilometers. Consequently, Europa may contain a global ocean of liquid water more than 100 km thick and covered by only a thin layer of water ice. The presence of liquid water is suggested by Galileo images showing blocks of ice, some of which are several kilometers across, that appear to have "rafted" away from a larger mass, possibly on a liquid-water or slushy-ice layer that subsequently froze. Moreover, Europa's relatively crater-free surface suggests that the rafting occurred in the recent geologic past (i.e., within the last few millions to tens of millions of years).

The possible presence of liquid water, combined with the presumed availability of geochemical energy within its interior, creates the potential for life to have originated on Europa and perhaps even to exist today within a

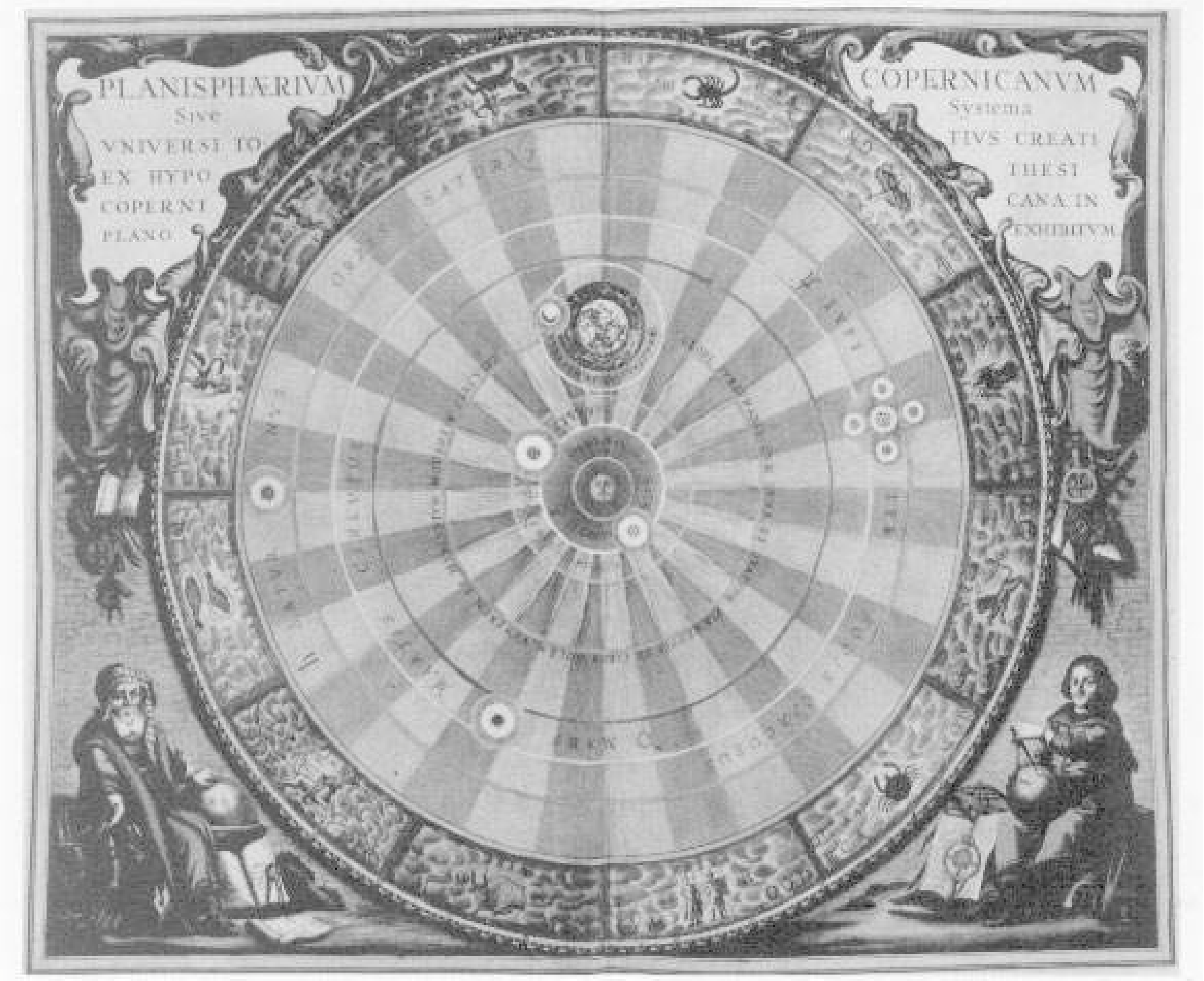
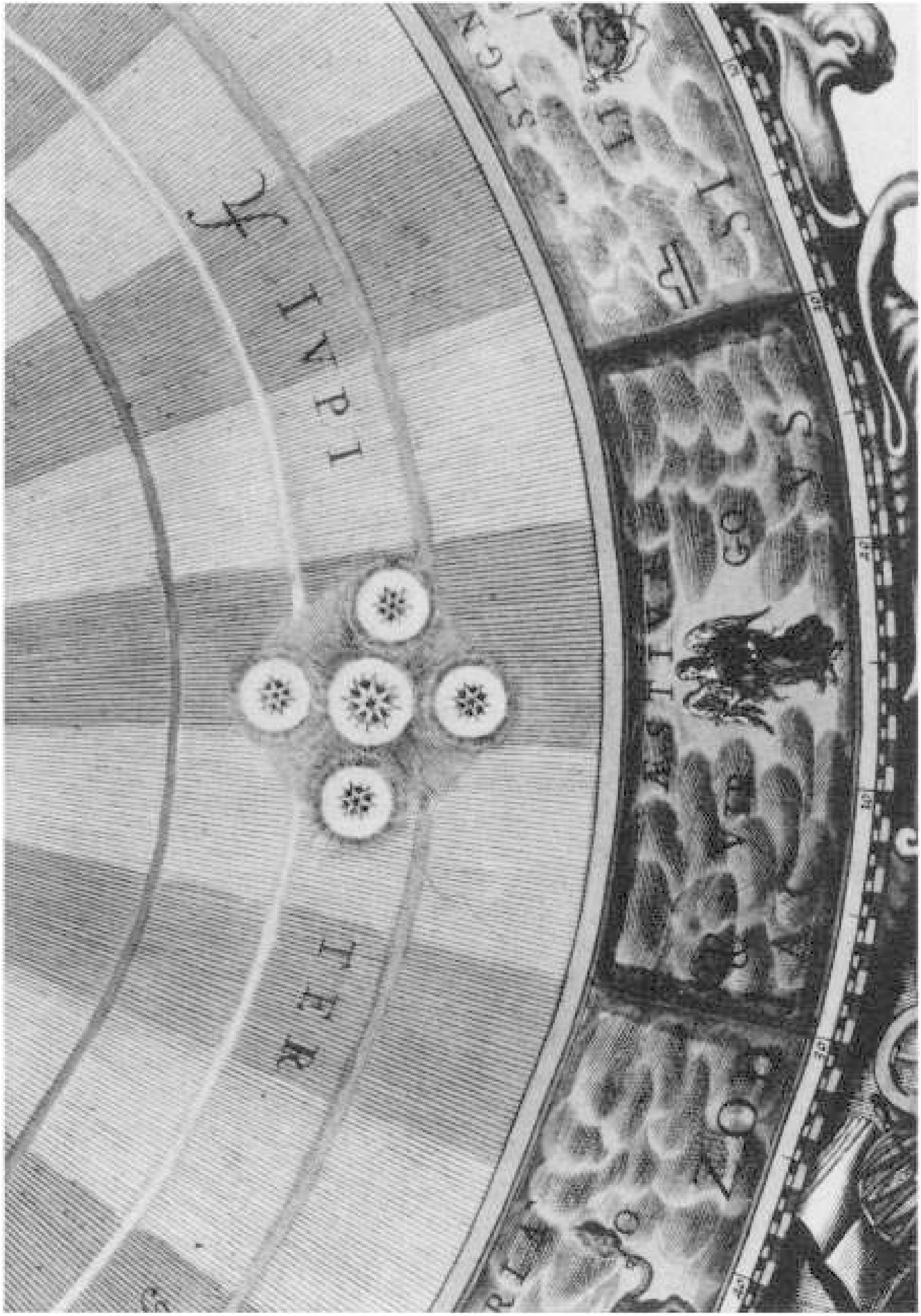


FIGURE 1.1 The heliocentric system of Copernicus, depicted in this mid-17th-century copper-plate engraving, included the recently discovered moons of Jupiter. Galileo's "Medicean stars" encircling Jupiter are today called the Galilean satellites, Io, Europa, Ganymede, and Callisto. (From *Atlas Coelestis seu Harmonia Macrocosmica* of Andreas Cellarius, 1660-1661 edition, Amsterdam; 25″ × 28 5/8″. Courtesy of the Mendillo Collection.)

FIGURE 1.2 *facing page* Detail from the *Planisphaerium Copernicanum* copper plate in a mid-17th-century celestial atlas summarizing the state of astronomy. In this elegant depiction of the heliocentric theory, Galileo's discovery (1610) shows Jupiter orbiting the Sun to be itself "a center of motion." The four Galilean moons are shown as star-like objects, equidistant from Jupiter. It would be 300 years before these "Medicean stars" would be shown to be the individual worlds of Io, Europa, Ganymede, and Callisto. (From *Atlas Coelestis seu Harmonia Macrocosmica* of Andreas Cellarius, 1660-1661 edition, Amsterdam. Courtesy of the Mendillo Collection.)


IVPITER

Box 1.1
About Europa

Europa was discovered by Galileo in 1610, along with the three other large satellites of Jupiter—Io, Ganymede, and Callisto. The four are now collectively called the Galilean satellites. Europa travels around Jupiter at an orbital distance of about 9.5 times the radius of Jupiter (9.5 R_J, or 670,900 km), which puts it deep within the strong jovian magnetic field and its associated radiation belts. With a radius of 1565 kilometers, Europa is 90% the radius of Earth's Moon. Its surface gravity is only some 13% that of Earth, and it has an escape velocity of about 2 km/s.

Europa's surface is highly reflective, and characteristic absorptions at certain wavelengths in the reflected sunlight, measured using ground-based telescopes beginning in the 1950s, indicate the presence of water ice. However, the mean density of Europa, about 3000 kg m^{-3}, is substantially higher than that of ice (about 1000 kg m^{-3}) and is lower than that of rock (about 3400 kg m^{-3}, including the compression that occurs deep inside Europa's interior), implying that Europa consists of a mixture of water and rocky material.*

The Voyager spacecraft showed the surface to be relatively free of impact craters, suggesting that Europa's surface is younger than the surfaces of Ganymede and Callisto. In addition, Voyager data revealed that ice tectonics shapes Europa's surface geology and raised the possibility that liquid water might exist beneath its icy surface. In 1994, observations made by the Hubble Space Telescope revealed the presence of a tenuous oxygen-bearing atmosphere, probably formed as a result of the impact of energetic particles trapped by Jupiter's magnetic field onto the icy surface.

Since 1995 when the Galileo spacecraft began its mission in the jovian system, significant new discoveries about the properties of Europa's interior, surface, and atmosphere have been made. Galileo's images revealed the existence of ice blocks on the surface that appear to have drifted like icebergs from their original positions. Moreover, Galileo's magnetic and gravitational measurements provided additional indications, but not conclusive proof, of the likely presence of liquid water beneath a relatively thin layer of surface ice.**

While the results from telescopic observations, theoretical studies, and data from Voyager indicated that Europa was a fascinating body for additional study, it was the results from Galileo that raised the serious possibility that Europa is a potential abode of life.

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*For more general information about Europa, see, for example, R. Greeley, "Europa," *The New Solar System,* fourth edition, J.K. Beatty, C.C. Petersen, and A. Chaikin (eds.), Sky Publishing Corp., Cambridge, MA, 1999, page 253.

**For a more complete general review, see, for example, R.T. Pappalardo, J.W. Head, and R. Greeley, "The Hidden Ocean of Europa," *Scientific American* 281(4): 54, 1999.

subsurface ocean.[5] Although multiple forms of metabolism are possible, it is likely that europan life forms, should they exist, would probably utilize chemical energy rather than photosynthesis to support metabolism. Thus, they might resemble terrestrial organisms found in environments that are considered hostile by human standards, such as hot springs and deep-sea thermal vents; these terrestrial organisms are often called "extremophiles." Certainly, a search for evidence of a liquid ocean and for the extent to which either prebiotic chemical activity or biological activity has progressed on Europa is warranted based on the currently available data, and the information obtained from such a search may help us to understand the chemical, prebiological, and biological evolution of our solar system.

In addition to the search for liquid water and the potential for the existence of either present or past life, the occurrence of relatively recent geologic processes on Europa makes it an appropriate and high-priority target for detailed exploration. Evidence for resurfacing and ice tectonics, dynamic interactions between the surface, atmosphere, and magnetosphere, and the possible presence of liquid water (even without life) make Europa a fascinating object and a suitable place to examine chemical and physical processes that may have preceded the emergence of living organisms.[6] These characteristics cause Europa to stand out as being important to understanding the jovian system and, in fact, the solar system as a whole, and to require further exploration after the completion of the Galileo mission. Indeed, NASA's current strategy for solar system exploration calls for the launch of the Europa Orbiter mission in the early part of the next decade (see Box 1.2). And such a mission received a new start as part of the "origins" initiative in the agency's FY 1998 budget. Since NASA has not yet selected an instrument complement for this spacecraft, it is not possible at this time for COMPLEX to comment on the degree to which NASA's proposed mission will address the scientific goals outlined in the remainder of this report.

Box 1.2
NASA's Europa Orbiter Mission

As part of its Outer-Planets/Solar-Probe project, NASA has begun development of the Europa Orbiter mission. The spacecraft, tentatively scheduled for launch in 2003, is currently under development. The Europa Orbiter Science Definition Team has already released its recommendations regarding the mission's scientific objectives and suggested instruments that can achieve these objectives.*

According to the Science Definition Team, the primary science objectives of the Europa Orbiter should be the following:

- "Determine the presence or absence of a subsurface ocean";
- "Characterize the three-dimensional distribution of any subsurface liquid water and its overlying ice layers"; and
- "Understand the formation of surface features, including sites of recent or current activity, and identify candidate sites for future lander missions."

The Science Definition Team's secondary science objectives are the following:

- "Characterize the surface composition, especially compounds of interest to prebiotic chemistry";
- "Map the distribution of important constituents on the surface"; and
- "Characterize the radiation environment in order to reduce uncertainties for future missions, especially landers."

The Science Definition Team suggested a set of observations that would likely satisfy the primary scientific objectives of the Europa Orbiter mission. These measurements included the following:

- Doppler tracking of the spacecraft to measure Europa's gravitational field with sufficient precision to determine the k_2 gravitational Love number to ±0.01;
- Laser altimetry to measure Europa's shape with sufficient precision to determine the h_2 tidal-height Love number to ±0.02;
- Probing Europa's surface shell with an ice-penetrating radar designed to maximize the likelihood of detection of an ice-liquid interface. The radar should have a globally distributed coverage, a depth resolution of 100 m at the surface and decreasing with depth, and a spatial resolution of the scale of major surface features or better; and

continued

Box 1.2 Continued

- Imaging Europa in at least two colors to produce a global map with a resolution of better than 300 m/pixel, and sampling all feature types at a resolution better than or equal to about 10 m/pixel.

The Science Definition Team suggested that the radar and Doppler-tracking experiments should be facility instruments (i.e., provided by the mission) and that the others be selected through open competition. NASA issued a single Announcement of Opportunity in September 1999, soliciting scientific investigations for the Europa Orbiter, Pluto/Kuiper Express, and Solar Probe missions.

According to current plans, the Europa Orbiter would have a total mass of some 900 kg, including 20 kg of scientific payload and more than 500 kg of fuel for its orbital maneuvering engine. The spacecraft would be powered by a new-generation, radioisotope power source. The Europa Orbiter is tentatively scheduled for launch aboard the space shuttle in November 2003 and will follow a direct trajectory to Jupiter. Following entry into orbit about Jupiter in February 2007, the mission will follow three distinct operational phases. The Science Definition Team dubbed these the satellite tour, the end game, and the Europa orbit. These phases encompass the following activities:

- ***Satellite tour.*** A Galileo-like ballistic cruise, lasting approximately 2 years, that utilizes multiple flybys of the Galilean satellites to circularize the spacecraft's initial, highly elliptical, orbit about Jupiter. Limited science operations will probably be conducted during this part of the mission, but their scope and extent have not yet been determined.
- ***End game.*** The final series of maneuvers, lasting approximately 3 to 4 months, designed to modify the spacecraft's trajectory so that it can be captured into a polar orbit about Europa.
- ***Europa orbit.*** The orbiter would conduct its observations of Europa from a precessing, circular polar orbit with an altitude of some 200 km and an orbital period of approximately 1.6 hours. The duration of this phase of the mission is limited by the total radiation dose the spacecraft can survive. With the spacecraft hardened to survive a radiation dose of 4 megarads (by comparison, Galileo was hardened to survive 150 kilorads), its expected orbital lifetime is approximately 1 month. Numerical simulations suggest that a spacecraft with an orbital inclination greater than some 45 degrees will impact Europa within a few months of its demise. Although the Europa Orbiter's expected lifetime is short, it is believed to be adequate to address the primary scientific objectives specified by the Science Definition Team.

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*C.F. Chyba, "Report of the Europa Orbiter Science Definition Team," letter to Dr. J. Bergstrahl, NASA Headquarters, May 18, 1998.

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4. For a review of current understanding of Europa and the other galilean satellites, see, for example, A.P. Showman and R. Malhotra, "The Galilean Satellites," *Science* 286: 77, 1999.
5. Space Studies Board, National Research Council*, An Integrated Strategy for the Planetary Sciences: 1995-2010*, National Academy Press, Washington, D.C., 1994, page 60.
6. Space Studies Board, National Research Council*, An Integrated Strategy for the Planetary Sciences: 1995-2010*, National Academy Press, Washington, D.C., 1994, page 61.

2

Current State of Knowledge About Europa

Before outlining the major outstanding scientific issues and questions regarding Europa, COMPLEX in this chapter summarizes the current state of knowledge about Europa. This summary, which includes discussion of the reasons for thinking that Europa has the potential for both liquid water and biological activity, focuses on the geology and composition of the surface, the structure and composition of the deep interior, the likelihood of a liquid-water mantle, the properties of Europa's tenuous atmosphere, and the possibility of conditions favorable for life. The final section of this chapter summarizes the outstanding scientific questions about Europa.

GEOLOGY AND COMPOSITION OF THE SURFACE

Europa displays a complex and diverse surface history involving disruption of its icy crust by fracturing, impact cratering on a wide range of scales, and possible eruptions of materials onto the surface from the interior. Although suggestions of these processes were provided by the Voyager spacecraft in the late 1970s and early 1980s,[1,2] image resolution was only about 2 km/pixel at best and was usually substantially poorer.

The Galileo spacecraft entered orbit around Jupiter in 1995 and has performed repeated flybys of Europa, returning images with resolutions as high as 6 m/pixel. (Table 2.1 summarizes Galileo's instrumentation.) Coupled with other remote-sensing data and measurements that provide insight into the interior, the Galileo mission has revealed that Europa is a remarkable object.

Early indications of Europa's geologic characteristics were derived from Earth-based telescopic observations indicating that the surface is predominantly water ice.[3–5] Determination of its density suggested that Europa is a rocky object, but with a substantial volume of ice. Theoretical studies have suggested that Europa, like its neighbor Io, experiences interior heating from tidal stresses. These ideas, coupled with the limited Voyager imaging data, contributed to making Europa a primary target for exploration by Galileo in both the prime mission and the extended phase, the Galileo Europa Mission (GEM; Box 2.1), which undertook a general global reconnaissance of Europa's geology, composition, and magnetic environment.

Geology

Recent measurements from the Galileo imaging experiment have had a dramatic impact on our understanding of Europa. As its average density, strong infrared signature of surface water ice, and moment of inertia (see below)

TABLE 2.1 Galileo Science Instruments and Investigators

	Instrument	Description	Investigator/ Team Leader	Objectives
Remote Sensing (Despun)	*SSI* Solid-State Imaging camera	A 150-cm focal length narrow-angle telescope (inherited from Voyager), with an image sensor, filter wheel, focal plane shutter, and electronics	Michael Belton, National Optical Astronomy Observatories	Geology of Galilean satellites; atmospheric motions and structures of small-scale clouds
	NIMS Near-Infrared Mapping Spectrometer	A 22.8-cm diameter (f/3.5), 80-cm focal length, Ritchey-Chretien telescope with a spatial scanning secondary mirror and diffraction grating spectrometer	Robert Carlson, Jet Propulsion Laboratory	Surface/atmospheric reflection/emission
	PPR Photo-polarimeter Radiometer	A Cassegrainian Dall-Kirkham telescope with a 10-cm aperture, a 50-cm focal length, and a 2.5-milliradian instantaneous field of view	James Hansen, Goddard Institute for Space Studies	Atmospheric particles, thermal/reflected radiation
	UVS/EUV (spinning) Ultraviolet Spectrometer	The UVS is a Cassegrainian Dall-Kirkham telescope with a 5.03 × 5.28-cm aperture and a 25.0-cm focal length. The telescope is the front end to a standard 12.5-cm focal length Ebert-Fastie scanning spectrometer.	Charles Hord, University of Colorado	Atmospheric gases, aerosols, etc.
	and		and	
	Extreme Ultraviolet Spectrometer	The EUV is an objective grating spectrometer with a mechanical collimator; it is a modified Voyager spare ultraviolet spectrometer with an electrical interface to adapt it to the Galileo command and data bus.	A. Ian F. Stewart, University of Colorado	
Fields and Particles (Spinning)	*MAG* Magnetometer	An electronics box and two sets of ring core triaxial fluxgate sensors	Margaret Kivelson, UCLA	Strength and fluctuations of magnetic fields
	EPD Energetic Particles Detector	Divided into two systems: the Low-Energy Magnetospheric Measurements System (LEMMS) and the Composition Measurements System (CMS), both contained in one package, with bi-directional, solid-state detector telescopes mounted on a platform that rotates via a stepper motor to eight positions	Donald Williams, Johns Hopkins University Applied Physics Laboratory	Electrons, protons, heavy ions
	PLS Plasma Subsystem	A concentric set of four spherical-plate electrostatic analyzers and three miniature magnetic mass spectrometers	Louis Frank, University of Iowa	Composition, energy, distribution of ions

continued

TABLE 2.1 Continued

	Instrument	Description	Investigator/ Team Leader	Objectives
Fields and Particles (Spinning)	*PWS* Plasma Wave Subsystem	One 6.6-m tip-to-tip electric dipole antenna (mounted on the end of the 10.6-m magnetometer boom) and two search coil magnetic antennas (mounted on the high-gain antenna feed)	Donald Gurnett, University of Iowa	Electromagnetic waves and wave particle interactions
	DDS Dust Detector Subsystem	An impact ionization detector and an electronics box containing signal conditioning and spacecraft interface electronics	Eberhard Grun, Max Planck Institut fur Kernphysik	Mass, velocity, charge of submicron particles
Engineering Experiment	*HIC* Heavy Ion Counter	Two solid-state detector telescopes called the Low-Energy Telescopes (LET B and LET E)	Edward Stone, California Institute of Technology	Spacecraft charged-particle environment
Radio Science	Celestial Mechanics	The team sampled the downlink in a frequency bandwidth of 2500 Hz at a rate of 5000 samples per second. For satellite occultations the spacecraft downlink is in the residual carrier (i.e., non-suppressed) mode and referenced to the on-board Ultra Stable Oscillator (USO). The Radio Science Digital Signal Processor (DSP-R) is also required for these experiments.	John Anderson, Jet Propulsion Laboratory	Masses and internal structure of bodies from spacecraft tracking
	Propagation		H. Taylor Howard, Stanford University	Jupiter/satellite radii and atmospheric structure from radio propagation

attest, Europa clearly has differentiated. It has a fairly pure ice crust estimated to be some 80 to 170 km thick and a denser deep interior. Within the interior, theoretical models suggest that dissipation of tidal energy may lead to melting of the water ice at relatively shallow depths and the presence of a global ocean.[6] The very small number of impact craters observed (Figure 2.1) indicates that Europa's surface must be fairly young by geologic standards.

The Galileo mission has provided substantial indications either that there is a liquid-water ocean on Europa or, at a minimum, that a soft, ductile layer has underlain the ice crust quite near the surface at some relatively recently time. Most spectacularly, disruption of the surface in some of the so-called "mottled" terrain clearly shows that small blocks (sizes near 5 km) have become detached from adjacent "ice sheets" and have been translated and rotated to new positions (Figure 2.2). These high-resolution images provide the best evidence that the ice crust of Europa was thin at the time that the disruption took place.[7] New varieties of pits, domes, and spots observed in the mottled terrain are consistent with the occurrence of solid-state convection near the surface and are interpreted as the surface expression of upwelling masses of warm ice or diapirs.[8]

The age and orientation of varying large-scale linear features seen in global images of Europa change systematically, as would be expected if the surface ice were decoupled from the interior by a liquid or ductile layer.

Box 2.1
Galileo Europa Mission (GEM)

Description

Galileo was originally scheduled to end its exploration of the jovian system on December 7, 1997, but NASA and Congress approved the extension of the mission through the last day of 1999. The Galileo Europa Mission (GEM), as it is called, was designed as both a streamlined, low-cost extension to Galileo's exploration of the jovian system and as a precursor to future missions to Europa and Io. GEM encompasses 14 orbits of Galileo around Jupiter and is divided into three phases, each with its own tightly focused objectives: the Europa, Perijove Reduction, and Io campaigns.

Mission Phases and Major Science Objectives

Europa Campaign—A 1-year intensive study of Europa comprising eight consecutive close encounters. Europa's crust, atmosphere, and possible subsurface ocean are studied using imaging, gravity, and space physics data gathered by Galileo's full complement of remote-sensing and in situ instruments. The design of this phase of GEM allows for a number of unique imaging opportunities. These include high-resolution imaging and spectral observations (<50 m/pixel for images) and stereo imaging of selected topographic features and views of Europa's polar regions.

Careful tracking of Galileo during this phase of GEM yielded geophysical information, such as Europa's moment of inertia, that will allow refinement of knowledge on the interior configuration of the satellite. Magnetospheric data obtained during close flybys and other periods chosen to provide maximum spatial coverage will help to further refine understanding of Europa's ionosphere and possible internally produced magnetic fields, and the satellite's interaction with the jovian plasma disk.

Although data were not collected during one encounter (E-13) because it occurred during solar conjunction, additional observations of Europa are planned for the final scheduled orbit (I-25) of the Io Campaign.

Perijove Reduction Campaign—A series of four encounters with Callisto designed to modify Galileo's orbit sufficiently to enable close flybys of Io. In addition to observations of Callisto, a major focus of this phase of GEM is observation to characterize the Io plasma torus, including studies of satellite/magnetosphere interactions.

Io Campaign—Close flyby of Io in October 1999 with the possibility of a second flyby 6 weeks later. The scientific focus of these flybys is high-resolution imaging as well as in situ observations of Io's volcanic processes, atmosphere, and magnetospheric environment.

Such decoupling leads to non-synchronous rotation of the surface ice shell with respect to the interior and appears to be expressed in stress fractures of the surface as the shell changes shape.[9] The non-synchronous rotation may arise because the balance between the torque exerted by Jupiter, tending to speed up Europa, and a resisting torque, associated with a slight departure of Europa's minimum-moment-of-inertia axis from the Jupiter line, cannot be permanently maintained if the material of the satellite can adjust in some way to bring the minimum-moment-of-inertia axis back into alignment with Jupiter. This may be the case on Europa if the ice shell is decoupled from the underlying rock. If so, the rate of non-synchronous rotation depends on the viscosity of the ice, which determines the readjustment time of the shell. The absence of any perceptible offsets in the positions of features imaged by both Voyager and Galileo implies that the current non-synchronous rotation period must be in excess of 10,000 years.[10]

Mission Characteristics

	Closest Flyby	Closest Approach Height	Best Resolution of Images	Best Resolution of Composition or Temperature Maps
Europa	Dec. 16, 1997	200 km	6 m	~ 10 km
Jupiter	Sept. 14, 1999	467,000 km	10 km	~500 km
Io	Nov. 26, 1999	300 km	6 m	~ 20 km

GEM Tour Summary

Body	Orbit Name	Date	Altitude
Europa	E-12	Dec. 16, 1997	200 km
Europa	E-13	Feb. 10, 1998	3562 km
Europa	E-14	Mar. 29, 1998	1649 km
Europa	E-15	May 31, 1998	2521 km
Europa	E-16	July 21, 1998	1837 km
Europa	E-17	Sept. 26, 1998	3582 km
Europa	E-18	Nov. 22, 1998	2281 km
Europa	E-19	Feb. 1, 1999	1495 km
Callisto	C-20	May 5, 1999	1311 km
Callisto	C-21	June 30, 1999	1047 km
Callisto	C-22	Aug. 14, 1999	2296 km
Callisto	C-23	Sept. 16, 1999	1057 km
Io	I-24	Oct. 11, 1999	612 km
Io	I-25	Nov. 26, 1999	300 km

Smaller-scale surface features, such as the arcuate lineaments known as cycloidal features, provide additional reason to believe that the surface-ice shell is relatively thin. These features, first spotted in Voyager images, consist of chains of arch-shaped segments, each some 100 km in length. Their distinctive shapes have been accurately reproduced by modeling the migration of tidal stresses across Europa's surface.[11] In this interpretation, each cycloidal segment marks the surface expression of the changing orientation of tidal stresses during the course of a single europan day. However, this model only works if the amplitude of the diurnal tides is some tens of meters, the value predicted for a relatively thin ice shell decoupled from the satellite's interior by a liquid layer.

The higher-resolution Galileo images have revealed many additional small impact craters. Although varying interpretations of cratering statistics and surface age dating leave the absolute age of the europan surface uncertain, current analysis suggests that the surface is quite young (10 million to 50 million years old) and therefore that these

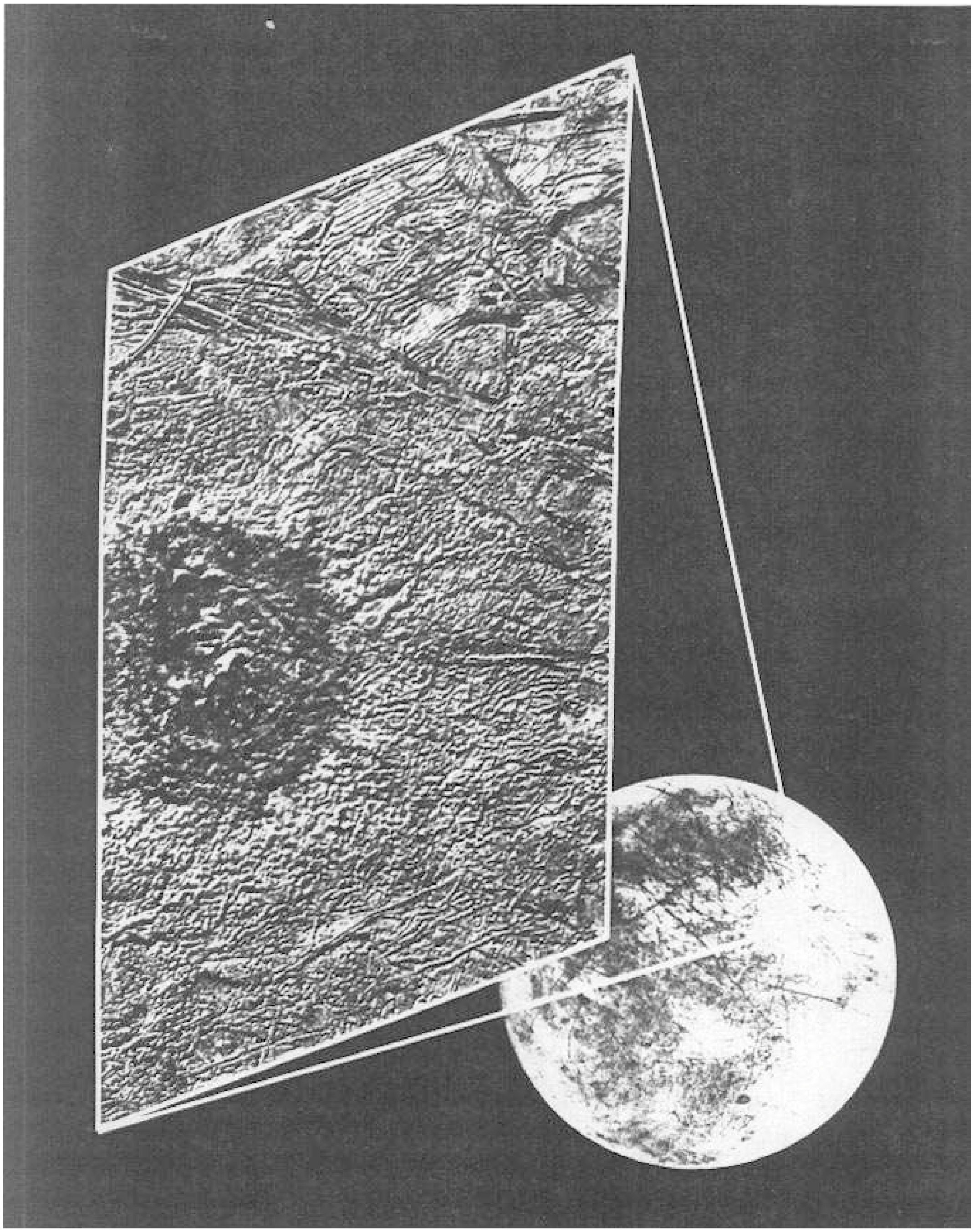

FIGURE 2.1 Although Europa's surface is remarkably free of craters, it does exhibit some large impact features. This composite of two Galileo images shows the area surrounding the 26-km-diameter crater Pwyll. The bright rays radiating from Pwyll in the global image indicate that this crater is geologically young. The close-up image reveals that, unlike most fresh impact craters that have deep floors, Pwyll's crater floor is at approximately the same level as the surrounding terrain. North is to the left, and the Sun illuminates the close-up image from the upper left. Pwyll is located at approximately 26 degrees south and 271 degrees west, and the close-up image covers an area some 125 by 75 km. The resolution of the close-up image is about 250 m/pixel. Images courtesy of the Jet Propulsion Laboratory.

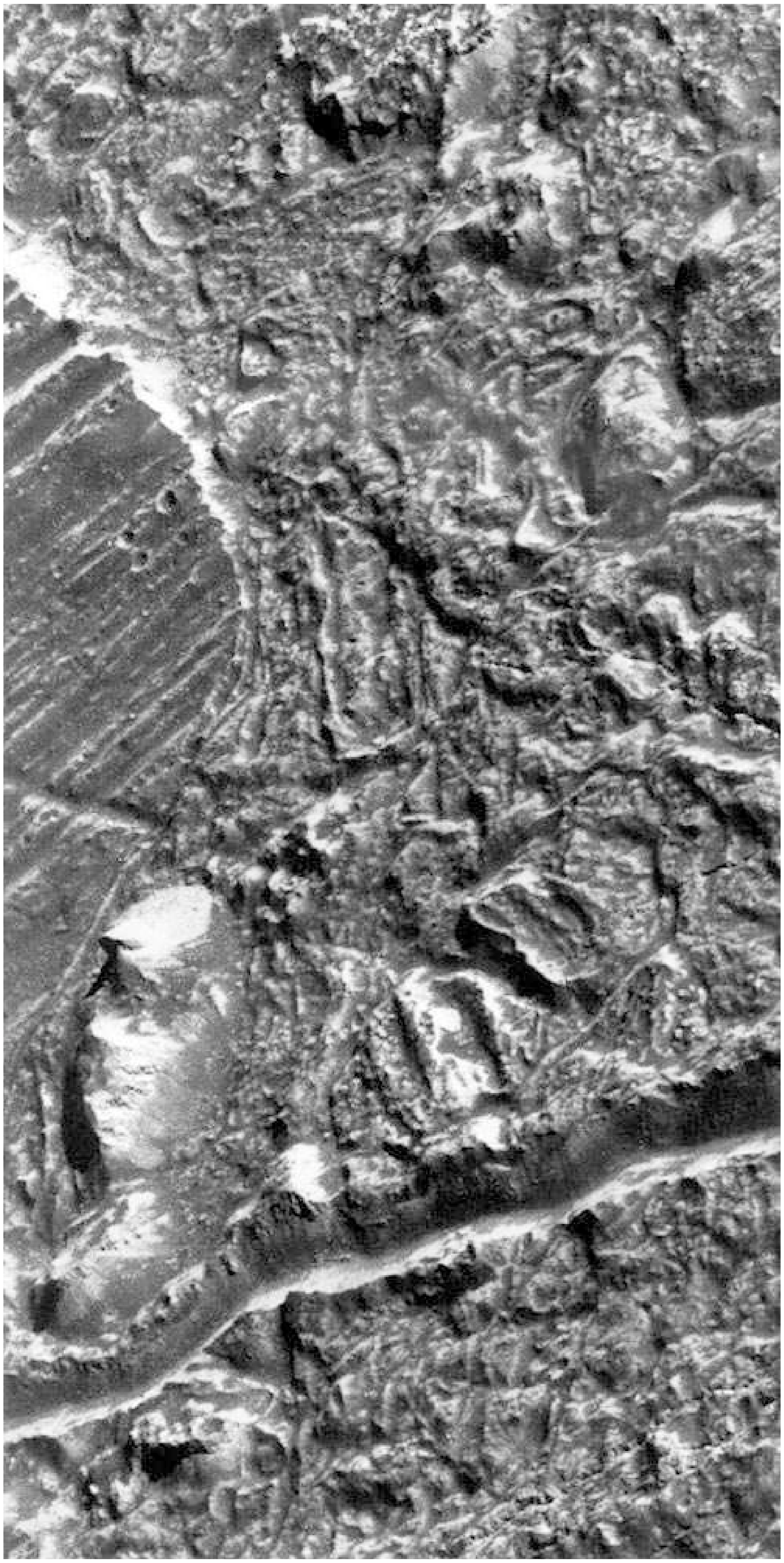

FIGURE 2.2 This view of the Conamara Chaos region of Europa shows an area where the icy surface has been broken into many separate plates that have moved laterally and rotated with respect to each other. North is to the top left of this image, and the Sun illuminates the surface from the east. This image, centered at approximately 8 degrees north and 274 degrees west, covers an area approximately 4 by 7 km. The resolution is 9 m/pixel. Image courtesy of the Jet Propulsion Laboratory.

resurfacing and crustal disruption events have occurred relatively recently. The young geologic age of this mobile surface leaves the potential for a liquid or ductile layer to exist near the surface of Europa to the present day.

Galileo observations reveal that the mid-latitude plains units can be distinguished based on their visible and near-infrared spectral properties, with differences attributed to varying grain sizes of water ice. Numerous new varieties of linear features have also been recognized. These features include triple bands that either "pinch out" or emerge from simple bands that can be either bright or dark; some bands become discontinuous, a string of dark or light pearls. New topographic features have been identified, such as the complex ridge structures of triple bands (Figure 2.3), usually with a central groove, and a few low-relief mountains and plateaus. Finally, features suggesting resurfacing from flows or material extruded onto the surface are seen in Galileo's images. The bilateral symmetry in wedge-shaped bands suggests that upwelling material emerges along a central zone as crustal blocks move apart, similar to terrestrial seafloor spreading.[12]

Surface Composition

Knowledge of the composition of Europa's visible surface comes primarily from ultraviolet, visible, and near-infrared reflectance spectra. These have been obtained by ground-based telescopes, the International Ultraviolet Explorer, and the Hubble Space Telescope in orbit around Earth, the Voyager flyby spacecraft, and, most recently, the Galileo spacecraft as it orbits Jupiter. From the early studies,[13–15] we know that water ice is the most abundant material on the surface of Europa and that the ice at the very surface has a fluffy, or porous, texture.[16] The surface of the leading hemisphere of Europa is brighter than that of the trailing hemisphere, presumably because the trailing hemisphere receives more impacts by charged particles from the jovian magnetosphere than does the leading side. Frozen sulfur dioxide (SO_2 frost) has been observed, especially on the trailing hemisphere where bombardment by the plasma is strongest;[17,18] the source of this sulfur appears to be volcanic eruptions and sputtering from Io. Some spectroscopic features are thought to be produced by elemental sulfur.[19]

The two spectrometers and a color camera carried by the Galileo spacecraft have increased our knowledge of the surface composition (see Table 2.1). Initial results from the Ultraviolet Spectrometer (UVS) confirmed the leading/trailing asymmetry of the ultraviolet albedo and the SO_2 frost absorption on the trailing hemisphere.[20] The Solid-State Imager (SSI) has distinguished water-ice grain size differences among plains units on Europa. Cross-cutting relationships among the linear features show that the youngest areas are dark and that they lighten with exposure to the space environment. This has been interpreted as indicative of weathering of sulfur to SO_2 frost or that solid, clear ice (such as that seen in frozen lakes) is being damaged by radiation and broken down into finer, brighter particles.

The data from Galileo's Near-Infrared Mapping Spectrometer (NIMS) show that Europa's water-ice absorption features are distorted in comparison with those seen in pure ice. This is true even in the brightest regions that were inferred to be nearly free of "contaminants." While this has commonly been interpreted as implying a contribution from hydrated minerals such as evaporite salts or clays in all regions of the satellite, it has been shown that light reflected from fairly clear ice with entrained bubbles or defects also exhibits band shifts similar to those observed on Europa. Many of Europa's dark regions exhibit spectral characteristics that appear distinct from those of water ice, and these have been interpreted as being consistent with the spectral characteristics of water-bearing salts such as hexahedrite ($MgSO_4 \bullet 6H_2O$), epsomite ($MgSO_4 \bullet 7H_2O$), and natron ($Na_2CO_3 \bullet 10H_2O$). It is not yet known how plasma-bombardment damage may affect the near-infrared absorption features of water ice. However, the detection of H_2O_2 by NIMS suggests that Europa's surface chemistry is dominated by radiolysis.[21]

At the spatial scales observed by NIMS (typically 10 to 20 km/pixel), it is likely that water ice of varying textures and clarity, and the presence of minerals, contribute to the observed spectral features. This view has, however, recently been challenged by an alternative interpretation based upon a radiolytic cycling of sulfur between sulfuric acid, sulfur dioxide, and sulfur polymers.[22] In this model, the dark features are radiolytically altered sulfur polymers and, if correct, indicate that sulfuric acid may play an important role in Europa's geologic activity. Other possible surface constituents such as ammonia and carbon dioxide ice have been searched for but have not yet been detected.[23]

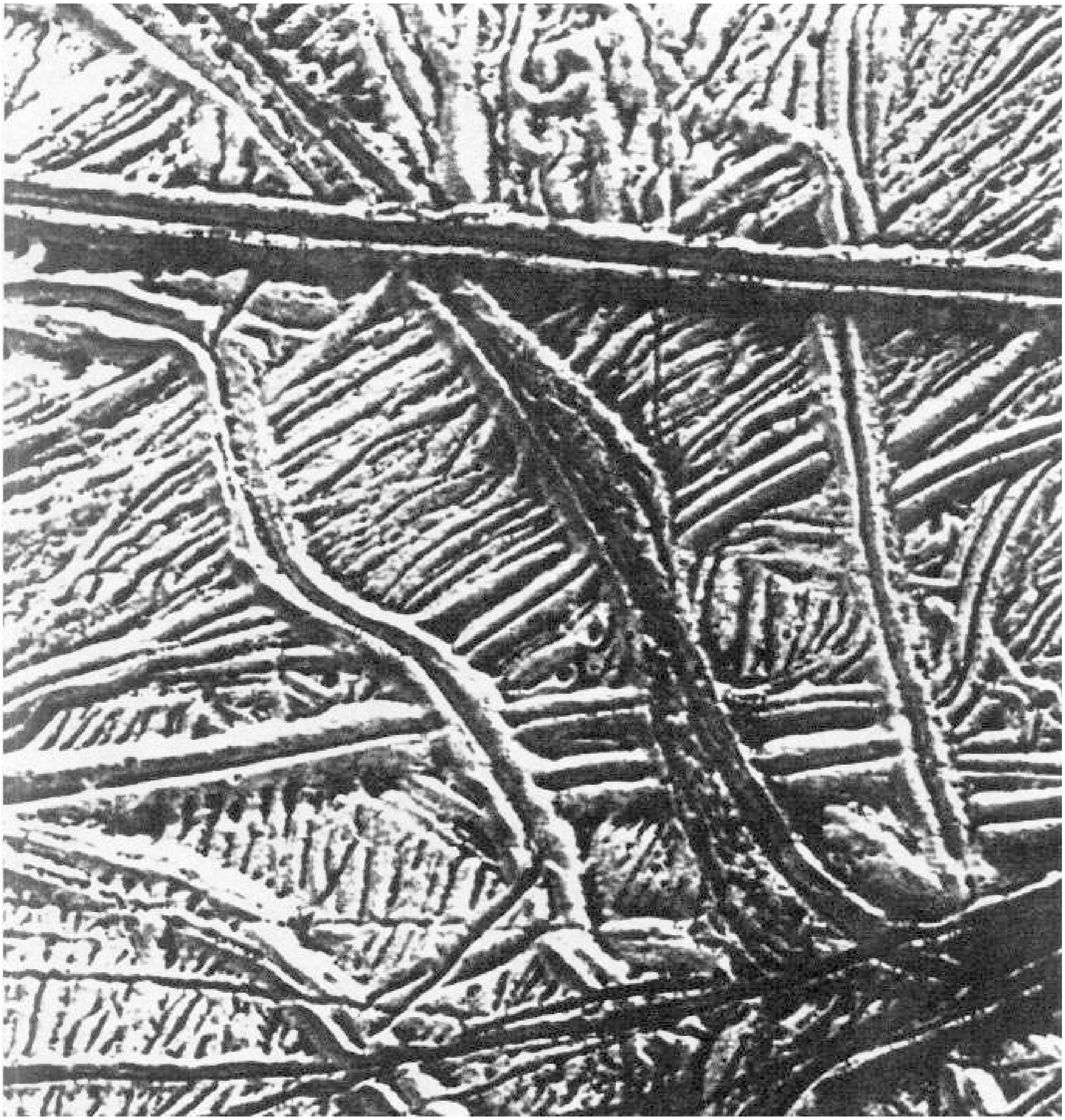

FIGURE 2.3 The complexity of the ridged plains on Europa is demonstrated by this Galileo image of several cross-cutting triple bands. Much of this surface is very bright, with the darker material concentrated primarily in the valleys between the ridges. Indeed, the most prominent ridges have dark deposits along their margins and in their central valleys, suggesting that the dark material may have moved down the flanks of the ridges and piled up along their bases. North is to the right, and the Sun illuminates the surface from the upper right. This image, centered at approximately 14 degrees south and 194 degrees west, covers an area approximately 20 km across. The resolution is 26 m/pixel. Image courtesy of the Jet Propulsion Laboratory.

STRUCTURE AND COMPOSITION OF THE DEEP INTERIOR

Prior to the Galileo mission there were two competing models for the internal structure of Europa.[24] In one model, Europa consisted of an anhydrous rocky core with a density like that of Io or the Moon, surrounded by a layer of water ice or liquid water that could be more than 100 km thick. In the other model, most of the water in Europa was retained in a hydrated silicate interior surrounded by a thin water-ice layer. The possibility that Europa might have a differentiated metallic core was not considered. Instead, debate centered on the extent to which Europa's interior was dehydrated and, in the fully dehydrated model, whether the outer water layer was completely frozen or had a melted liquid layer beneath an outer solid layer of ice.

Today, as a consequence of the Galileo measurements of Europa's gravitational field, the model of Europa with a thin ice shell above a largely hydrated silicate interior is no longer tenable. Moreover, the density of Europa's deep interior is high enough that it argues strongly for a metallic core at the center of the satellite. Unfortunately, we still do not know with certainty whether there is a liquid-water ocean beneath Europa's icy surface. Neither do we know if the metallic core is solid or liquid.

The gravitational field of Europa has been measured in four flybys of the satellite by the Galileo spacecraft.[25,26] The measurements have yielded quite accurate determinations of the degree-two spherical harmonic contributions to Europa's gravity. On the assumption that the shape of Europa's gravitational field results from a physical distortion caused by its spin and by the tidal forces it experiences as it orbits around Jupiter in synchronous rotation, the gravitational field can be used to infer Europa's axial moment of inertia C and tell us about the distribution of mass in Europa's interior. Normalized to MR^2 (M is the mass of Europa and R is its radius), the moment of inertia is $C/MR^2 = 0.346 \pm 0.005$.[27] This value of C/MR^2 is substantially less than 0.4, the value for a uniform-density sphere, and requires that the density of the interior increase toward the center of Europa.

The implications of Europa's mean density and moment of inertia for the structure of its interior have been explored in terms of simple two- and three-layer models of the satellite.[28] Two-layer models of Europa with an ice outer shell and a uniform silicate/metal inner region are possible, but only if the interior density is greater than about 3800 kg m^{-3}. This structure is considered implausible because the interior density would be higher than Io's mean density, and because it is likely that radiogenic heating in such an interior would cause a metallic core to differentiate.[29] Therefore, Europa must have a three-layer structure with an Fe or Fe-FeS core at its center, a rock mantle surrounding the metallic core, and a water-ice or liquid-water shell around the rock. The size of the core is between 40 and 50% of Europa's radius, depending on its composition. The thickness of the outer shell of water must lie in the range of about 80 to 170 km, with a value of some 100 km being the most likely.[30] The gravity data do not allow any conclusion regarding the physical state (i.e., liquid or solid) of either Europa's metallic core or its outer water shell. Lack of detection of a europan magnetic field also precludes any unique inference about the physical state of Europa's metallic core.[31]

EVIDENCE FOR THE PRESENCE OF A LIQUID-WATER MANTLE

Thermal models of Europa provide additional insight into the possibility that a liquid-water ocean may exist under Europa's surface ice.[32] Modeling suggests that accretional and radiogenic heat sources are large enough to have dehydrated Europa early in its evolution, leaving the satellite covered with a layer of liquid water 100 km or more thick. Early models, which considered only the conductive cooling and freezing with time of the outer layer of water,[33] resulted in the presence today of liquid water beneath the ice shell. However, other models showed that the outer layer of ice would become unstable to convection with sufficient thickening, thereby promoting heat transfer through the ice and the cooling and solidification of the underlying water.[34] These models predicted the complete freezing of the outer layer of water in a small fraction of geologic time. However, the predicted freezing of Europa's ocean by efficient subsolidus convection (i.e., the slow deformation and flow of a material below its melting temperature in response to a source of heat) assumed only radiogenic heating in Europa's silicate interior. Other models included the additional heating produced by tidal dissipation in the ice shell and indicated that this heat source could offset the subsolidus convective cooling of the ice and prevent complete solidification of the water ocean.[35] Basically, a steady state could be achieved in which the balance between the dissipative heat source and the convective cooling would leave the ice layer with a constant thickness. Modifications to the latter model resulted in a reduction in the estimated amount of tidal heating, again opening the question of whether the water layer on Europa would freeze completely over geologic time.[36] Various other thermal models have been constructed, including those that took into account the effects of an insulating regolith on the stability of the ice shell.[37]

The competition between the tendency of tidal heating to maintain a liquid-water ocean and that of subsolidus ice convection to freeze the ocean has now been analyzed for nearly two decades without a definitive conclusion having been reached. The major uncertainty in the modeling is the uncertain rheology of ice and of its control of both convection and dissipation.[38] Both dissipative heating and convective cooling involve nonlinear feedback mechanisms associated with the dependence of rheology on temperature and the dependence of temperature on the heating and cooling mechanisms. The amount of tidal heating in the ice depends on the rheology of the ice at tidal periods and on the magnitude of tidal deformation, the latter in turn depending on the internal structure and, in particular, on whether there is a liquid ocean beneath the ice layer and on the ice thickness.

Other properties of the ice are also both important and highly uncertain. The thermal conductivity of the ice is dependent on the temperature and physical state of the ice (its density and the distribution of cracks, for example). A thermally insulating layer at the surface of Europa would promote stabilization of a liquid-water ocean.[39] The occurrence of minor constituents in the ice and ocean such as salts and ammonia would affect both the rheology of the ice and the freezing temperature of the ocean.[40] Tidal heating along major faults in Europa's ice shell may be important,[41] and tidal heating due to forced circulation in a thin liquid-water ocean sandwiched between the rock interior and the overlying ice may prevent complete solidification of the ocean.[42] Tidal heating is too dependent on many unknown or poorly known properties of Europa's ice shell, therefore, to settle the debate on the existence of a liquid-water ocean beneath the ice of Europa theoretically, without the benefit of direct observations.

ATMOSPHERE AND IONOSPHERE

Europa's Neutral Atmosphere

That the moons of Jupiter should have transient atmospheres, undergoing continual production and loss, is one of the many enigmas of the complex jovian system. While volcanism is accepted as the ultimate source of Io's atmosphere, other processes must be responsible for Europa's atmosphere.

To date, remote-sensing techniques have identified two constituents of Europa's atmosphere—molecular oxygen (O_2) and atomic sodium (Na). The former is inferred from ultraviolet emissions,[43] while the latter comes from detection of light scattered at visible wavelengths.[44] The vertical column abundances (the number of molecules sitting above a unit of area on the surface) are estimated to be $\sim 10^{15}$ cm^{-2} for O_2 and $\sim 10^{10}$ cm^{-2} for Na, with number densities just above the surface of $\sim 10^{8}$ cm^{-3} and ~ 70 cm^{-3}, respectively. Although sodium is far less abundant than oxygen, it is more easily observed and has been traced out to distances of more than 20 times the radius of Europa. Other gases must also be present with greater or lesser abundances than these and, collectively, may serve as important tracers of the chemical composition of Europa's surface; they have not been detected, however.

While some atmospheric constituents may arise from the impact of micrometer-sized dust grains or from simple evaporation of surface materials, the dominant source for Europa's O_2 and Na atmospheres is thought to be sputtering (i.e., the ejection of molecules or atoms from a surface resulting from the impact of ions or electrons) by energetic (100- to 1000-keV) magnetospheric ions (Figure 2.4). The oxygen comes from water ice at the surface. Laboratory experiments have confirmed that ice subjected to ion bombardment yields gaseous H_2O, H_2, and O_2[45]; the water vapor quickly freezes again at Europa's surface temperatures, the hydrogen quickly escapes to space due to the weak surface gravity (with a surface acceleration of about 1.3 m s^{-2}), and the oxygen remains to form a bona fide atmosphere, albeit one subject to loss by subsequent ionization and transport processes. Sodium, on the other hand, comes from impurities (such as salts) intrinsic to the icy surface material, as well as from Io, where sodium escapes and can be implanted subsequently onto Europa's surface. The eventual detection of additional species,

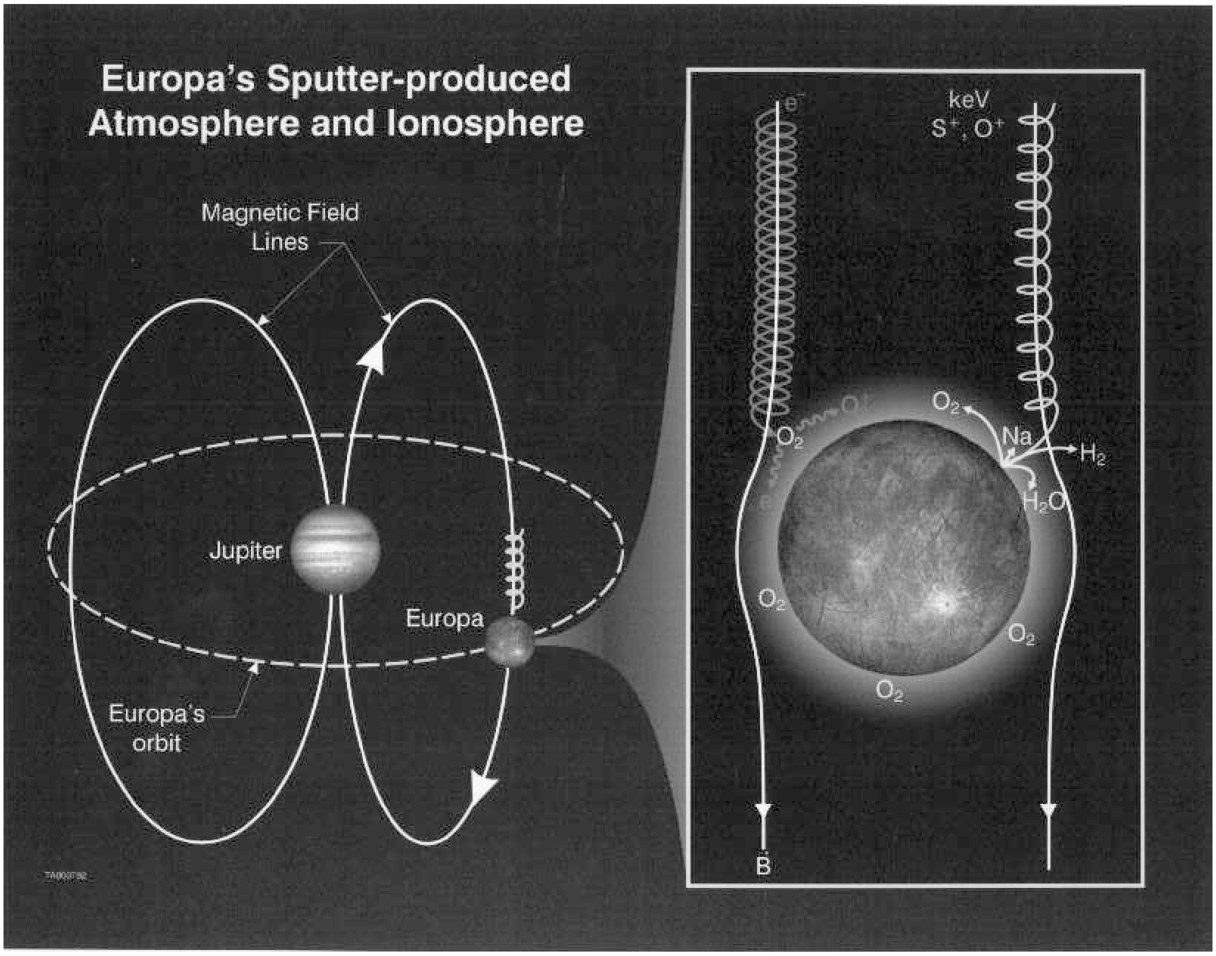

FIGURE 2.4 Europa's neutral atmosphere and ionosphere are produced by a complex chain of interactions between energetically charged particles trapped in Jupiter's magnetic field (B) and the elements in Europa's icy surface. Sampling the neutral gases and plasma in Europa's atmosphere will reveal the chemical composition of the ice on its surface. Image courtesy of Southwest Research Institute, San Antonio, Texas.

such as potassium, calcium, and magnesium (and, potentially, organic molecules) will allow determination of the chemical makeup of Europa's icy terrain.

Europa's Ionosphere

The presence of a tenuous neutral gas surrounding Europa leads naturally to an ionospheric plasma. The ionization sources are collisional ionization and photoionization. The energetic magnetospheric plasma that sputters the surface materials to form the neutral atmosphere also is able to ionize the gases once they are in the atmosphere. While energetic ions are probably the dominant sputtering agent, it is the energetic electron population incident upon O_2 that can lead to the formation of plasma. Since incoming ions and electrons can penetrate the atmosphere all the way to the surface, the peak neutral and ionospheric densities are probably just above the surface. This is in marked contrast to having a well-defined ionospheric layer with peak density (N_{max}) at some height (h_{max}) significantly above the surface, as found in more-typical planetary ionospheres. A photoionization source in the ultraviolet region of the spectrum will act similarly, and thus both processes act to some (unknown) degree to produce Europa's ionosphere. Preliminary results from Galileo suggest an $N_{max} \sim 10^4$ $e^- cm^{-3}$ just above the surface.[46]

Once produced, the ionospheric plasma has a short residence time at Europa since there is no intrinsic magnetic field or dense atmosphere to keep it bound to the satellite. Rather, the ions and electrons will immediately begin to gyrate about the jovian magnetic field. Since the magnetic field is coupled to Jupiter's rapid rotation, the ionospheric plasma becomes entrained in the corotating magnetospheric plasma that impinges on the trailing side of Europa (upstream in the magnetospheric flow) and is swept away downstream, ahead of the satellite in its orbit.

The current state of knowledge of Europa's neutral atmosphere and its embedded ionosphere is extremely rudimentary. The day-to-day variability of both and their responses to the stresses caused by electrodynamical interactions with the magnetosphere in which they reside are essentially unknown at this time. However, in contrast to the terrestrial situation, the atmosphere and ionosphere on Europa are highly representative of surface materials, and therefore the detection of all possible species is important.

MAGNETIC-FIELD AND ENERGETIC-PARTICLE ENVIRONMENT IN THE VICINITY OF EUROPA

Europa is located in the inner magnetosphere of Jupiter (at a radial distance of ~ 9.5 R_J), a region populated mainly by plasma derived from the Io plasma torus. The plasma there consists of protons, oxygen and sulfur ions, and their corresponding electrons. The background magnetic field of Jupiter is quite strong near Europa's orbit (~ 500 nT), and the fluxes of energetic electrons and ions are among the highest found in the solar system. The plasma is nearly corotational, being dragged around Jupiter by the magnetic field as Jupiter rotates; with the magnetic field rotating at a faster rate than Europa revolves around Jupiter, the plasma hits Europa with a relative velocity of ~ 120 km/s on Europa's orbital trailing hemisphere. Most of the plasma resides in a thin plasma sheet (with a half-thickness ~ 2 R_J), located approximately in the plane of Jupiter's magnetic equator. Because Jupiter's magnetic field is tilted by 10 degrees relative to its rotation axis, the plasma sheet and the magnetic equator appear to move up and down as seen from Europa, with a period of 11.2 hours (i.e., the synodic period corresponding to the 9.9-hour rotation rate of Jupiter's magnetic field and Europa's 3.6 day rotation rate). This relative motion produces dramatic changes in the charged particle fluxes and the magnetic field experienced by Europa.[47]

Though several spacecraft have traveled interior to the orbit of Europa, Galileo is the first to have provided in situ field and plasma measurements near Europa. Galileo collected data in Europa's vicinity four times during its primary mission and, ultimately, an additional seven times during the subsequent Galileo Europa Mission (see Box 2.1). Plasma measurements from Galileo show that Europa acts in a manner similar to a cometary source of plasma; while it both absorbs and emits charged particles, it is a net source of plasma emitted into the magnetosphere. Measurements from the E-4 and E-6 orbits show that the plasma density was enhanced by a factor of two or more within a large volume around Europa. Simultaneous measurements from the energetic-particle detectors showed that the radiation environment near Europa is extremely variable, changing by an order of magnitude between orbits. These are the energetic particles that bombard the surface of Europa to produce its transient neutral atmosphere and ionosphere and to cause resurfacing and migration of material on its surface.

When Europa is located above or below the central plasma sheet, the fluxes of charged particles are relatively low and sputtering is at a minimum. During this time, the variations in the background magnetic field that result from the rotation of the tilted jovian dipole produce a response from Europa.[48,49] The oscillating jovian field is somewhat "neutralized," apparently by the presence of a conducting material within Europa that produces an eddy current in its surface. Simple modeling calculations suggest that the induced field is dipolar in nature and that its magnitude at its pole is equal and opposite to that of the applied oscillating field (thereby canceling it out). The electrical conductivities of the ionosphere ($< 10^{-4}$ S/m) alone, however, or of the ice crust ($< 10^{-6}$ S/m) are too small to shield out the oscillating field in this manner. A possible explanation for the presence of a more-conductive medium is that there is a global liquid-water ocean and that it contains dissolved salts.[50,51] The conductivity of salt water is high (~ 1 S/m), and a wave driven by a changing magnetic field with a period of just over 11 hours would have a penetration skin depth of ~ 100 km. Thus, if the ocean thickness is in the range of tens of kilometers or larger, it would be able to produce an induction response to the varying background field. In this limit, the strength of the induced response depends only on the depth of the conducting layer below the surface.

A second type of response to the field and plasma conditions occurs when Europa is at the center of the plasma sheet. There, the much higher fluxes of energetic particles produce a large escaping flux of sputtered and ionized material; this flux can be greater than 50 kg/s. Europa is similar to a comet in such a situation, and the newly picked-up plasma affects the background magnetic field at distances as great as 8 Europa radii from Europa. In this situation, the magnetic field drapes around the cloud of plasma and its strength increases upstream of Europa and decreases downstream. Measurements from Galileo's E-12 orbit showed that the field indeed increased by more than 400 nT upstream of Europa. The expected induction response was of the order of 40 nT during the E-12 flyby and could not be separated from the very large comet-like response.[52]

POTENTIAL FOR BIOLOGICAL ACTIVITY

If liquid water exists beneath the surface ice layer on Europa, then one of the environmental requirements for life will have been met. If, in addition, the satellite has provided a source of energy for metabolism and access to the requisite biogenic elements, then it is possible that life may have originated on Europa independently of life on Earth, and even that it may exist now.

On Earth, organisms use either sunlight (via photosynthesis) or chemical reactions (via chemosynthesis) as energy sources for their metabolic processes. However, plausibility arguments based on the phylogenetic tree of all life on Earth suggest that chemosynthesis likely predates photosynthesis.[53,54] The chemosynthetic microorganisms that branch most deeply in the tree are autotrophs; they gain energy from inorganic chemical reactions such as reduction of sulfur to hydrogen sulfide or formation of methane (methanogenesis) from carbon dioxide and hydrogen. Because these microorganisms do not require sunlight as a source of energy and carry out reduction reactions involving inorganic compounds, they suggest both the type of life that might thrive beyond Earth and the first kind of organism that might form in an energetic extraterrestrial environment. On Earth, many of these microorganisms are "hyperthermophiles" that require temperatures above 70°C for growth and live in hot springs and hydrothermal systems.[55,56] It is not yet known whether high temperatures are a necessary condition for the origin or early evolution of life, but there are many indications that hydrothermal systems are ideally suited for providing geochemical sources of metabolic energy and may be sites of organic synthesis.[57,58]

Chemosynthesis is possible on Earth owing to numerous environments that are not in a state of chemical equilibrium. In many of these environments, the chemical interaction of water with rocks, and the movement and circulation of the resulting solutions between regions of differing temperatures, establish disequilibrium states by bringing together compounds that are in different oxidation states. For example, water-rock reactions in rocks containing ferrous silicates (like basalts, peridotites, and other igneous rocks) can lead to a small amount of H_2 production from H_2O as some of the ferrous iron is oxidized to ferric iron. The H_2 can be generated in solutions that contain bicarbonate, leading to a mixture that is thermodynamically unstable and that should react to form methane. However, the inorganic reaction by which methane forms is extremely slow, providing a situation in which methanogenesis by organisms becomes a viable energy-producing metabolic strategy.[59] Autotrophic methanogenesis illustrates how chemosynthetic biological systems can be fueled by geochemically generated reduction-oxidation (redox) disequilibria. If there are sources of redox disequilibria on Europa, then energy-producing chemical reactions may occur there and may have the potential to support life (see Box 2.2).

Water-rock interactions on Europa seem plausible given the possible presence of liquid water surrounding an underlying rocky mantle that is likely to contain ferrous silicates near the boundary. In addition, the rocky interior by itself would be nearly comparable in size to the Moon and may have been volcanically active in the past, and may even be so at the present; circulation of water through volcanically heated rock in the form of hydrothermal systems can provide access to energy.[60] Finally, a geologically active interior could provide access to the biogenic elements in a form that would allow their utilization in prebiological or biological chemical reactions.

Other sources of energy might also be available on Europa to support metabolism. For example, although

Box 2.2
Redox Chemistry and Its Role in Biological Systems

Redox is the chemical process by which a reaction between two chemical species can result in the oxidation of one of the reactants and, simultaneously, the reduction of the other. For example, H_2 and O_2 are out of redox equilibrium in the modern terrestrial environment, and they can be driven to react chemically by a small input of energy (from, for example, a spark) to form H_2O, releasing energy in the process. The hydrogen is said to have become oxidized and the oxygen reduced. The essence of the redox process is the transfer of electrons from the oxidized species to that which is reduced (it is the charge on the electron receptor that is being "reduced"). The energy released in such reactions can be used to drive other chemical reactions. As such, redox chemistry plays an important role in most biological systems.

Any species out of equilibrium can, in principle, react by exchanging electrons until they are in equilibrium. Moreover, in the proper situation, just about any chemical species can act as either an oxidizing (electron acceptor) or reducing (electron donor) agent. Common electron donors include H_2, CO, Fe, Mn, CH_4, S, NO_2, H_2S, and NH_3. Common electron acceptors include O_2, CO_2, CO, S, NO_2, Mn, and Fe. The diversity of donors and acceptors means that a wide variety of different redox systems can power life.

photosynthesis is thought to have developed later than chemosynthesis, organisms in a europan ocean might have access to sunlight in regions of recent eruption of liquid water to the surface. Some organisms might be able to survive by metabolizing organic molecules that arrive in meteoritic or cometary debris and become entrained into an ocean or are remnants of organic molecules previously produced in situ or of prior living organisms. Still others might utilize H_2 and CO_2 in the formation of acetogen.[61] Organisms utilizing each of these metabolic strategies are found on Earth and might be able to survive in an oceanic environment on Europa.

Recent calculations have cast doubt on the idea that sufficient energy is available to sustain life in a europan ocean. Researchers have argued that the water in a closed europan ocean would rapidly become chemically reduced due to interactions with hot rocks in hydrothermal systems.[62] If this view is correct, a europan ocean would not be an energetically favorable environment for life. This view has, however, been challenged. Additional calculations have indicated that even if the chemical nature of the ocean is reducing, abundant redox chemistry can still take place and, thus, provide an energy source for metabolism.[63] Nevertheless, it is still far from clear whether or not a europan ocean contains sufficient energy to support an origin of life. Moreover, if life did originate at some time, it is unclear if it survived to the present day.

SUMMARY OF OPEN ISSUES REGARDING EUROPA

The major outstanding questions about Europa that remain unanswered at the close of the Galileo Europa Mission are whether Europa has a liquid-water ocean beneath its icy surface and whether there is the potential for the existence of life there. The former is amenable to investigation by spacecraft in the immediate future, whereas the latter will require development of new technological approaches and implementations.

The question of the presence or absence of a europan ocean is central to our understanding of the satellite as a whole. It provides the intellectual underpinning for our understanding of the geology, geophysics, atmosphere, and history of the satellite. Though Europa's gravity field may be known to spherical-harmonic-degree three or better through analysis of Galileo-tracking data, knowledge of the properties of this field will not tell us if there is liquid water beneath the surface.

The two most intriguing arguments in favor of a subsurface liquid-water ocean on Europa at present or in the recent geologic past are the geologic evidence for rafting of blocks of ice floating on an underlying fluid and the detection by the Galileo magnetometer of an electromagnetic induction response in Europa that appears to be explainable only by the presence of a salty ocean.[64–66] The problem with accepting the latter as a definitive detection of a europan ocean is that a similar electromagnetic response is seen at Callisto, yet this moon displays no surface morphological evidence for the existence of a subsurface ocean. Could such an ocean exist on Callisto without being reflected in the geologic processes that have created its surface?

A summary, then, of the major outstanding scientific issues and questions for Europa includes the following:

- Is there liquid water on Europa and, if so, what is its spatial distribution? If there is a globally distributed "ocean" of water, how thick is the layer of ice that covers it, and what are the properties of the liquid? If there is not liquid water today, has there been any in the relatively recent past, and what is the time dependence of its occurrence?
- Are the kilometer-scale ice rafts seen on Europa's surface a product of the movement of ice on an underlying liquid-water sea or through a warm, soft (but not necessarily melted) ice? What is the overall relationship between the surficial geologic units and the history of liquid water?
- What is the composition of the deep interior of Europa, including both the presumed silicate mantle and the iron (or FeS) deep core? Is the core solid or liquid, and is it actively convecting to get rid of heat? Is there a global magnetic field produced by motions of the core? What are the dynamics of the interior, especially regarding the possible physical decoupling of the rotation of the surface ice from the deep interior and the possible non-synchronous rotation of the surface or of the entire satellite? What is the magnitude of tidal heating of the interior, and how is the heating distributed within the interior?
- What is the composition of the non-ice component (such as salts) of the surface materials that are seen in imaging and spectroscopic investigations? How do they vary over the surface? What are the source and history of these materials, and how do they relate to the geologic history of the surface and the potential for the at-least-intermittent presence of liquid water?
- What is the nature of the ice-tectonic processes that have affected the surface, and how are they reflected in the features that are seen (such as triple bands and spots)? Is there active or ongoing cryovolcanism? What are the absolute ages of the various surface geological units?
- What is the composition of the neutral atmosphere and of the ionosphere? What are the sources and sinks of these species? What are the spatial and temporal variations in the atmosphere, and how do they relate to the physical processes that might control them? What is the composition of the magnetospheric ions that can sputter the surface, and of the sputtering products?
- What are the characteristics of the radiation environment at the surface of Europa (currently and in the past), and what are the implications for organic/biotic chemistry and the survival of life on the surface?
- What is the abundance of geochemical sources of energy that could support an origin of life on Europa or its continued existence? Is there extant life, or has there been life in the past? If there has been liquid water, access to biogenic elements, and a source of energy but there is no life present, what factors might explain the lack of occurrence of life, and does the potential exist for an independent origin of life in the future?

These fundamental science questions about the nature and evolution of Europa can be addressed through an ongoing program of telescopic and spacecraft exploration. Some of these issues may be tackled in part or in full by NASA's proposed Europa Orbiter mission. It is almost certainly the case that they cannot all be addressed by a single, short-lived spacecraft mission. Rather, answering these questions will require an ongoing program that progresses from flybys to orbiters to landers to subsurface penetrators. In the following chapters, COMPLEX discusses how these scientific questions can be addressed.

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3

Strategy for the Post-Galileo Exploration of Europa

In this chapter COMPLEX provides additional discussion of the outstanding scientific issues regarding Europa that are outlined in the final section of Chapter 2 and, in particular, details the measurements that are required to address these issues. Although the geological and geophysical topics are discussed separately for simplicity, information elucidating them must be integrated to obtain an overall understanding of the nature of Europa and its history through time, the possibility for liquid water, and the potential for life.

GLOBAL CHARACTERIZATION OF GEOLOGY AND SURFACE COMPOSITION

The complexity of the europan surface was determined primarily from reconnaissance imaging provided by Voyager and Galileo camera systems and enhanced by other remote-sensing data, including those from the Near-Infrared Mapping Spectrometer (NIMS), which provided data on surface compositions. These data, however, covered only limited parts of the europan surface and are inadequate for characterization on global scales. Moreover, regional and local analyses are very limited. Characterizations on a wide range of scales are required not only to enable a more complete understanding of Europa's complex history, but also to provide critical information for potential landing operations, such as site selection and the global and regional scientific context in which to understand lander results.

Galileo results suggest that the general geology of Europa can be characterized with imaging data of a few hundred meters per pixel covering a substantial fraction of the surface (note that as indicated in Table 3.1, only a very small fraction of the surface was imaged at this resolution during GEM). These data enable the general terrains to be mapped, the major structural features to be identified, and the stratigraphic relationships to be determined, from which surface histories can be derived.

Information on surface compositions should be determined from orbital observations conducted at spectral resolutions of 10 to 15 nm in the near infrared with contiguous wavelength sampling of spatial locations. Significant uncertainty was introduced by NIMS's discontinuous spectral coverage at a given spatial location. NIMS's design is such that it acquires data in only 17 spectral channels at a given time. As a result, its grating must be moved between 6 and 24 times to obtain data spanning its full spectral range of 0.7 to 5.2 microns. Thus, pointing uncertainties and the motion of the spacecraft between observations can cause the spatial mislocation of adjacent spectral channels. This misregistration can cause apparent spectral patterns when observations are taken as the spacecraft is moving over terrain with a rapidly varying albedo.

TABLE 3.1 Galileo's Imaging Coverage of Europa's Surface

	Percentage of Surface Covered	
Resolution	Prime Mission	Galileo Europa Mission
>4 km	77	87
1 to 4 km	61	80
0.1 to 1 km	7.4	11
20 to 100 m	0.02	0.4
6 to 20 m	0.004	0.08

NOTE: Includes actual coverage through encounter E-19 and expected coverage during encounter I-25.

If all wavelengths are observed simultaneously, then the compositional information is free of such artifacts. Indeed, reflectance spectroscopic determination of surface composition works remarkably well for ices. The widely spaced and relatively deep absorption bands of different ices make unique identification of ices straightforward. Band shapes and depths allow determination of relative abundances with precisions and accuracy approaching 5%. This type of information, obtained on a global scale at a spatial resolution of 1 km, will allow models of surface origins to be tested and will help resolve the spectral contributions from water ice of varying textures and clarity in addition to the contributions from non-ice components.

In addition to conducting low-resolution global imaging and compositional mapping, selected regions should be targeted for coverage at higher spatial resolutions. For example, the Galileo Europa Mission (GEM) identified several regions exhibiting terrains that have been disrupted, presumably by internal activity, and that have a paucity of superposed impact craters, indicative of relative youth. These areas should be imaged at resolutions better than 50 m/pixel (with compositional mapping at 300 m/pixel) to determine if there have been changes on the surface that would be indicative of ongoing activity. Imaging at similar resolution is recommended for sites identified by GEM as being of high interest for exploration by future landers.

Orbital imaging should also be used to search for active eruptions such as geysers. Although GEM has so far failed to reveal current activity, viewing and lighting geometries precluded this type of observation on all but one brief encounter. Current estimates of the height to which geyser plumes would rise suggest that surface features produced by them would be about 15 to 20 km across; thus, images should have resolutions of 1 km or better for their detection.

GLOBAL MAPPING OF TOPOGRAPHY AND GRAVITY

Topography and gravity are basic geophysical data sets that provide information on the internal structure and dynamics of planetary bodies. Flybys of Europa during the nominal Galileo mission and GEM will yield information on the lowest-degree and lowest-order spherical harmonic contributions to the gravity field. The degree-two gravity field has been used to infer the moment of inertia of Europa and its layered internal structure.[1,2] Only limited data exist on the very subdued topography of Europa. Its average shape, inferred from Galileo limb profiles, is not very different from that of a sphere and, given the precision of current measurements (>500 m), is indistinguishable from an object in hydrostatic rotational and tidal equilibrium (P. Thomas, Cornell University, private communication, 1999). A more precise determination of the radii of the three principal axes of the ellipsoid defining Europa's shape (accurate to approximately 100 m) would provide a crucial verification of the hydrostatic equilibrium assumed in the interpretation of the second-degree spherical harmonic gravity data. It would also provide an independent measure of C/MR^2.

To proceed further in the exploration of Europa's interior after the completion of GEM requires determination of both the gravity field and topography of the satellite over the entire surface. This can be accomplished from an orbiting spacecraft, for example, by radio tracking and laser altimetry. The relationship between gravity and topography and their connection to geologic features can be exploited to provide information on internal structure and dynamics and surface tectonics. Most importantly, it will enable better constraints on the thickness of the outer water ice-liquid shell and determination of variations in this thickness. The nonhydrostatic contributions to the gravity field will be characterized and internal mass anomalies identified. Modes of compensation for surface loads can be determined, thereby constraining the rheology of the ice shell.

The periodic distortion of Europa as it revolves around Jupiter produces variations in Europa's shape and gravitational field with a period equal to Europa's period of orbital revolution (3.55 days). The distortion of Europa is caused by the forced eccentricity of its orbit and the consequent variation in the tidal force from Jupiter with Europa's orbital position. Also contributing is the small periodic motion in the position of the sub-jovian point on Europa's surface. Europa's periodic changes in shape redistribute its mass and result in periodic changes in the gravitational field. These periodic variations in Europa's shape and gravity field are superimposed on the permanent and much larger ellipsoidal shape and degree-two gravitational field that result from Europa's rotation and Jupiter's tidal force, already measured by Galileo.

Measurements of the time-varying shape and gravity field of Europa can readily be taken by an orbiting spacecraft with a minimum lifetime of a few tens of europan orbital periods. If Europa has a global liquid-water ocean, the surface of its icy shell will rise and fall by about 30 m during a revolution around Jupiter. If there is no ocean, the periodic displacement of the surface will be only a few meters. The tidal response of a patchy shell will be intermediate between these two limits, with its exact amplitude determined by the degree to which the icy shell is decoupled from Europa's interior.

Determination of the topography will make it possible to distinguish easily between these possibilities. Radio tracking of the orbiting spacecraft could measure periodic changes in the gravitational field. The detection of the periodic variations in the gravitational field of the larger mass redistribution that would occur if Europa has an ocean would also readily determine if indeed there was an ocean. Comparison of the periodic changes in the topography and gravity could provide information on the ice thickness and rheology.

MAPPING OF ICE THICKNESS AND INTERNAL STRUCTURE OF THE ICY SHELL

In explorations of Europa, spatial patterns of ice thickness and the internal structure of the ice shell are first-order scientific objectives. Thickness patterns reveal information about present dynamics, the origin of surface structures, and the relationship of the ice cover to the underlying ocean and/or the ocean floor. The internal structure of the shell also may hold clues to past dynamics as well as provide information on the geologic evolution of the shell since its formation.

The relatively simple dielectric behavior of pure ice means that high-frequency radar waves penetrate great thicknesses of cold ice with relatively little attenuation, allowing for the application of radar technologies to subsurface exploration. Geophysical applications of radar technology for subsurface exploration have been demonstrated on Earth over the past 30 years. Although there is a wealth of experience in the use of ground- and airborne-radar systems of this type, the technique has not yet been successfully used by Earth-orbiting spacecraft, let alone a spacecraft orbiting another planetary body.

Sounding radars with average powers of less than 200 watts have penetrated deep ice on the Greenland ice sheet.[3] Indeed, the ice in some locations studied is greater than 3000 m thick. Earlier observations conducted in Antarctica with more powerful but less sophisticated radars successfully sounded ice approaching 5000 m in thickness.[4] These techniques have been used to determine the locations of subsurface structures to an accuracy of 10 m, as has been verified experimentally with boreholes drilled through the ice to bedrock.[5]

The reason sounding-radar techniques work so well is that the wave velocity (or, equivalently, dielectric constant) depends most strongly on the density of the ice sheet, and there are well-established mixing formulas for estimating velocity given an ice density. For most parts of Greenland and Antarctica, important density variations are confined to the upper 100 or so meters of ice, and the shape of the densification curve is well understood. Consequently, small uncertainties in density with depth tend to be unimportant in the determination of ice thickness from radar data.

The situation is dramatically different for sea ice, which in general is a mixture of ice, brine, air, and precipitated salts. Brine pockets within the ice are strong scatterers and attenuators that greatly reduce the depth of penetration into ice even at radio frequencies. There can be strong vertical variations in the dielectric constant as well. These change seasonally as thermodynamic forcings cause brine to migrate within the icy matrix. Consequently, the inversion problem is considerably more difficult,[6] even with radar systems sufficiently powerful to penetrate sea ice, which is typically only several meters thick.

Radar technology offers the unique potential for detailed and direct mapping of Europa's ice shell and its internal structure. Information on the phase and amplitude of radar echoes from the bottom of the shell may also reveal something about the interface, for example, if the ice rests on water. Nevertheless, the potential of radar has to be tempered against the possibly complicated, three-dimensional variations of the dielectric constant in Europa's ice shell. For example, radar absorption through materials that might compose portions of the shell ranges from 10^{-5} dB/m for pure ice at 200 K to 1 dB/m for briny ice (Figure 3.1). Recent calculations suggest that available constraints on the properties of Europa's ice place a limit of about 10 km on the depth to which an ocean might be detectable by an orbiting radar system.[7] Of course, the actual performance may be better or worse depending on the true temperature and chemical composition of the icy shell.

CHARACTERIZATION OF DEEP INTERIOR STRUCTURE AND DYNAMICAL PROCESSES

Measurements of the topography, gravity field, and magnetic field of Europa will aid efforts to characterize Europa's deep internal structure and dynamics. It is important to determine if Europa has a magnetic field, which will indicate whether convection and dynamo action are occurring in a liquid part of Europa's core. Although Galileo's magnetometer has been able to detect Ganymede's magnetic field,[8] it has not been able to detect an intrinsic europan magnetic field.[9] A small field, however, could exist but remain undetectable in the presence of larger magnetic-field perturbations due to induction effects in Europa and plasma effects around Europa.

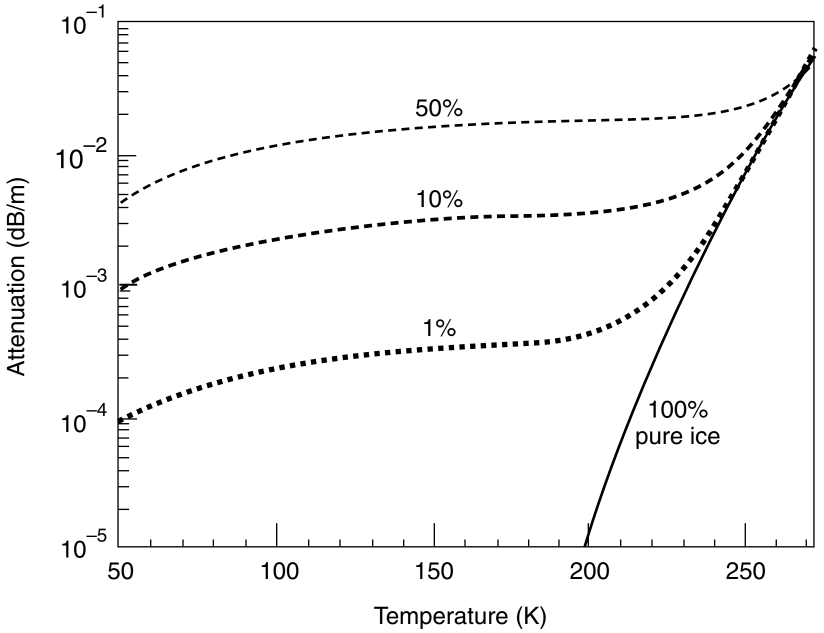

FIGURE 3.1 The attenuation of 50-MHz (or 6-m-wavelength) radar in ice as a function of temperature and impurity content. The solid line shows the attenuation in pure ice, and the dashed curves show the effects of contaminating the ice with varying percentages (by volume) of lunar soil. The attenuation caused by briny ice is even more extreme. Illustration adapted from C.F. Chyba, S.J. Ostro, and B.C. Edwards, "Radar Detectability of a Subsurface Ocean on Europa," *Icarus* 134: 292, 1998.

A magnetometer and a plasma detector on a spacecraft orbiting Europa would provide global data on the charged-particle populations and magnetic field over long periods of time and be able to distinguish a permanent intrinsic field from time-varying plasma and induction fields. New, lightweight plasma detectors, such as the Plasma Experiment for Planetary Exploration (PEPE) instrument now operating on Deep Space 1, are able to make good measurements while placing fewer demands on spacecraft mass or power resources than past instruments. Additional data on the induction field would also help to characterize the highly electrically conducting near-surface layer, perhaps a liquid-water ocean, in terms of depth, thickness, and electrical conductivity.

If it turns out that Europa does not have an intrinsic magnetic field, it will be possible to conclude only that there is no convection or dynamo activity in its core. Whether its core is liquid or solid will still be uncertain.

More accurate and complete determinations of Europa's gravity, global shape, and topography will enable refinement of interior structural models; tests of hydrostaticity; and inferences about ice thickness and variations thereof, topography on the water-rock boundary, and mechanical properties of the ice.

DETERMINATION OF THE GEOCHEMICAL ENVIRONMENT OF THE SURFACE AND POSSIBLE OCEAN

The prospect of skipping a systematic geochemical assessment of Europa and discovering some form of life is exciting but has a low probability of success. It is more likely that many geochemical properties of the europan environment will have to be characterized before the probability of the origin and development of life there can be sensibly assessed. Among the properties of interest are the presence and concentrations of chemicals that might serve as nutrients or as poisons, the energy sources available that might support life, the present and past redox states, organic materials that might be residues from living organisms or prebiotic processes, or the characteristic times for physical processes, both in sequence and duration. In this section COMPLEX takes a "top-down" approach to the study of europan geochemistry, beginning with the atmosphere.

The Atmosphere and Ionosphere

Europa has a thin neutral atmosphere and an ionosphere derived from it. The current state of knowledge of Europa's neutral atmosphere and its embedded ionosphere is still rudimentary, however. The vertical structure and the horizontal patterns (latitudinal and longitudinal morphologies) are yet to be measured. The day-to-day variability of both the neutral atmosphere and the ionosphere and their responses to the stresses caused by electrodynamic interactions with the magnetosphere in which they reside are essentially unknown. Atmospheric species cannot yet be accurately sorted into endogenous and exogenous components. Most of the atmosphere consists of chemical species produced by sputtering of the materials that are found in the surface ice, but the compositions of those materials are surely changed as a consequence of the chemical reactions induced during their ejection into the atmosphere. Certainly, without the strong interaction of the bombarding plasma, the atmosphere would be much more meager than it is.

The atmosphere of Europa informs us of the presence of molecular oxygen (O_2) and molecular hydrogen (H_2) and perhaps of their rates of formation. The O_2 and H_2 are produced by plasma irradiation of water ice, and it is likely that some of these gases do not escape from the ice but remain buried in it (as is observed, for example, on Ganymede). In principle, if the ice convects more rapidly than those species in the ice are destroyed, they might be transported downward to the water-ice interface. There, the O_2 could serve either as an energy source or as a poison for possible organisms.

Also, because ion sputtering is an important process contributing to the atmosphere, atoms and molecules of all types that are present in the ice are released into the atmosphere. For example, ground-based spectroscopy in 1995 revealed the presence of sodium (Na) in the atmosphere. Additional detailed sampling of the atmosphere can provide information about these minor and even trace constituents of the ice. Key element ratios may be obtainable from analysis of atmospheric species. Thus, if the atmosphere is sampled in detail, so that its trace constituents are measured, the composition of the surface materials can be determined.

The atmosphere also seems an especially appealing location to search for organic substances. The concentrations of some organic species may be high enough in the atmosphere for ready observation. Fragments of complex organic molecules may appear as sputtering fragments, analogous to the fragments used to identify organic compounds by analytical mass spectrometry. Other molecules may be intrinsically volatile, such as methane, perhaps released from clathrates. Carbon dioxide might be present from oxidation of organic species or from destruction of organic acids or other carbonyl groups as a consequence of particle or ultraviolet radiation.

Although some clues to the makeup of Europa's neutral and ionized gas can be achieved from ground-based telescopes and their counterparts in low Earth orbit (e.g., the Hubble Space Telescope), major progress will come only from in situ observations from an orbiter, a suite of landed instruments, or both.

The discovery of Europa's atmosphere/ionosphere offers a significant opportunity for investigations of the physical and chemical conditions on Europa's surface. This results from the fact that Europa's thermal gases and plasmas are derived directly from the surface. The agent responsible for their release is the harsh, ever-present magnetospheric charged-particle populations at Europa's location (~9.5 R_j) in the jovian magnetosphere. A systematic study of the cause-and-effect cycles in this relatively isolated surface-bounded exosphere represents both a remarkable opportunity and a significant technical challenge to our understanding of surface-environment interactions as a tool for solar system exploration. Several sophisticated techniques can be brought to such studies.

Photon Spectroscopy

Both remote and in situ methods can be used in various portions of the electromagnetic spectrum to identify neutral and ionized species, as well as their relative abundances, in the europan system. Numerical modeling studies show that the radial extent of a detected species depends primarily on its ejection speed from the surface. This, in turn, depends on surface structure and on the ability of incident charged particles to liberate gases. Since the fluxes above Europa can be measured in space and the sputtering process studied in the laboratory, the characterization of atmospheric constituents will be a robust way to address the details of surface properties and their global morphologies.

Observations should be made in the ultraviolet and in the infrared to document the abundances of as many species as possible. In the visible, observations of the spatial distribution of sodium and, potentially, potassium are needed to determine if they are produced locally or transported to the surface from Io. COMPLEX notes that Earth-based observations of Europa's atmosphere prior to and during the lifetime of an orbiter will be important for establishing a baseline from which any unusual conditions during the mission might be recognized.

Mass Spectrometry

Both neutral mass and ionized mass spectrometers operating in low orbit above Europa can be used to observe the composition and global distribution of gases released from the surface. The identification by mass offers information at a single (orbital) height that is complementary to information obtained by optical methods above and below that height. It offers potentially unique capabilities for the detection of entire organic molecules at low altitudes. Neutral and ion mass spectrometers with a resolution of 1 amu will be required. Such instruments have a long history of successful use on sounding rockets, Earth orbiters, and planetary spacecraft such as the Pioneer Venus orbiter; a neutral mass spectrometer is currently on its way to Mars aboard Japan's Nozomi spacecraft.

Because the picked-up plasma in the vicinity of Europa is derived from its surface, measurements of plasma and field conditions in the vicinity of Europa also provide valuable clues about the composition of the surface of Europa (with careful modeling of the interaction and sputtering processes). In addition to the charged material, a large fraction of the sputtered material in the vicinity of Europa would be neutral, and studies of it using a neutral mass spectrometer would provide further information on the composition of Europa's surface. However, to derive relative abundances of surface materials from the measurements made in space, a good determination of the energy and fluxes of the bombarding plasma would be required. Thus, a simple, lightweight, charged-particle instrument is needed to address this question.

Energetic Particles and Fields

The measurements of the electromagnetic induction response from Europa using a direct-current magnetometer on an orbiter would provide indirect evidence about the possibility of the existence of a salty ocean within Europa. Because of the limited coverage of Europa from Galileo, investigators have so far used only the 11-hour periodicity in the background magnetic field as the basic forcing signal for sounding. However, other short- and long-period waves are present in any background environment. Shorter-period waves would be affected by the ionosphere of Europa, because their penetration skin depth is smaller. On an orbiter that makes measurements continuously over several months, such waves could be used to study the properties of the ionosphere. Longer-period waves would sound Europa's interior to large depths directly. One source of longer-period fluctuations in the background field is the small dawn/dusk asymmetry in the magnetic field of Jupiter even at the location of Europa's orbit. As Europa and the orbiting spacecraft orbit around Jupiter (with a period of ~ 3.55 days), they would sample a changing background. Magnetic reconnection between the interplanetary magnetic field and the field of Jupiter also would create longer-period fluctuations in the background field. Similar very-small-amplitude fluctuations have been used to study the variations of electrical conductivity within Earth's mantle. As mentioned above, distinguishing between different sources of magnetic signatures (intrinsic field, induction, or plasma effects) requires measurement of the plasma environment as well as the magnetic field.

The Ice

In addition to water ice, a variety of other materials may exist on Europa's surface.[10] There is spectral evidence for some of these materials, but most of them have not been identified to a high level of confidence, nor have their exact nature and origin (if they are indeed present) been determined. Some materials are exogenous in origin, at least in part. These include the chemical element sulfur, presumably implanted from the plasma surrounding Europa and now apparently present as SO_2.[11,12] Although Europa probably has abundant sulfur within its rocky interior, this material is likely not accessible to the surface. The most plausible source of the sulfur is Io, whence it is erupted by this satellite's volcanoes and, having been carried by Jupiter's magnetosphere, is implanted onto the surface of Europa. Other candidate materials are those from comets, interplanetary dust, and perhaps other objects that have bombarded the europan surface. These include minerals (silicates, sulfides, iron and iron alloys, and minor minerals) and carbonaceous materials; none of these has yet been observed. Europa appears to have been resurfaced continually with water from beneath, either as liquid or ice. If as liquid it most likely would be briny, and salts spilled onto the surface would separate from the water when the brines froze. Evidence for such salts in the form of distorted water-absorption features in reflectance spectra has been obtained in some areas of Europa. This distortion has been interpreted as water of hydration, and it resembles that seen in laboratory spectra of the salts hexahedrite ($MgSO_4 \bullet 6H_2O$), epsomite ($MgSO_4 \bullet 7H_2O$), and natron ($Na_2CO_3 \bullet 10H_2O$).[13]

Although materials present at depth within Europa are of great interest to the question of life, it is anticipated here that near-term studies of Europa will focus on the surface. Determination of deeper properties will depend on processes that might expose once-deeper ice at the surface. Such processes include tectonic and solid-state convective motion, or impact cratering. Upwelling of water from the interior of Europa similarly could bring material from depth to the surface. The salts proposed to explain the distorted water spectra are examples of such material.

Sampling and examination of ice from a depth of at least several centimeters below the surface will likely be required to observe properties of ice undisturbed by the continual bombardment by magnetospheric ions. Some of these bombarding ions, such as sulfur, are implanted. Other ions break up water molecules or sputter them into the atmosphere. Many of these molecules re-condense onto the surface, changing its texture. As a precursor to detailed study, certain geological and geophysical properties of the ice need to be characterized to provide context for interpretation of geochemical properties of the ice and the possibility of life. Lateral and vertical temperature profiles and the rate of interior heating, if known, would constrain models of the interior composition of the aqueous outer shell and the distribution of heat-producing, radioactive elements below that crust, which in turn constrains models of silicate differentiation. Determinations of some of these physical properties may require geochemical measurements. In addition to hydrated minerals crystallized from the ice, there may be gases and solids dissolved within the ice and solids occluded within the ice, all possibly brought to the surface from depth. Determining the mineralogy and chemical composition of the materials associated with the ice will help distinguish between those of exterior and interior origin. Ratios of chemical elements of materials of interior origin will enable the geochemist to infer the nature of the sub-ice interior of Europa. Conceivably, the ice may contain fine rock flour originating from any one of a number of geological processes, including water-rock chemical weathering and glacier-like scraping if the ice shell touches the surface of the rocky mantle.

The history of past motions and subsurface environments of the ice may be recorded in the mineralogical properties of the ice. Textural properties such as grain size distributions, preferred grain orientations, and evidence of crystal strain or shock features, breakage, and annealing may provide this information. These properties can be used to search for ice that has not been badly deformed, including, perhaps, ice that suffered relatively little stress during transport from depth. Surface ice that has undergone convection or was extruded onto the surface as a slushy melt may have brought material up from substantial depths. This material could include chemical species that had been dissolved in the ocean, debris that had become entrained in the ice, or even silicates from the rocky interior. Such ice would, therefore, be rich in chemical information about the interior of Europa. Substantial recrystallization may have occurred during motion of the ice as it moved from depth toward the surface (if it did), or through surface metamorphism caused by tectonic movement of the crust. Such alteration of the original ice grains and textures may erase pressure and temperature conditions from the initial formation of the ice but should not substantially alter the abundances or character of entrained chemical or mineralogical species.

The number of chemical elements required by living organisms as we know them is large. Most are important only as trace constituents, however. The principal building blocks of cells are carbon, hydrogen, oxygen, nitrogen, sulfur, phosphorus, calcium, iron, and potassium. Determining the concentrations, concentration ratios, and chemical forms of these and other elements in the ice will provide insights into the sources of these elements in the ice and their transport mechanisms. It may then be possible to say whether these elements are available within Europa's interior. Surface concentration ratios for many elements can be used to predict concentration ratios in the europan ocean.

The presence, variety, and concentrations of organic substances are of obvious interest to questions of life. Organic materials are continually supplied to the europan surface in cometary material. Conceivably, there could be a mechanism by which any of this material can reach the ice-ocean interface where it could serve as nutrients; alternatively, sputtering may remove such material before it enters the subsurface. Residual carbonaceous material from the accretion of Europa may be present in the interior, although its nature has likely been altered by metamorphism anticipated at high temperatures (see below).[14,15] Of paramount interest would be forms of organic material that might be indicative of life and those that are precursor materials of life.

Chemical substances that originate beneath the surface of Europa may be products of rock-water interactions, discussed below. Others may be in the form of dust or fragments of rock produced by a variety of geologic processes. Convection of the ice might deliver this material to the surface, or the ice may deliver the material to the ocean, where part of it might remain suspended for long periods as colloidal particles. The mineralogical composition of this material would provide insight into the rocky mantle. Measurements of concentration ratios of a few well-chosen elements in the material would provide general information about the rocky mantle, including probable abundances of elements such as potassium and phosphorus that are essential for life on Earth. Isotopic properties of the material can constrain time scales for a variety of events, including europan igneous differentiation and ice movement.

Charged-particle fluxes are high at the europan surface. These charged particles cause a variety of nuclear reactions within the uppermost part of the ice. In addition to the products of such radiation chemistry mentioned above, hydrogen, oxygen, and hydrogen peroxide are produced within the uppermost ice. Oxidizing and reducing agents are thus produced, and these, as well as highly reactive species such as free atoms and free radicals such as OH, can interact with organic matter trapped within the ice. The most energetic charged particles cause spallation reactions and generate a flux of neutrons within the ice. Products of these reactions would include isotopes such as tritium (^{3}H) and ^{10}Be; profiles of these radioisotopes versus depth would be useful in determining deposition, erosion, or burial rates. Neutron energies would moderate rapidly and the thermalized neutrons would be captured. Although most of the capture would be by hydrogen, other components of the ice would be activated and, if abundant enough, could provide additional time markers for processes such as erosion and convection in the ice.

Hydrogen and oxygen isotopic ratios will yield crucial information about the origin of the ice and the processes that have brought it to its current state. Measurement of isotopes of other light elements such as carbon and nitrogen also can lead to understanding of the sources of compounds containing them and the properties of these sources and constraints on their origins.

The Possible Europan Ocean, Present and Past

If the putative europan ocean can be accessed directly, numerous characterizing measurements can be made. Some bulk characteristics such as density, depth, temperature profile, and convection pattern and rates should be determined. Simple geochemical measurements include conductivity, ionic strength, and pH and the mechanism of its control. Identification of the principal dissolved salts and measurement of their concentrations will help to characterize the water-rock reaction, as will the identity and concentrations of dissolved gases. Concentrations of redox-sensitive elements will reveal the extent to which redox equilibrium has been attained. Lack of redox equilibrium is required for energy to be available to drive metabolism in chemosynthetic life. Earth's ocean, which harbors life and may have been the site of its origin, is buffered at a slightly alkaline pH by dissolved HCO_3^- and it is sufficiently oxidizing to produce Fe^{3+}. This enables precipitation of hydrated oxyhydroxides of Fe^{3+}, which in turn scavenge the ocean of many trace ions. Measurements of the pH of europan ocean water, together with the other geochemical measurements, would reveal much about the water-rock chemical reactions and the likely composition of the rock. Of course, we do not know how the factors that control the composition and properties of a europan ocean would relate to those that control Earth's oceans, due both to the very different chemical environment at Europa and to the tremendous uncertainty in current knowledge of that environment. Therefore, it is prudent to be prepared for a much wider range of possible properties.

The clarity of the ocean and the content and nature of suspended solids should be determined. Organic substances are of particular interest, both as possible life-supporting chemicals and as precursors to or residues of living organisms (or, more optimistically, the organisms themselves). Another possible suspended solid, rock flour, may have been converted to phyllosilicate minerals such as clays. Such material may be the principal form of sediment at the bottom of a europan ocean. A more exciting prospect is that biological precipitates may have formed. The most promising method for early detection of such material may be its observation in ice of deep origin that has carried the material to the surface.

Europa's Biological Potential

For biological systems to occur on Europa or to have occurred in the past, Europa would have to have undergone extensive geochemical differentiation. The aqueous outer shell (whether it be predominantly solid ice or liquid water) indicates that it probably did. Silicate materials in contact with water at some point in its history would have a chance to react with water (or may even have done so prior to accretion). At some point there would have been sedimentation of silicates and Fe oxides from fully melted and slushy regions, perhaps producing a mineral assemblage similar to that of carbonaceous chondrites. Hydrated phyllosilicates, Fe_3O_4, and soluble salts (predominantly magnesium sulfate) may have been the principal chemical products.[16] The presence of water-rock interactions thus seems plausible on Europa. Circulation of water through magmatically heated rock in the form of hydrothermal systems could have provided access to abundant energy, and may still.[17]

Most of the chemical constituents crucial for life are relatively low in abundance in solid planets. On Earth, life is possible because these elements are strongly concentrated into the crust. We can reasonably believe that, on Europa, the key elements will have been extracted out of the rocky mantle along with the water and are thus either dissolved in the water or are available at the water-rock boundary in a manner that should make them accessible. However, we do not truly know the chemical composition of Europa's interior, how thorough its igneous differentiation may have been, or what elements of biological interest may have been lost to space as that differentiation took place.

Chemosynthesis may have occurred either at the present or in the past. Terrestrial chemosynthetic organisms take advantage of sluggish oxidation-reduction reactions as energy sources. Many redox reactions remain far from equilibrium owing to kinetic constraints, and life has evolved many ways of taking advantage of redox disequilibria involving iron, sulfur, carbon, nitrogen, manganese, arsenic, uranium, and other redox-sensitive elements. Redox reactions may also supply the chemical energy that could drive organic synthesis or the processing of organic compounds into primitive versions of biomolecules.

One test of whether Europa can support life is to identify whether there are sources of chemical energy available that are sufficient to drive metabolism. Measurements of the nature and abundance of chemical species within the water, the extent of any redox disequilibrium, and the abundance, if any, of organic molecules will help to determine the biological potential within the ocean.

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4

Earth-based Studies and Technology Development

In addition to in situ and remote-sensing measurements of Europa and its environment that must be made from spacecraft at or near Europa, studies that can be done on Earth or from Earth-orbiting telescopes will be essential for understanding the overall nature of Europa. These terrestrial studies include field studies of Earth analogs to Europa's environment, laboratory studies of processes that might occur on Europa, theoretical analyses of Europa's physical processes and of their ramifications for its interior, and development of new technology that will allow us to explore Europa. These issues are discussed in this chapter.

TERRESTRIAL FIELD AND REMOTE-SENSING STUDIES

Earth's ice cover is distributed in glaciers, ice caps, and ice sheets that are found from pole to pole. From the thickest and coldest ice deep within the Antarctic Ice Sheet, to the seasonal and thermodynamically active ice cover of the polar oceans, the structural and physical properties of Earth's ice cover are highly variable and can be very complex. These different environments can provide challenging places to test instrument design and data processing and analysis concepts for sounding Europa's icy shell.

Terrestrial Analogs

Below, COMPLEX summarizes categories of terrestrial ice cover that may prove suitable for proof-of-concept studies for exploring Europa-like environments. Examples include polar and temperate glaciers and ice sheets and ice resting on either bedrock or liquid water. A range of terrestrial analogs will be needed for proof-of-concept studies that emphasize technologies, measurement techniques, and analysis methods planned for Europa missions. It is useful to keep in mind that the process of conducting proof-of-concept studies may lead to new techniques and information for studying Earth's own ice cover. This potential argues for a strong programmatic linkage between the terrestrial and planetary science communities in a joint Europa venture.

Temperate Glaciers and Ice Caps

Temperate glaciers contain ice that is everywhere near the melting point. Free water may be present in inclusions that are centimeters to tens of centimeters in size. The inclusions may eventually connect to form drainage channels within the glacier. The glacier itself may be several hundreds of meters thick; its structure may be further complicated by the presence of medial moraines, composed of rocky debris that snake across many valley glaciers. The moraine patterns are good indicators of past dynamical instabilities.

Extensive geophysical studies have been conducted on temperate glaciers in the Pacific Northwest such as the Blue and Columbia Glaciers. The Bering and Malaspina Glaciers, located along the Gulf of Alaska, are examples of surging glaciers with highly crevassed surfaces, complex subglacial hydrology, and surface and internal moraines. Each has been intensively studied with surface, airborne, and spaceborne remote-sensing techniques.

Polar Ice Sheets

Greenland and Antarctica are blanketed by the last of Earth's great ice sheets. Continental in size, the ice sheets are characterized by complex dynamics driven in part by external climate forcing and by spatial and temporal variations at the glacier bed and at internal boundaries. The dynamical processes manifest themselves on the ice sheet surface by the presence of exotic structures such as ice streams. These are rivers of ice within the ice sheet, hundreds of kilometers long, that discharge ice from the interior ice sheet toward the floating ice shelves and eventually to sea. The margins of ice streams are heavily crevassed and are strong targets for microwave radar, and they can effectively attenuate signals from high-frequency radar (Figure 4.1).

Antarctic ice streams ride over a bed lubricated by subglacial water. The nature of the bed enables the ice streams to move at speeds of several hundreds of meters per year, whereas nearby ice frozen to the bed may move at speeds of only tens of meters per year. Greenland ice streams (such as the Jacobshavn Glacier) apparently flow via the deformation of a basal layer of relatively warm ice—the combination of warm basal ice and the presence of extensive surface crevassing makes Jacobshavn one of the last important glaciers to resist detailed sounding of the glacier bed.

Ice sheets preserve an important stratigraphic record of past changes in climate and dynamics. The record takes the form of vertical and horizontal gradients in density, temperature, crystal size, crystalline fabric, impurity content, and deformation rate. Local vertical variations in these properties can lead to stratigraphic horizons that are detectable and apparently continuous for more than hundreds of kilometers (Figure 4.2).

Polar Ice Shelves

Ice shelves are enormous slabs of floating ice that are fed by a combination of ice flow from the interior ice sheet and accumulation on the ice sheet surface. The largest ice shelves are found in Antarctica. Both the Ross and Filchner-Ronne Ice Shelves are about the size of Texas. Ice thickness ranges from about 800 m near the grounding line to about 250 m near the calving margin. Water-layer thickness beneath the ice shelves varies from a few meters near the grounding line to hundreds of meters.

A few ice-shelf-like environments have been identified recently in northern Greenland. For example, Peterman Glacier occupies a long fjord. Much of the length of Peterman Glacier is floating on ocean water that fills the fjord. Pockets of water upstream of the grounding line are also believed to exist based on the strength of radar returns from deep subglacial valleys (Figure 4.3).

The interior structure of ice shelves can be complex. Moraine material deposited on the surface of East Antarctica's outlet glaciers, for example, is carried downstream and buried, only to show up as a strong scattering layer in radio-echo sounding data. Rifts through the ice shelf can form near grounding lines or around ice rises. Upwelling brine is forced horizontally through lower-density firn (i.e., granular ice formed by the recrystallization of snow) near the surface, forming a layer nearly opaque to radar. These brine layers are carried downstream and can completely obscure the ice bottom from radar. Bottom and surface crevasses can tear through a significant thickness of ice. Once identified, the crevasses can be useful indicators of the stress regime within the ice shelf (Figure 4.4).

Ice-thickness gradients of the ice shelf and currents within the subglacial ocean can plate large thicknesses of sea ice onto the base of the ice shelf. Direct measurement has shown a 6-m-thick layer of briny sea ice on the bottom of the southeastern Ross Ice Shelf. Several hundred meters of sea ice are believed to be accreted onto the

FIGURE 4.1 This synthetic-aperture radar image of the confluence of West Antarctic Ice Streams A and B was obtained by the Radarsat-1 spacecraft. Ice Stream A appears vertically oriented in this image. The area imaged is about 100 km wide, and north is roughly toward the bottom. Streaming flow is evidenced by the regular patterns of flow stripes and the bright shear margins. Arc-shaped features on the right flank of Ice Stream A are suggestive of non-steady flow. Image courtesy of K.C. Jezek.

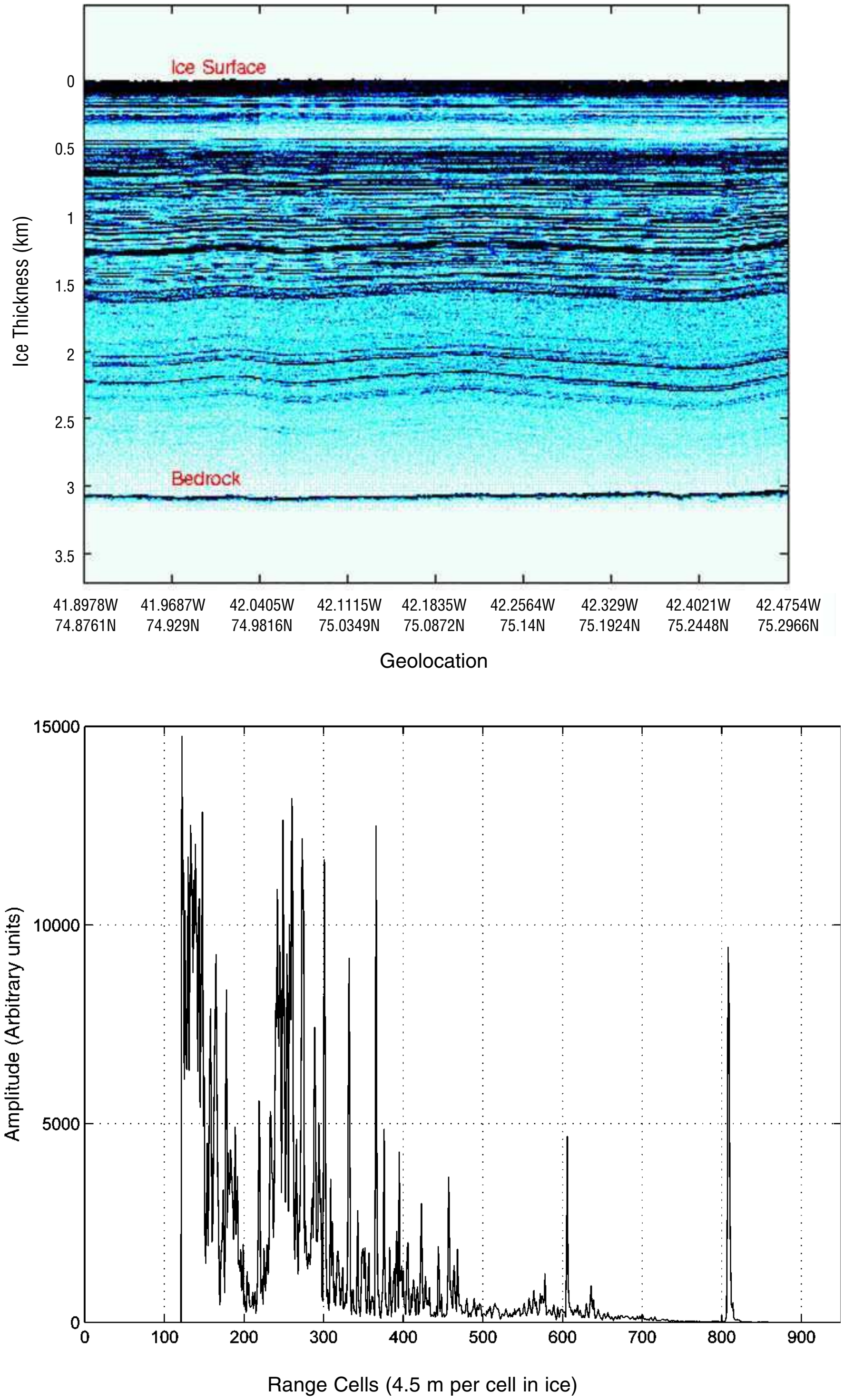

FIGURE 4.2 Radio-echo sounding of North Central Greenland. Internal layers and the ice bottom are illustrated by the radar profile shown in the upper panel. A single echogram is shown in the lower panel. (From S. Gogineni et al., "An Improved Coherent Radar Depth Sounder," *Journal of Glaciology* 44: 659, 1998.)

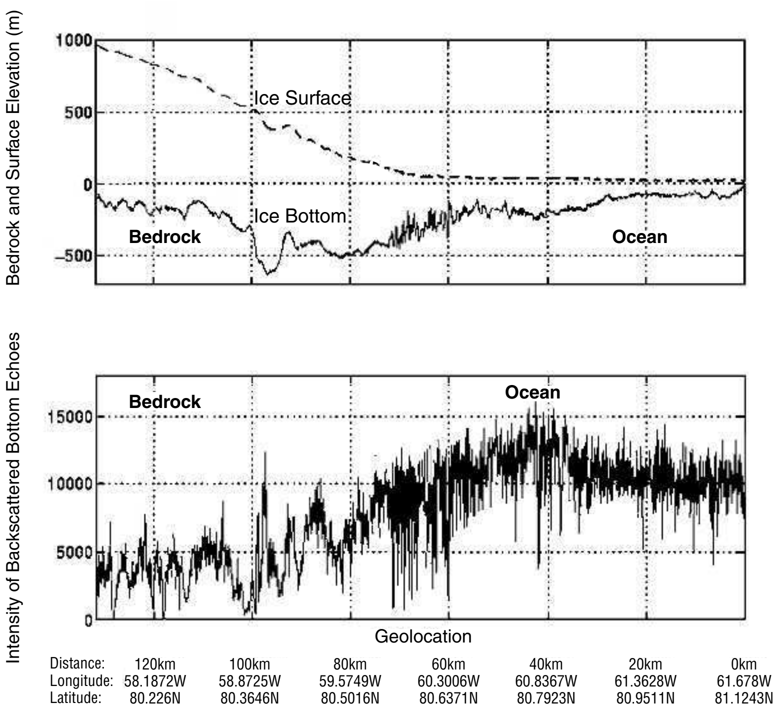

FIGURE 4.3 A radar profile of the Peterman Glacier in northeastern Greenland. The ice goes afloat at approximately 70 km inland from the calving front. This is demonstrated by the increased intensity associated with the glacier's transition from a rocky bed to ocean (lower panel). It is also demonstrated by the sequence of rapid changes in ice thickness which are, in fact, bottom crevasses opened in the presence of seawater. The data illustrate how radar measurements of ice structure and basal reflectivity can be used to infer information about the glacier bed. (From S. Gogineni et al., "An Improved Coherent Radar Depth Sounder," *Journal of Glaciology* 44: 659, 1998.)

base of the central Filchner-Ronne Ice Shelf. The brine in the sea ice is a strong internal reflector of radio frequency energy and a strong absorber of energy that enters the sea ice. Consequently, the sea ice has resulted in the misinterpretation of Filchner-Ronne ice thicknesses.

The combination of relatively thick fresh ice, the presence of a basal saline ice layer, and an underlying ocean ecosystem suggest that ice shelves are attractive sites for proof-of-concept studies. Results from previous borehole campaigns on Antarctic ice shelves can be used as direct validation of results acquired from Europa-like systems.

Lake Vostok and Other Subglacial Lakes

Lake Vostok, discovered during radio-echo sounding campaigns over Antarctica in 1974-1975, is one of many bodies of water buried under the Antarctic Ice Sheet.[1,2] Located in East Antarctica, Lake Vostok is the largest subglacial lake so far discovered. The lake itself is probably composed of fresh water and may be 250 m or more deep (Figure 4.5).

Exploration of Lake Vostok offers a unique opportunity to develop and test new technologies for the exploration of Europa. Similarities in the requirements for the characterization of Lake Vostok and a europan ocean include the following:

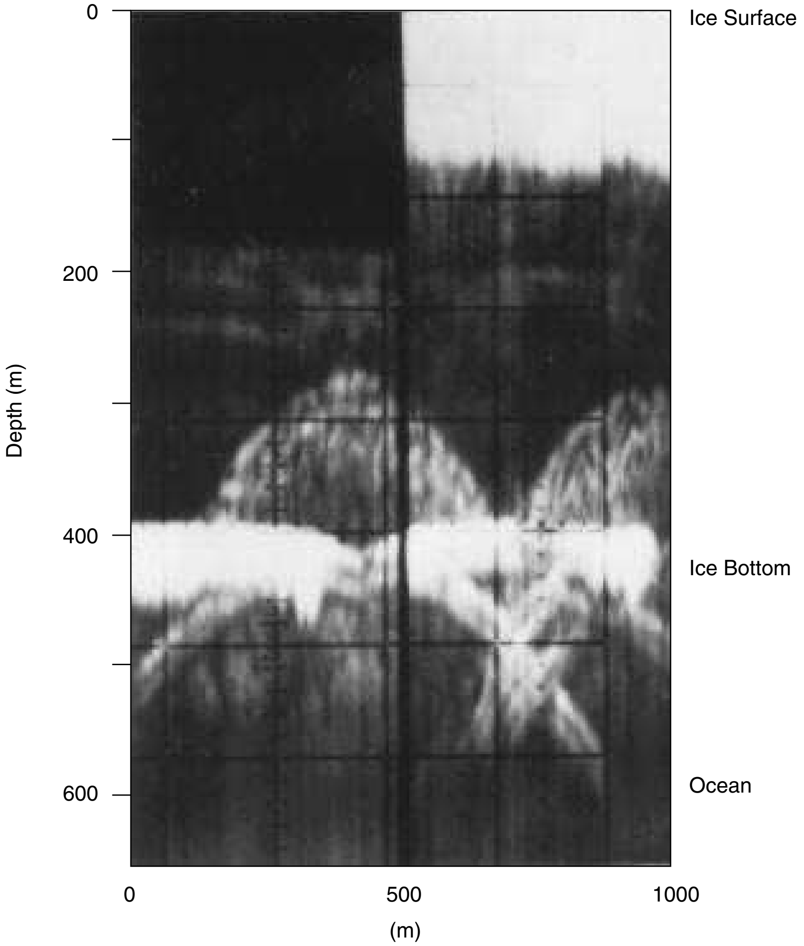

FIGURE 4.4 Radar diffraction hyperbolae from bottom crevasses are shown here in these results from high-frequency radio-echo sounding measurements at a location in the interior of the Ross Ice Shelf in Antarctica. The top of the 1-km-wide image represents the surface of the ice shelf, and the thick horizontal band in the lower center of the image is the ice bottom. The ice is about 420 m thick and is floating over some 200 m of ocean water. Crevasses, formed by strong extensional stresses, penetrate up approximately 120 m from the bottom of the ice shelf. These bottom crevasses appear as diffraction hyperbolae located in the center and right-hand side of this image. The basal edges of the roughly 100-m-wide crevasses also appear as hyperbolae with vertices near the ice-bottom echo. Note the missing data in the upper right-hand corner of this plot. (From K.C. Jezek, C.R. Bentley, and J.W. Clough, "Electromagnetic Sounding of Bottom Crevasses on the Ross Ice Shelf," *Journal of Glaciology* 24: 321, 1979.)

- Potential for use of remote sensing (radar) to determine the extent of water;
- Requirement for physical penetration of a considerable thickness of ice to access the water;
- Application of in situ measurements to determine the chemical and physical properties of the aqueous environment; and
- Possible presence of microbiological organisms and the need to practice appropriate planetary protection policies and procedures (lest investigators contaminate the lake, in this case, with surface organisms).

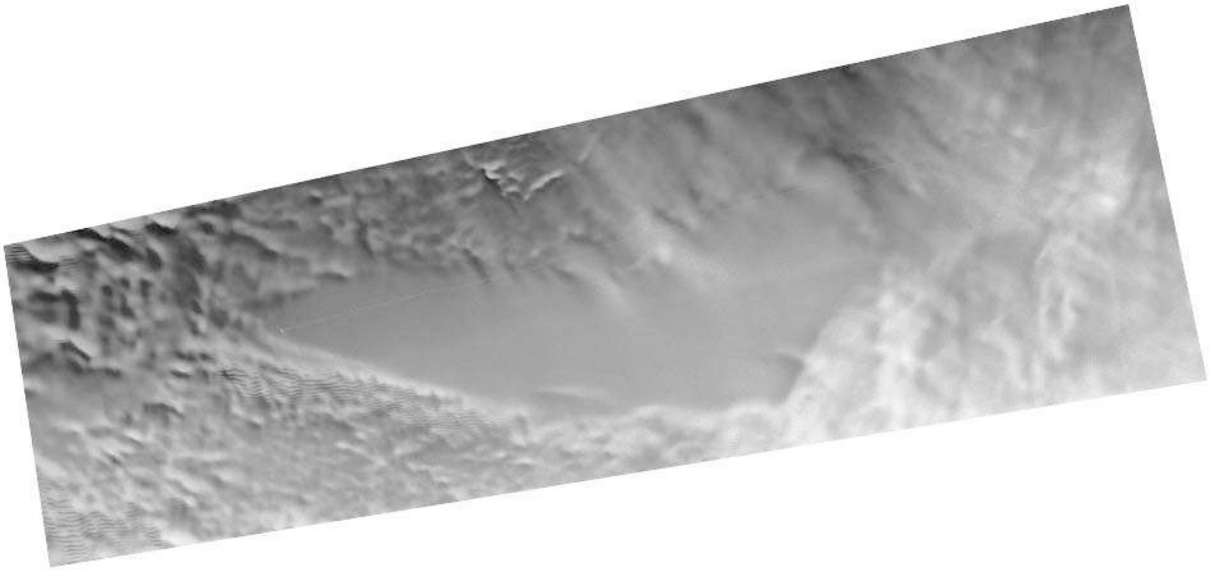

FIGURE 4.5 This mosaic of synthetic-aperture radar images from Radarsat-1 shows the surface expression of subglacial Lake Vostok. Located in East Antarctica, this lake is buried beneath almost 4000 m of ice and is roughly the size of Lake Ontario. Image courtesy of K.C. Jezek.

These similarities make the exploration of Lake Vostok an invaluable tool for evaluating and testing techniques for exploring physically buried bodies of water such as might be found on Europa. In situ analysis of the aqueous environment might be accomplished using a cryobot/hydrobot,[3,4] a development of the so-called thermal or Philberth probes developed more than 30 years ago for polar and glacial studies on Earth.[5] Appropriate measurements to be made of the water would include salinity, pressure exerted by the overlying ice, light-scattering properties, and acidity. Temperature profiling will allow a search for geothermal inputs, which are thought to be critically important for long-lived biotic systems functioning in isolation from sunlight. Measurement of chemical gradients in key redox compounds have proven to be good indicators of functioning ecosystems. Such stratified chemical fingerprints would include oxygen, hydrogen, methane, carbon dioxide, nitrogen and sulfur compounds, and dissolved iron and manganese. The presence of various classes of organic compounds, and even microorganisms themselves, might be determined using fluorescence spectroscopy.

A desired analysis strategy would include measurements made at various depths in the water column and in the bottom sediments (although it is unclear whether an ocean on Europa would be floored by sediments, or even whether the ocean floor could be reached). It would also be desirable to be able to make measurements in Lake Vostok after stirring the bottom waters and/or sediments to monitor possible effects of anaerobic activity. Finally, it would be useful to operate the hydrobot on the sediment interface for an extended time, to monitor changes in variables over time that would result from biological activity.

The above in situ experiments could demonstrate that even unknown biological systems might be capable of being discovered and studied using relatively simple chemical and physical measurements. Moreover, characterization of the habitability of Lake Vostok would be as useful for testing strategies for exploring a completely foreign ecosystem (including appropriate planetary protection issues) as for testing the required technology. Environments to be evaluated include ancient systems with extinct biota, contemporary functioning ecosystems, and "extremophile" populations in the overlying ice. All activities relating to the exploration of Lake Vostok and other pristine environments should be conducted only within the framework of an appropriate awareness of the ecological sensitivity of such endeavors.

Ice-Probing Technology Development and Demonstration

Radar sounding can provide high-resolution, global mapping of the internal structure of Europa's ice shell. Given knowledge about Europa's depth-varying dielectric properties, ice thicknesses could be estimated to better than several hundred meters using a system operating between 1 and 100 MHz. A source of uncertainty in the interpretation of radar data is the lack of information about the dielectric properties of the ice that are needed for estimating both propagation velocities and attenuation. An estimate of the thickness of Europa's ice accurate to 10% is not possible unless the ice's average bulk dielectric properties are known to the same degree of certainty.

Within terrestrial glaciers, and presumably on the europan surface ice, there will be physical structures that can scatter radar energy. These can take the form of a surface roughened by physical stress, compositional variations associated with the presence of rocky debris or salt deposits, or even meteoritical debris deposited onto the surface. Moreover, because radar is a ranging instrument, energy from targets distributed at different locations, but at the same electrical range, are unresolvable with a simple radar. It is particularly challenging to separate clutter owing to the surface-illuminated footprint of the radar from weaker signals reflected from a deeper ice-water interface. Indeed, ice-sounding radars have not been successfully used from orbit because of the clutter-separation problem. Clutter rejection algorithms must be tested over complicated terrain (such as Jacobshavn Glacier, Greenland) as part of proof-of-concept studies.

Exploration of Life in Extreme Environments

Earth-based field studies of life in extreme environments have identified deep subsurface organisms that thrive in the dark on chemical reactions, organisms that conduct redox reactions in hydrothermal systems at temperatures in excess of 100°C and that are energetically independent of photosynthesis, and organisms that live in ice or rock or in thin films of liquid water stabilized below 0°C. All of these discoveries of extremophiles contribute to the notion that life may be possible on Europa.[6] As more is learned about life in all of these extreme environments, the results will continue to inform ideas about whether there is or can be life on Europa. Progress in studying these environments is likely to be brisk now that the National Science Foundation has initiated the Life in Extreme Environments (LExEn) program and NASA has established its Astrobiology Institute.

Life is found in an enormous diversity of surface and deep environments on Earth, many of which were long thought to be sterile.[7] It now appears that life may be present anywhere on Earth that there is a source of energy, and, at least occasionally, liquid water. In recent years microorganisms have been found living in the ice at both poles,[8] at the bottom of the deepest oceanic trenches, in continental hot springs, in submarine hydrothermal systems where elevated pressure keeps water from boiling at 100°C,[9] at pH values from 0.4 to 12, in brines and saturated salt solutions,[10] within rocks at the surface, and deep in the continental crust (up to several kilometers deep) and oceanic crust (to a depth of at least 700 m).[11] As a result, it is currently known that life thrives at temperatures ranging from several degrees below 0°C to nearly 115°C, and at pressures up to at least 1000 bars. Several investigators expect to find life at temperatures up to 150°C or so, and at several kilobars pressure.[12,13]

Both high- and low-temperature environments on Earth provide analogs for what may be possible on Europa. The potential for life in plausible environments on either planetary body can be tested by assessing the forms of available energy, the quantity of energy, and the extent to which that energy can be focused. An enormous contribution to this effort can be made by quantifying the availability of chemical energy forms in extreme terrestrial environments that support life.

Much of the effort to quantify energy sources could profitably focus on autotrophs, organisms that capture energy from the environment to generate organic compounds from inorganic forms of carbon, nitrogen, sulfur, phosphorus, and other elements. In the case of chemoautotrophs (organisms that gain their energy from chemical reactions), recent progress has been made in quantifying the geochemical energy available in terrestrial environments if an organism can mediate reactions and take advantage of this energy.[14–16] Recent progress provides the ability to calculate the thermodynamic data at almost any temperature and pressure of interest.[17–21] What is generally lacking are adequate analytical data appropriate to the environment of interest.

Carbon, sulfur, nitrogen, iron, and other redox-sensitive elements exist in more than one oxidation state, and these various forms can be present at concentrations that are far from chemical equilibrium. As an example, H_2S in contact with Earth's O_2-rich atmosphere is unstable and should react to form sulfate. If the reaction is slow, as this oxidation reaction is at low temperatures, then coexisting H_2S and O_2 represent food to a sulfide-oxidizing microorganism. At high temperatures, terrestrial geochemical constraints necessitate that most energy-yielding reactions are reduction reactions, like the formation of CH_4 from bicarbonate and H_2 in submarine hydrothermal systems.[22] In any event, the thermodynamic calculations require analytical data on iron, sulfur, carbon, nitrogen, and other elements that can exist in variable redox states.

Quantitative inventories of available energy in terrestrial environments can be complemented with laboratory studies of the energetic demands of microorganisms. It will then be possible to answer questions about the amount of biomass that can be supported by a geochemical process in a surface or subsurface environment.[23] At present, microbial growth experiments on extremophiles focus on optimum temperatures, and ranges of salinity, pH, and temperature, at which an organism can live. Missing from this approach is an assessment of the amount of energy provided by chemical reactions that is required to grow and maintain a given cell concentration. For example, although we know that *Methanococcus jannaschii* is an autotrophic methanogen living optimally at 85°C in submarine hydrothermal systems, we do not know how many cells of this organism can be supported on the disequilibrium between hydrogen and bicarbonate present in the natural system.

In addition, little is known about the energy requirements of the metabolic pathways used by chemolithoautotrophs and other extremophiles at the actual temperatures and pressures where they live. Does a hyperthermophile require more or less energy to make peptide bonds than is required by a low-temperature organism? What is the energy yield of ATP hydrolysis at the high temperatures and pressures encountered deep in hydrothermal systems? How do the redox potentials of important biochemical processes change with temperature and pressure? Although hints about the answers to these questions are currently available, more definitive results could help identify likely metabolic strategies used by novel organisms in unfamiliar environments.

A unifying theme of energy availability and energy demand, if quantified, would enable transport of microbial growth data from the laboratory to the study of natural environments. It would then be possible to test whether a given geochemical process can yield enough energy to support a given metabolic strategy, and, if it can, how many organisms can be supported. These studies would permit quantitative estimates of the potential for life on Europa or in terrestrial environments that might be close analogs to conditions on Europa.

LABORATORY STUDIES

Space Weathering of the Surface Materials

There is considerable observational evidence that it is necessary to understand space weathering in order to interpret reflectance properties and ages of surface features on Europa. The surface materials are weathered by plasma ions and electrons from the jovian plasma torus, solar ultraviolet photons, and micrometeorite bombardment, all occurring in the presence of a tenuous oxygen atmosphere that is itself a product of ion bombardment. These are processes that also occur on the surfaces of other objects that have tenuous or no atmospheres. Whereas laboratory studies directed toward lunar materials are extensive, however, the materials of interest for Europa (ices, salts, and organics) have been little studied. The principal need is data on irradiation effects—plasma and ultraviolet weathering of these materials. The types of data required pertain to the effects of weathering on the production of gas-phase molecules (sputtering and decomposition), changes in reflectance, and chemical alterations induced in the surface. These effects are clearly interrelated. Because of the detection of S (as SO_2) and Na, the chemistry of an H_2O-S-Na system subjected to a radiation environment needs to be understood.

In the last 10 years there has been a considerable effort to understand the ion bombardment of water ice. This process results in redistribution of H_2O molecules across the surface of Europa and also in the production of O_2 that contributes to Europa's atmosphere and H_2 that escapes into space. These data, along with those for the sputtering and chemistry of other frozen volatiles of potential importance (e.g., SO_2 and CO_2), have been summarized in *Solar System Ices*.[24] However, there is still a dearth of data on the spectral changes linked to irradiation of these ices, including the absorbance properties produced by implantation of S and Na ions from the jovian torus into water ice, which are especially relevant to Europa. Careful laboratory measurements are required to allow derivation of ages of surface materials from absorption band depths and ion fluxes.

Over the same period, data on the effects of irradiation on organic materials have increased, in part motivated by space science studies, but also owing to the fact that heavy energetic-ion bombardment ejects whole molecules into the gas phase, a process of interest in the study of biomolecules. However, key pieces of data are missing. Surprisingly, there is much more data on the spectral properties of irradiated organics than there are absolute yields for small-molecule production (e.g., CO_2, HCN, and HCO) due to decomposition induced by ion bombardment. Such data are key to understanding the ambient gas and local plasma that can, in principle, be detected either by the Hubble Space Telescope or by a mass spectrometer on an orbiter. A key issue is to identify decomposition products that are indicative of prebiotic materials brought to the surface. In addition, because the dominant sputtering agents at Europa are the energetic heavy ions (~100 keV S^+ and O^+), large fragments or whole molecules can be ejected. However, measurements of absolute yields of these large molecules and/or fragments are needed.

The most urgent need is data on the sputtering and irradiation alteration of salts and hydrated minerals. The presence of materials such as magnesium and sodium sulfate or carbonate hydrates is suggested by modeling and observations by Galileo's NIMS. Although it is known that bombardment will lead to ejection of H_2O from these hydrated minerals and Na is a principal product of Na-containing minerals, other ejecta are less certain. In an oxidizing environment, SO_2 from the sulfates and CO_2 from carbonates might be expected as decomposition products. A longitudinally correlated dark stain seen in images of Europa is inferred to be due to polymerized sulfur, but in high-resolution images the younger linea are darker and seem to lighten with age. Therefore experiments on the alteration of minerals by irradiation are critical for understanding how the effects of sulfur implanted by the plasma compete with the effects of sulfates created by sputtering of tectonically emplaced subsurface materials. Finally, also, almost no data exists on isotopic effects in radiation-induced alterations.

Rheological Properties of Impure Water and Ice

Abundant theories exist to explain Europa's obvious differentiation and the subsequent tectonic mobility of its surface. Extensive studies on the viscosity, density, and shear strength of pure water ice have been conducted.[25] However, Galileo's images have established cross-cutting relationships that suggest that the most recent, up-welling material may not be pure ice but is, rather, rich in sulfur, sulfur-bearing minerals, or other dark, red materials, based on the visual albedo. Galileo has resolved linear features and lineaments that are strings of splotches, as well as larger patches of mottled terrain, all of which show that surface tectonism is widely variable in both style and color, with an implied concomitant compositional heterogeneity.

Some theoretical and laboratory work has been done on the $MgSO_4$-H_2O system that is applicable to Europa.[26,27] However, early theoretical predictions that Europa's ice crust should contain abundant sulfates seem to have been countered by subsequent measurements suggesting that, in the $MgSO_4$-H_2O system, pure water ice nucleates first and this pure ice should be more buoyant than the solution. Condensed sulfate solids should "sink" within the solution, so it remains enigmatic how such impure systems become sufficiently unstable gravitationally to emerge in the observed dark lineaments on the surface. It may be that systems akin to terrestrial sea ice are a better Europa model, where nearly pure water ice forms a crust on the saline "ocean," increasing the salinity of the underlying liquid in the process. Local circulation controls the temperature and hence the stratification of this layer, and tidal flexure or circulation in the underlying liquid creates cracks through which the saline solutions appear. Alternately, localized heating from the rocky core may create "hot spots" that are then convectively unstable and push to the surface to create the more lobate or splotchy forms seen in Galileo images. Surface weathering processes then erode or redistribute the emergent material. In all likelihood a combination of scenarios is required to explain the diversity of geologic forms observed on Europa.

Clearly more observational work on impure ice systems at europan temperatures is required to help assess whether Europa's crust is stratified either as a solid/liquid or as compositional stratification in solid and/or possibly liquid layers. In addition to the $MgSO_4$-H_2O system, observations of both sulfur- and silicate-H_2O systems are important. Other relevant properties that have not been determined include the effects on strength properties of the inclusion of various amounts of impurities—e.g., is a salty ice-block crust more susceptible than pure ice to tidal flexure and heating? Would such a system preserve an interior "ocean" to the present day, or are the disturbed terrains only frozen-in remnants from a tectonically active period earlier in the satellite's history?

Geochemical Processes That Influence the Composition of a Potential Ocean

Compounds can reach oceans on Europa in essentially two ways: melting or overturning of the overlying and surrounding ice, or reaction of water with the underlying rock. Besides water and salts (or other compounds brought out from the interior during cryovolcanism), ice melting and overturning would deliver the other volatile constituents of the ice (such as NH_3, CO_2, and organic compounds) to the oceans, along with their alteration products resulting from sputtering processes or photochemistry. In addition, the ice would also contain embedded ions responsible for the sputtering processes (largely S^+, O^+, and H^+ from Io and/or Jupiter), as well as dust, meteorites, and other exogenous material. Water-rock reactions will contribute soluble compounds to the solution and are likely to strongly influence the pH, oxidation state, and concentrations of the major ions. Depending on the temperature and oxidation state of the water-rock system, there may be a potential for hydrothermal organic synthesis.

Sputtering experiments on ice-salt mixtures that could be appropriate to the study of the surface of Europa are lacking. Nevertheless, there are speculations that sputtering of sodium and magnesium sulfates in ice could produce compounds like NaOH and H_2SO_4, either of which could affect the pH if the ice were to melt. Redox conditions in the melt would be affected if potential sputtering products like SO_2, MgS, or O_2 were released to the solution. In addition, sputtering of organic compounds in ice from exogenous or endogenous sources may lead to ejection of small molecules like CO or HCN, and to cross-linking reactions in more refractory residues. Sputtering of hydrocarbons can lead to the production of H_2, CH_4, larger molecules, and a carbonized residue,[28] and experiments on other organic compounds have yielded CO, CO_2, HCN, HCO, other fragments, larger molecules, and carbonized residue.[29–31] The consequences of hydration reactions in the molten equivalents of these ices are unexplored.

Laboratory simulations of water-rock reactions appropriate to conditions on Europa are lacking. The suggestion that water on Europa would be a sulfate-rich solution if the composition of the rock were like that of carbonaceous chondrites may be corroborated once better resolution of NIMS spectra is achieved.[32,33] These measurements also suggest the presence of natron or other carbonate minerals in the ice of Europa. Experiments are needed that test the production of salt solutions during heating, dehydration, and decarbonation of model compositions for the interior of Europa.

The presence of sulfur as sulfate may require that the water-rock reactions occur at relatively low temperatures. As temperature increases, water-rock reactions should be capable of reduction of the sulfate. The range of temperatures at which sulfate reduction can occur depends largely on the composition of the rock, and to a lesser extent on the water-to-rock ratio. For example, calculations of water-rock reactions using the Murchison meteorite's bulk composition show that sulfate reduction is possible above about 100°C at low water-to-rock ratios.[34] However, the rates of sulfate reduction may be extremely slow at low temperatures even if they are strongly favored by thermodynamics. Although many hydrothermal sulfur redox experiments have been conducted in terrestrial systems, experiments designed to represent processes that can occur in icy satellites are lacking.

THEORETICAL STUDIES

Thermal History of Europa

Previous studies of Europa's thermal history argue convincingly that enough heat is generated by radioactive decay in the rocks inside Europa that separation of rock and metal from water must have occurred early in the evolution of the satellite. There is also enough energy from radiogenic heating for early differentiation of a metal core from the silicate-metal mixture. The present structure of metal core, rock mantle, and water outer shell must have been set early in the thermal history of Europa. Further thermal history modeling is needed, however, to assess whether Europa's core could have remained liquid and convective to the present and whether the outer water shell could have been prevented from completely freezing. Models that have already addressed the issue of freezing of the outer water shell have been equivocal in their results and have oversimplified or neglected important aspects of the problem.

The thermal history of Europa is, firstly, not only a thermal history but also a dynamical history. The two evolutionary aspects are coupled in an essential way because of the potential importance of tidal heating in the evolution of Europa. The dynamical problem involves not only Europa, but Io and Ganymede as well because of the dynamical resonance these bodies are in today—the Laplace resonance—and the possible role of other resonances in the past. The coupled dynamical evolution of these satellites depends on the tidal dissipative heating in all the satellites, particularly Io, so the thermal evolution of all the satellites is tied together. Researchers must therefore calculate the coupled thermal and dynamical evolution of Io, Europa, and Ganymede as a single system. Still other nonlinear couplings and feedbacks contribute to the challenge of modeling the thermal-dynamical history of the system through the dependence of the dissipative heating rates on the temperature-dependent and deformation-dependent rheologies of the satellites and their dynamically dependent and rheologically dependent deformations. The problem is a formidable one, and only isolated aspects of the evolutionary calculation have been attempted so far. The solution will require code development and significant computational resources by today's standards. Adding to the difficulties is the uncertainty in the relevant rheological behaviors and the parameter values of potentially applicable constitutive laws. The numerical code will have to be extremely efficient to allow the exploration of broad ranges of parameter space.

Theoretical Exploration of the Biological Potential of Europa

Theoretical studies can constrain the abundance of energy available on Europa for life, once some additional compositional data are available. Only the most general tests are possible with the observational data currently available, even when augmented with results of condensation models for the jovian nebula. As compositional and geophysical data from Europa missions become available, the results of theoretical models may be considerably different than at present.

Europa's volatile budget depends on the kinetics in the protojovian nebula. If hydration of silicates occurred in this nebula,[35] then Europa's ice layer/ocean may be a product of the dehydration of the silicate interior. Otherwise, Europa's ice may have condensed directly from the protojovian nebula, either locally or in more distant, cooler regions, and then been scattered inward gravitationally. One particular set of thermochemical models of the composition of ice in the protojovian nebula suggests that melting europan ice could yield an aqueous solution with abundant NH_3, together with traces of HCN and HCO_3^-.[36] This assumes maximum radial mixing in the nebula, and that such mixing may have extended as far in as Europa at some stage of condensation. This solution composition is relatively depleted in carbon, but it is unlikely that Europa accreted without at least a few percent nonvolatile carbon phases, as in carbonaceous chondrites. During initial heating and dehydration of Europa's silicate interior, and subsequent volcanism, this carbon would most likely have been driven out as CO_2 (similar to the case of Triton),[37] and the europan ocean has been estimated to contain as much as ~0.3 mole % CO_2.[38] Greater CO_2 concentrations would result in plating out of CO_2-clathrate at the base of the ocean, which if sufficiently thick might seal the ocean from hydrothermal interaction.

Results of theoretical studies of water-rock reactions show that the single most important factor in determining the potential for hydrothermal organic synthesis is the oxidation state imposed by the composition of the rocks that host hydrothermal systems.[39] It follows that rigorous constraints on the compositions of the outermost layer of silicates, and their influence on the compositions of hydrothermal fluids, are major determinants in testing the potential for hydrothermal organic synthesis on Europa. Preliminary results suggest that hydrothermal systems on Europa are likely to generate altered rocks that have many similarities with altered basalts in the oceanic crust of Earth.[40] On the other hand, the fluid compositions, which may be extremely reduced or have highly alkaline pH, may be dramatically different from those in black smokers (i.e., terrestrial submarine hydrothermal vents). In addition, if the potential for organic synthesis during hydrothermal alteration is considerable it may have implications for the composition and physical properties of the lower-most layers of ice, as well as the possibility that living systems could emerge in the dark using chemical energy supplied by the disequilibrium between hydrothermal fluids and molten ice.

Although essential, characterization of geophysical, petrological, and geochemical properties is not sufficient to reveal the difference between a hydrothermal system and a hydrothermal ecosystem. The possibility that a hydrothermal system can support life depends on how well it can meet the demands that life places on it. Is the supply of carbon sufficient for biosynthesis? Are nutrients available at useful concentrations? Is sufficient energy available in usable forms? As mentioned above, the energetic requirements of hyperthermophilic organisms are largely unknown. Given sufficient analytical data, it is possible to evaluate the geochemical energy available from various inorganic reactions used by autotrophs in terrestrial hydrothermal ecosystems. As an example, it is now possible to determine the amount of energy that can be obtained by a methanogen in a seafloor hydrothermal system at the precise temperature and pressure at which it lives. However, we do not know why this is enough energy, because the energetics of many biochemical reactions and metabolic processes have not been studied at elevated temperatures and pressures.

Dynamics of Ice in the Europan Environment

Terrestrial ice sheets deform under the force of gravity in a fashion determined by boundary conditions at the sides and bottom. On short time scales, ice behaves elastically and, for large stresses, ice undergoes brittle fracture. For low stresses, operating over long times, ice undergoes creep deformation.

The terrestrial sea-ice pack moves under the influences of ocean currents and winds that frequently exert forces strong enough to fracture individual floes. The effective rheology of the polar ice pack is governed primarily by consequent macroscopic processes such as ridging, rafting, and lead formation rather than the intrinsic rheology of the sea ice itself.

The surface of Europa seems to be composed of features suggestive of icebergs locked in a sea-ice matrix, block rotation and displacements, brittle fracture, and, perhaps, creep deformation as evidenced by flow-stripe-like structures on the surface of some blocks. Consequently, and perhaps at different times, the surface of Europa may have behaved somewhat like terrestrial ice sheets and sea ice cover. More enigmatic are the banded ridges running for hundreds of kilometers across the surface. These features, more reminiscent of terrestrial tectonic processes, have no apparent analog in the terrestrial ice environment and may be related to the tidal stresses exerted on Europa by Jupiter.

Observations such as these lead to several questions that could be explored by modeling of ice dynamics. These include the following:

- What long-term processes might lead to creep deformation?
- Where and how did the ice sheet fracture, and did fracturing result in an upwelling of liquid water?
- What forces caused rotation of the ice blocks? and
- Is convection possible within the ice sheet?

TELESCOPIC OBSERVATIONS

Earth-based telescopic observations have played an important role in advancing current understanding of Europa (see Chapters 2 and 3). The key advantages of future Earth-based (as opposed to spacecraft) data collection are the ability to look for long-term (yearly or decadal) variability, the capability of using very-high-spectral-resolution spectroscopy, and the advantages afforded by telescopes with large apertures.

At ultraviolet wavelengths, the Hubble Space Telescope (HST) will continue to provide high-resolution spectral capability, along with moderate spatial resolution. These are the most important for studies of the atmospheric composition and the morphology of the gas distribution. Detection of magnesium, for example, could rule out Io as a source of Europa's tenuous atmospheric constituents. Additional HST observations of the oxygen atmosphere could provide limits on its temporal variability.

An explosion of large-telescope construction heralds a new era of Earth-based observations of Europa at visible and near-infrared wavelengths. More than a dozen new large telescopes are expected to have first light by 2003, and virtually all of them are expected to have instrumentation with spectroscopic capability in the visible and near infrared. Even moderate-sized telescopes, when combined with the power of high-spectral-resolution spectroscopy, can provide valuable observations of Europa. For example, long-slit high-resolution spectroscopy of the sodium 589-nm line made in 1995 revealed a large-scale atmospheric component sputtered from the surface.[41] Subsequent observations suggest that the sodium originates on Europa and may be coming from surface salts.[42] With the new larger-aperture telescopes, similar observations for potassium and calcium should be feasible, giving good geochemical constraints on the presence of trace species on the surface. In particular, ratios of abundances of sodium, potassium, and calcium, combined with HST measurements of magnesium, will help to constrain the types and sources of salts on the surface. Calcium observations in particular could be used to definitively rule out Io as a source of europan atmospheric elements.

Perhaps most exciting will be advances in near-infrared technology for telescopes with large (≥6 m) and very large (≥10 m) apertures. A 10-m telescope using adaptive optics at 2 microns has a diffraction-limited resolution of 170 km on Europa, or more than 20 resolution elements across the planet's diameter (Figure 4.6). This is sufficient to resolve diverse surface units for spectral mapping. Longward of 2.5 microns, Europa is faint, and thus a large-aperture telescope provides substantial gains in signal-to-noise ratio, even compared to observations from spacecraft located near Europa. Although many of the spectral signatures of frozen volatiles tend to appear in the near infrared, features do continue beyond 3 microns. When combined with the capability for high-spectral resolution (for example, using a Fabry-Perot imaging system or an infrared image slicer), the large apertures of these new telescopes will provide a useful tool for probing surface composition on Europa.

Other Earth-based investigations include the thermal infrared and radar observations. In the thermal infrared, observations have revealed a featureless spectrum at the 3% level.[43] Further investigation, at higher spectral resolution and looking for temporal variability, may be warranted. Expected resources include the Space Infrared Telescope Facility, the Stratospheric Observatory for Infrared Astronomy, and several of the large ground-based telescopes. With the newly refurbished Arecibo telescope, radar mapping of Europa may be revisited. Past observations have revealed the unique character of ice satellite radar reflection and scattering properties;[44] these observations can now be done with higher spatial resolution, potentially allowing regional terrains to be identified.

A key factor enabling large, ground- and space-based telescopes to observe Europa and other solar system objects will be their ability to track objects moving at a non-sidereal rate. Solar system objects move relative to the stars and more distant bodies that exhibit only the sidereal motion caused by Earth's rotation. Thus, telescope guidance systems must be able to lock onto a guide star moving at the sidereal rate and generate the necessary non-linear corrections to enable the telescope to track the independent motion of a planetary object. The correction can vary from an arc second per hour for a distant comet to an arc second per second for a near-Earth object. Europa's motion is closer to the former than to the latter extreme.

In principle, implementing such a capability is not technically difficult provided that the need for it is recognized early in the design of a telescope and its software. Unfortunately, in some notable cases this was not done. The guide-star systems on many ground-based telescopes are ill equipped to handle moving targets. Moreover, the procedures to enable tracking of solar system objects were not in place when the Hubble Space Telescope was launched, and work over several years was required to implement this capability. HST can now observe Europa relatively easily using linear approximations of the actual non-linear tracking rates. The rates are low enough that errors from the approximations are small. New ground- and space-based facilities must have a non-sidereal tracking capability with an accuracy analogous to that of HST.

TECHNOLOGY DEVELOPMENT FOR FUTURE EUROPA MISSIONS

Europa presents a challenging target for spacecraft exploration, a challenge that is multiplied by the complexity of the scientific tasks researchers are motivated to undertake there. While many of the scientific instruments needed for the successful exploration of Europa already have a heritage in past planetary missions, all will,

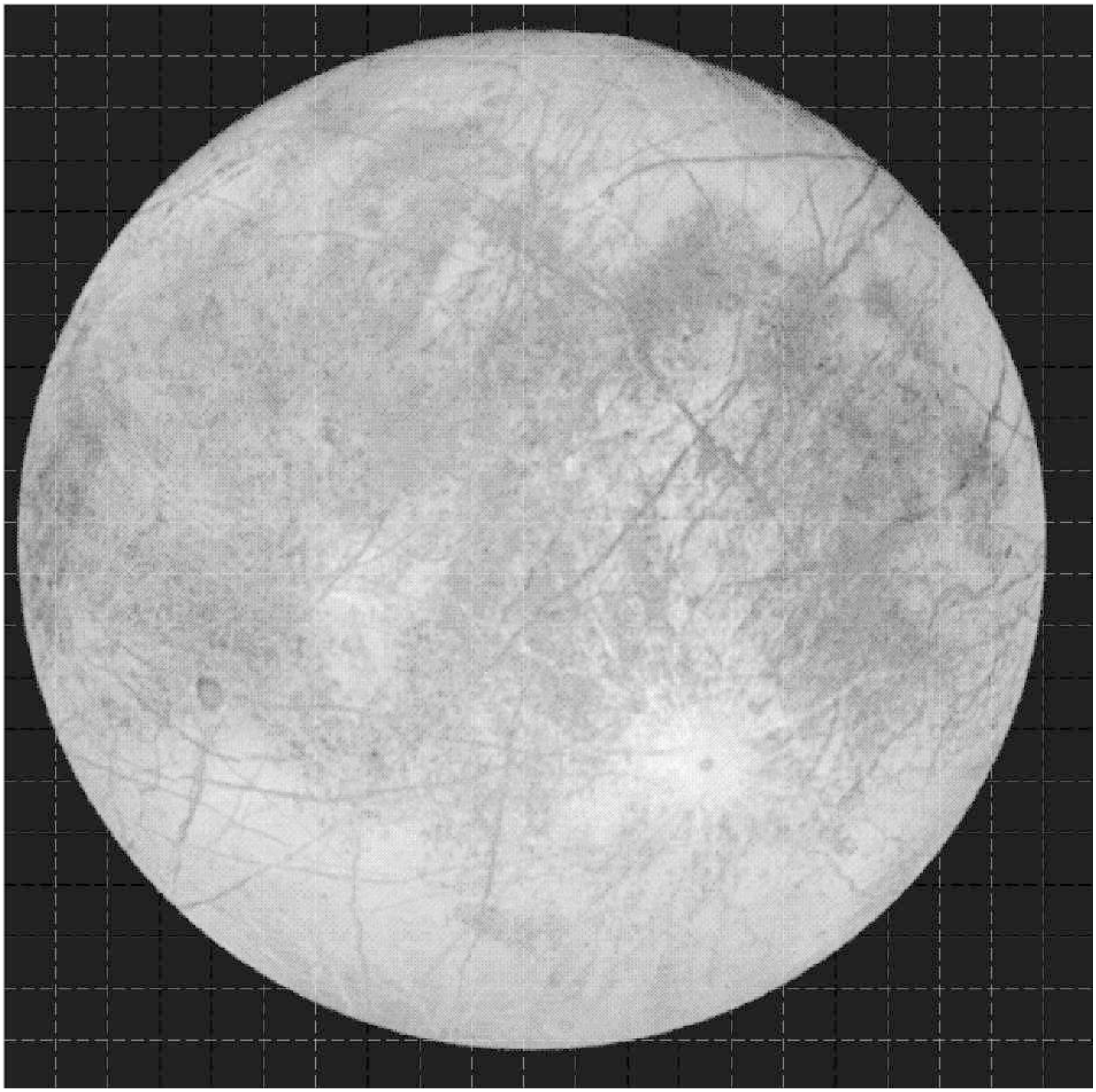

FIGURE 4.6 A Galileo image of Europa showing the size of the diffraction-limited resolution elements that can be obtained at a wavelength of 2 microns using a 10-m, ground-based telescope equipped with active optics. Image courtesy of M. Brown.

nevertheless, require technology development in many areas. These developments include (in approximate order of the relative priority assigned to each):

- Low-mass, radiation-hardened instrumentation to be used on orbiting spacecraft and on surface-deployed packages (including landers, rovers, and penetrators);
- Low-mass, compact-size, wavelength-tunable radar systems, or other subsurface remote-sensing systems, with a broad range of capabilities for measuring the thickness and structure of an ice layer with unknown and poorly constrained dielectric and mechanical properties;
- High-capacity communications to enable sophisticated application of microscopic and spectroscopic imaging techniques;
- Robotic systems capable of physically penetrating through substantial thicknesses of ice that may contain some unknown fraction of admixed rock with unknown size distribution;
- Robotic systems capable of in situ study of the organic chemistry and, perhaps, biochemistry of deep ice cores and/or subsurface liquid water;
- Robotic systems capable of reaching and exploring a subsurface layer of liquid water; and
- Robotic systems capable of returning samples of deep ice cores and/or subsurface liquid water to Earth.

Radiation hardening of sensitive electronic components presents, perhaps, the greatest near-term technological impediment to the future exploration of Europa. As discussed, the critical measurements of Europa's topography and gravitational and magnetic fields that provide the best hope for determining the existence of a global ocean require orbital measurements lasting for approximately a few tens of europan days (i.e., a few months). In this period, a spacecraft in a low orbit about Europa will accumulate a total radiation dose of more than 2 megarads. While many electronic components can be hardened to survive in such a radiation environment, it is unlikely that all can and, thus, they will have to be shielded. Shielding will increase the mass of the spacecraft or, more likely, reduce its payload capacity.

Thus, the design of an orbiter mission requires that a complex balance be struck between competing factors, including mission lifetime, instrument complement, and the scientific capability of those instruments. If the right balance is not found, an orbiter may not be able to provide a definitive answer to the fundamental question—Does Europa possess an internal ocean?—which is key to determining the priority assigned to future studies of this body.

If the existence of a europan ocean is confirmed by an orbiter, then attention will inevitably shift to sophisticated delivery vehicles such as cryobots and hydrobots, which offer the promise of eventual in-depth exploration of Europa. Penetrating to significant depths within the ice will be extremely difficult, but may be required to provide definitive answers to questions about europan life. The design, delivery, emplacement, and operation of such vehicles present many technical challenges, not the least of which is relaying data from a vehicle through many kilometers of ice.[45] Much preliminary exploratory, experimental, and theoretical work needs to be done prior to their final design, outfitting, and deployment, however. Most direct measurements of europan properties in the foreseeable future will be made above, at, or on the surface, or at very shallow depths within the ice. Much about the interior can be learned from measurements from orbit and by detailed examination of materials at the surface.

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5

Related Issues

PLANETARY PROTECTION

Planetary protection issues for Europa, like those for other solar system bodies, have two components—forward contamination and backward contamination.[1,2] The former relates to the potential for inadvertently transporting terrestrial organisms to Europa and either causing potential harm to extant europan life or contaminating experiments to determine whether life exists. The latter relates to the return to Earth of samples from Europa that have the potential to contain living organisms, with the possibility that inadvertent release of such organisms into the terrestrial environment may cause harm. These issues are dealt with separately below.

Forward Contamination

Prevention of the forward contamination of Europa and other planetary bodies is motivated by two different, but complementary, objectives.[3,4] The first is the desire to minimize the introduction of any material that can interfere with or confound measurements of the europan environment, especially as they pertain to the efforts to understand prebiotic or biotic activity. The second is the very unlikely, but non-zero, probability of introducing a terrestrial microorganism that might conceivably take hold in some ecological niche in the europan environment and, as a result, become directly or indirectly detrimental to the indigenous biosphere.

Differences Between Mars and Europa

To date, considerations of forward contamination have focused principally on Mars, the most plausible abode of past or present life to which spacecraft have been dispatched. Several characteristics of the martian environment have, however, led to the drafting of planetary protection requirements that emphasize the preservation of science rather that the protection of biospheres.[5] These characteristics include the following:

- *Indications based on the Viking mission and subsequent studies that the martian surface is not, in general, conducive to the proliferation of life.* The lack of liquid water and resources to support metabolism, an average temperature well below freezing, and the presence in the near-surface regolith of oxidizing materials that can destroy organic molecules or organisms all make life extremely unlikely.

- *The low current rate of geologic activity on the martian surface.* Spacecraft hardware on the martian surface thus may not be substantially disturbed for millions, perhaps billions, of years.
- *The likelihood that plausible martian environmental niches conducive to life are localized rather than globally connected.* Thus, even if a single location were to become contaminated by terrestrial organisms or organic molecules, it is unlikely that the contamination would spread either regionally or globally.

Europa's environment, however, is sufficiently different from that of Mars that more attention may have to be paid to the protection of any indigenous europan biota.[6] Factors arguing for a possible shift toward protection of potential biospheres over preservation of the science include the following:

- *Europa has been geologically active at global scales in the geologically recent past.* It has been resurfaced relatively recently, and the average age of the surface is probably no more than 10 million to 100 million years. Radiogenic heating in Europa's rocky core and the dissipation of tidal energy in its icy shell drive the extrusion of water or ice onto the surface, resulting in the erasure of existing surface features and, presumably, the entrainment and subduction of old surface materials.
- *The global character of any ocean enhances the hazard of contamination.* If terrestrial organisms were to make their way into a europan ocean and were able to grow and multiply using resources there, they would quickly be distributed globally.

Thus, spacecraft hardware and other contaminants emplaced onto Europa's surface would be incorporated into the ice, and, if it exists, a sub-ice ocean on a time scale of 10 million to 100 million years. Moreover, it must be assumed that contamination that did make its way into the ocean has the potential to contaminate the entire ocean and not just a localized part of it.

Europa's harsh radiation environment would only partly mitigate this effect. Although radiation can break the chemical bonds in organic molecules like those found in terrestrial organisms, thus effectively killing any introduced organisms, the radiation would penetrate only to very shallow depths (meters) into the subsurface. Thus, a spacecraft that made an uncontrolled descent onto Europa's surface and buried debris into the subsurface, or a successful lander that deployed a subsurface penetrator, could emplace material at depths where terrestrial organisms might survive for extremely long periods of time.

Protecting Science Versus Protecting Biospheres

Although it is premature to assume that Europa has either an ocean or indigenous biota, prudence dictates the adoption of controls on forward contamination that assume both are present. Similarly, although it is extremely unlikely that any known terrestrial organism could survive the long journey to, and intense radiation around, Europa, nevertheless the survival of terrestrial organisms in a variety of extreme environmental conditions, including low temperatures and high radiation, is well documented.[7,8] Moreover, a variety of terrestrial microorganisms could possibly grow in a europan ocean, including methanogens, sulfate reducers, anaerobic methane oxidizers, oligotrophic anaerobic heterotrophs capable of growing (albeit slowly) on low concentrations of organic compounds, and acetogens (John Baross, University of Washington, private communication, 1999).

Thus, prudence also dictates that measures be taken to ensure that terrestrial organisms are not inadvertently transferred to Europa. The scope of the provisions will depend on the degree to which emphasis is placed on preserving the scientific integrity of future observations or on protecting any indigenous europan organisms.

COMPLEX has made no attempt to determine the relative weight that should be given to these imperatives. Indeed, such a determination would require a study in itself. Such a detailed consideration of imperatives, particularly as they apply to the Europa Orbiter mission, is currently being undertaken by the Space Studies Board's Task Group on the Forward Contamination of Europa. Rather than attempt to prejudge the outcome of the task group's study, COMPLEX outlines two possible positions, one that favors preserving the integrity of studies of Europa's biotic and prebiotic conditions and another favoring the protection of possible europan organisms.

Preserving Scientific Integrity. A great deal of attention has been paid to the procedures that need to be taken to prevent contaminating planetary bodies to such an extent that future scientific studies are compromised.[9] Most of the attention has been paid to Mars, for which current procedures include careful cleaning of spacecraft, ensuring that orbiters do not crash within 50 years of launch, and determination of the geographic locations of landing and crash sites.[10] The detailed requirements for Europa remain to be determined, but they would probably be similar to those for Mars. That is, they would be designed to protect Europa for a finite period of time during which biological exploration could proceed unencumbered by terrestrial contamination.

One issue of particular concern for Europa is the potential for inclusion of organic material in spacecraft arriving at Europa. This concern stems from the great interest in finding out whether or not any kinds of primitive biochemical building blocks—including amino acids and sugars, fatty acids, and also nitrogen bases and phosphate esters—are available on Europa. The search for biochemicals would likely begin on Europa's surface. Indeed, it is possible that the coloring agent in the "dirty" ice may contain interesting organic material. Analysis of ice cores would likely be undertaken with technology that has already been developed for ice analyses on Earth; subsequent analysis of material from beneath the ice might be even more revealing. Precautions would have to be taken to ensure against contamination during the operation of coring and other types of subsurface sampling devices.

If biochemical signatures were ever detected on Europa, immediate consideration would have to be given to the possibility that they were in fact contaminants from Earth. Mass-isotopic analysis of any such material might be an easy way to confirm the nonterrestrial origin of the material. Beyond that, the presence of biochemicals ought not to be taken as prima facie evidence of past or existing life. Further analysis, including measurements of optical activity, hydrolyzable polymers, and many others would have to be performed. In every case, the caveat would be to ensure that the measuring device did not contaminate or interfere with any of the measurements being undertaken. (For example, nylon and other hydrolyzable materials should not be included as a part of any of the instrumentation without proper analysis and precautions.)

Preserving Indigenous Organisms. Accepting the goal of not harming possible europan organisms requires that planetary protection proceed not just for a brief period of biological exploration. Rather, it must continue indefinitely or until it can be demonstrated that no ocean or no organisms are present.

This requirement means that any spacecraft reaching Europa's surface must have undergone some form of bioload reduction, perhaps analogous to that achieved following the dry heating of the Viking landers. Moreover, this requirement would probably apply equally to orbiters that would eventually impact Europa's surface and to landers. A reduced level of protection might apply to spacecraft whose design or mission profile was such that the most heavily shielded portion of its interior would receive a sterilizing dose of radiation prior to contacting Europa's surface.

Backward Contamination

Sample-return missions from Europa are still a long way off, and the opportunity to learn from planned sample-return missions to Mars is obvious. Indeed, all of the discussion about planetary protection for upcoming Mars missions is directly applicable to Europa.[11] The gist of those discussions is that the threat of returning material from space that is potentially hazardous or deleterious to the terrestrial environment is exceedingly small but cannot be set at zero; as a result, appropriate precautions must be taken.[12] Indeed, a recent NRC study concluded that samples from Europa "should be contained and handled similarly to samples returned from Mars."[13] Included among these precautions is that attention must be paid to the important matter of public relations and education. Given the high level of public interest in the exploration of Europa and the search for life elsewhere in the solar system, it is important to ensure that any rumors or misinformation about potential hazards do not become exaggerated.[14]

Nonetheless, as the dates for potential sample-return missions draw nearer, it would be prudent to appoint a program oversight committee that can reconsider these issues in the light of new knowledge and technology.

INTERAGENCY COOPERATION

Studies of Europa can benefit in several ways from cooperative interactions between NASA and other federal agencies. For example, the National Science Foundation (NSF), through its Office of Polar Programs, funds a broad variety of research activities in the Antarctic and other icy terrestrial regions; much of the work relating to ice cores and glaciers has clear importance for planning studies of Europa. Studies of Lake Vostok, mentioned in Chapter 4, are an example of research in which close cooperation between NASA and NSF is critical. Scientific activity in the Antarctic is governed under the terms of the Antarctic Treaty, which guarantees cooperation and unrestricted scientific access that in turn requires coordination through various national agencies and with international bodies (e.g., the Scientific Committee for Antarctic Research). Because NSF is tasked with coordinating all U.S. Antarctic research activities, access by NASA must be through interagency cooperation. In turn, NASA can provide technologies useful to NSF-funded scientists, so mutually beneficial cooperative activities can occur.

The NSF also supports studies of life in extreme environments, most recently through its Life in Extreme Environments (LExEn) program. These studies extend and complement work in exobiology and astrobiology funded by NASA. Cooperation between the two agencies may enable more rapid progress and reduce overlap in exobiological research.

Another important area of potential interagency cooperation is the development and testing of electronic and optical components hardened to survive the intense europan radiation environment. Although NASA and DOD requirements once drove innovations in electronics, commercial users have recently become dominant. As a result, radiation-resistant hardware is not being developed as extensively as it once was, and the development of radiation-hardened electronic components has become prohibitively expensive. Thus locating off-the-sheet electronic and optical components suitable for spacecraft use requires extensive searching, and extensive testing must be done to prove their capabilities.

Finding such components, however, does not necessarily result in identifying a steady source of suitable components, because variations across manufacturing lots may lead to significant differences in the radiation tolerance of a given component, or subcomponents may come from different suppliers. Moreover, most companies are not forthcoming about uniformity in manufacturing and do not trace from which lot a particular set of units came, or whether procedures or suppliers have changed. Thus, testing of the actual flight components is often necessary. Further, miniaturization of electronic components has led to a higher degree of catastrophic failures, as opposed to the mere inconvenience of transient losses of information or operations.

Agencies besides NASA that would benefit from access to a long-term, stable supply of radiation-hardened components include the Department of Defense and the Department of Energy, which need flight components that can survive exposure to high levels of radiation. Similarly, the National Oceanic and Atmospheric Administration will need to pay greater attention to radiation hardening as its increasing role in the monitoring of space weather (i.e., disturbances in the solar-terrestrial environment) will require the deployment of operational monitoring satellites beyond geosynchronous orbits. Moreover, civilian users, such as the communications-satellite industry, may require radiation-hardened components for communications satellites that may be placed at altitudes within Earth's radiation belts. A cooperative program to provide better sources for radiation-hardened electrical and optical components could offer broad benefits. The December 1998 announcement that NASA and other government agencies will have access to a radiation-hardened version of the Pentium processor, thanks to an agreement between Intel Corporation and the Department of Energy, is a useful beginning.

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6

Conclusions and Recommendations

PRIORITY STATUS OF EUROPA EXPLORATION

With the likelihood that it has vast quantities of liquid water beneath its icy surface, Europa is one of the places in our solar system with the greatest potential for life. Along with Mars, it appears to possess all of the environmental conditions necessary to support the origin and the continued existence of biota. As a result, finding evidence that might indicate whether life had existed on either Mars or Europa would help us to understand whether our theories for the origin of life on Earth are correct and would help us to understand whether life might be widespread outside our solar system.

Thus, COMPLEX concludes that Europa is an exciting object for additional study following the completion of the Galileo mission. It presents the opportunity for major new discoveries in planetary geology and geophysics, and planetary atmospheres. In addition, Europa offers the potential for studies of extraterrestrial life. In light of these possibilities and the equal priority given to the exploration of Mars and the Jupiter system by COMPLEX's *Integrated Strategy*,[1] COMPLEX feels justified in assigning the future exploration of Europa a priority equal to that for the future exploration of Mars. This equality must, however, be tempered by the uncertainty as to whether liquid water is actually present and the technological challenges posed by the exploration of Europa.

The two highest-priority overall science goals identified by COMPLEX for exploration of Europa reflect the emphasis on the potential for life as a major driver in Europa's exploration:

1. Determining whether liquid water has existed in substantial amounts subsequent to the period of planetary formation and differentiation, whether it exists now, and whether any liquid water that is present is globally or locally distributed.
2. Understanding the chemical evolution that has occurred within the liquid-water environment and the potential for an origin of life and for its possible continuation on Europa.

THE NEED FOR A SYSTEMATIC PROGRAM OF EXPLORATION

COMPLEX recognizes the frustration that will inevitably result from following a well-conceived strategy for conducting a thorough and detailed investigation of the potential for life on Europa that likely will take one or two decades to carry out. With the excitement today about understanding the limits of life on Earth and searching for life elsewhere, it is tempting to try to initiate a spacecraft mission that will immediately search for europan life or return samples of surface ice to Earth for such analyses. However, the history of space exploration suggests that a phased approach, in which the results of one mission provide the scientific foundation for the next incremental advance, is more productive in the long term.

We need only look to the history of the search for life on Mars, however, to see the difficulty of crafting such an approach. While the Viking missions seemed very well conceived in 1970, they look naive today in the light of current understanding of the martian environment, and of the diversity of life on Earth and its ability to survive in extreme environments. Viking did not sample the most appropriate environments in its search for extant life on Mars. The results from the Viking biology experiments, though, have provided a remarkable foundation for an understanding of martian geochemistry that is playing a key role in knowing how and where to look for life on Mars today.

In a similar vein, the absence of identifiable surface environments that might support life or contain evidence of life on Europa and our complete lack of understanding of the chemical environment of the icy surface layer, the liquid water layer that may or may not underlie it, and the rocky interior of Europa suggest that a detailed exploration of the satellite will provide the best opportunity to answer these exciting questions.

Thus, **COMPLEX recommends that Europa be explored within the framework of a well-conceived and planned strategy designed to create a scientific base of information that is sufficient to provide a global context for interpreting data pertaining to the possible presence of life on Europa.** A comprehensive understanding of the geology, geochemistry, and geophysics of Europa, and of the nature of its atmosphere, is not strictly necessary in order to determine if liquid water is present. Knowledge of these is necessary, however, to assess the potential for life, and to determine whether life is present.

COMPLEX concludes that, should it turn out that liquid water is not present on Europa and has not been present in geologically recent times, the strong evidence for comparatively recent or ongoing geologic activity still makes it an appropriate target for exploration. However, the priority accorded Europa in the solar system exploration program and the sequence of exploration activities would have to be reassessed at that time.

The search for extinct or extant life on Mars, and the geophysical and geochemical analyses that are a fundamental part of the search, will provide substantial new insights into the environments in which life might exist and the precursor and resulting molecules that might obtain. Similarly, the search for life in extreme environments on Earth is providing key new insights into the potential for life elsewhere in the universe. In both cases, the new results need to be integrated into the ongoing Europa program to ensure a solid basis for investigation and analysis.

Thus, **COMPLEX recommends that the search for evidence of present or past life on Europa, or for evidence of chemical evolution that has the potential to lead to life, should be coordinated with other aspects of the search for possible abodes of life in the solar system.**

ELEMENTS OF A COMPREHENSIVE EXPLORATION PROGRAM

A comprehensive exploration of Europa that can address the major scientific goals will require a combination of spacecraft missions, ground-based telescopic observations, technology development, and supporting research and analysis. The scientific priorities for exploring Europa should proceed from the global to the local scale in searching for liquid water, determining the composition of the surface and near-surface ice, and exploring any pockets or oceans of liquid that might be discovered. The set of spacecraft missions to Europa that follows from this, then, likely should proceed from a polar orbiter, to landed experiments, to subsurface devices that can penetrate to depths necessary to reach liquid water. COMPLEX recognizes that implementation of such an ambitious sequence of spacecraft, with each being able to take advantage of results from the earlier missions, may require decades.

COMPLEX recommends that a staged series of missions be utilized to explore Europa, with the scientific focus of the first mission being to determine whether liquid water exists at the present epoch or has existed

relatively recently. If liquid water is present, the focus of follow-on missions should be to characterize surface materials and to access and study the liquid water.

PRIORITIES FOR THE INITIAL EUROPA MISSION

COMPLEX recommends that the primary goals for the first Europa mission should be determining whether a global ocean of liquid water exists beneath the icy surface, determining if possible the spatial and geographical extent of liquid water, determining the bulk composition of the surface material, and characterizing the global geologic history and the nature of any ongoing surface and atmospheric processes. These science objectives can best be met by observations from polar or near-polar orbiting spacecraft.

Specific measurement objectives include, in priority order:

1. Obtaining measurements of the time variations of Europa's global topography and gravity field over a period of several tens of orbits of Europa around Jupiter, with a precision and accuracy of ±2 meters to uniquely distinguish between tidal distortions of several meters (expected for a completely solid body) and several tens of meters (expected if a global layer of liquid is present). The results of these efforts will allow a unique conclusion regarding the present-day existence of a global liquid-water layer;
2. Imaging Europa's surface, with resolution of at least 300 m/pixel for global coverage with higher resolution (< 50 m/pixel) for selected regions, to understand the global geologic history and identify regions where liquid water may be readily accessed;
3. Performing radar sounding of Europa's subsurface structure to a depth of 5 to 10 km, to identify possible regions where liquid water might exist close to the surface. If the ice is less than 5 to 10 km thick, use of ice-penetrating radar may allow determination of the vertical extent of the surface ice layer (and possibly a direct detection of any underlying liquid water), as well as the local structure of the ice;
4. Mapping the near-infrared reflectance spectrum of Europa's surface materials globally at kilometer-scale resolution, supplemented by 300-m resolution in selected areas, and using the results to identify the bulk composition of the surface materials, their abundances, and their spatial distributions. A spectral resolution of 10 to 15 nm will be required;
5. Measuring the magnetic field to a precision of 0.5 nT under a variety of different background conditions (i.e., at different jovian longitudes), combined with coordinated measurements of the plasma environment, to determine whether there is an intrinsic magnetic field and what the properties of either the intrinsic or induced field are. Such measurements may provide important information about the structure of and dynamical processes operating in Europa's deep interior; and
6. Determining the composition and properties of the atmosphere using both in situ and remote-sensing experiments.

PRIORITIES FOR FOLLOW-ON EUROPA MISSIONS

Following the systematic orbital characterization of Europa, the focus of follow-on missions should shift to studies of the nature of Europa's surface materials and the means to access and study any liquid water present.

COMPLEX recommends that the science objectives for follow-on experiments designed to elucidate the properties of Europa's surface materials include in situ determination of the composition of the ice and of any non-ice surface components, including the bulk material, trace elements, isotopes, and mineralogy; analyses of any organic molecules at or near the surface, and identification of endogenic or exogenic sources; determination of the composition and properties of the atmosphere and of any materials sputtered from the surface; and estimation of the absolute ages of surface materials. These science goals probably can best be met using a landed package of instruments on Europa's surface.

If subsurface liquid water is detected and found to be accessible with an instrumented probe, **COMPLEX recommends that the science objectives of subsequent missions include determination of the physical and chemical properties of the water, including salinity, acidity, pressure and temperature profiles within the**

water, abundances and chemical gradients in key redox compounds, and existence and abundances of organic materials; determination of the composition and abundance of suspended particles; exploration of the properties at the water-ice interface; and a search for extant life in the water.

LABORATORY, THEORETICAL, AND TELESCOPIC STUDIES

Much additional laboratory and theoretical work is required in order to interpret and understand existing and likely future spacecraft observations. This will be the case whether or not liquid water has been present during geologically recent periods. As this is an area of active pursuit, specific measurement requirements are not enumerated here. However, the measurements generally center on reflectance spectroscopy of hydrated salts, salt-ice mixtures, and other potential components of the europan surface; measurements are needed of the physical and chemical effects of radiation from the near-Jupiter environment on surface materials, including salts, ices, and possible organic compounds, and the sputtering properties of these same materials.

COMPLEX recommends that a vigorous program of laboratory measurements and supporting theoretical analyses be carried out, to encompass the nature of materials at temperatures, pressures, and irradiation conditions likely to be found on Europa.

Theoretical analysis is involved not just in interpreting laboratory measurements but also in understanding the structure and composition of the interior and the interactions of Europa with its environment. Such theoretical analysis, for example, led to the first predictions of tidal heating of Europa and the potential for liquid water to exist.

COMPLEX recommends that NASA support a program of theoretical analysis of the geophysical and geochemical environment at Europa, including the nature of the interior, surface, atmosphere, and magnetospheric interactions.

Earth-based (both ground-based and orbital) telescopic observations and analyses will play an important role in further exploring the nature of the atmosphere and surface, providing input into understanding the geological and geochemical context of spacecraft measurements of Europa and the composition and evolution of its atmospheric and surface materials.

In order to be able to take advantage of the next generation of telescopes and instruments that are currently being developed, **COMPLEX recommends that new large telescopes and instrumentation that are being developed incorporate, from the beginning of the design stage, the ability to observe relatively bright targets moving with respect to the background stars, and that these capabilities be implemented in a timely manner. For new ground- and space-based facilities, a non-sidereal tracking capability with an accuracy analogous to that of the Hubble Space Telescope would be appropriate.**

TECHNOLOGY DEVELOPMENT

New technology and methods will be required for the operation of spacecraft in the challenging europan environment, as well as for exploring the properties of a possible ocean and its potential for life. It is necessary, for example, to measure the thickness and structure of an ice layer that has unknown dielectric and mechanical properties, to physically penetrate through substantial thicknesses of ice in order to reach liquid water, to move in a controlled manner in making measurements in a sub-ice layer of liquid water, and to relay information derived during subsurface activities to the surface and then to Earth.

COMPLEX recommends that low-mass, radiation-hardened instruments be developed for use on orbiting and surface spacecraft.

COMPLEX further recommends that devices that can penetrate through any surface ice and explore the subsurface ice and possible liquid water ocean on Europa be developed, on a schedule that will allow them to be launched on possible spacecraft missions a decade from now.

COMPLEX recommends the development of appropriate diagnostic remote tests and instrumentation for determining the physical and chemical properties of a sub-ice ocean and for detecting the presence or potential for life.

TERRESTRIAL ANALOGS

Research on terrestrial analogs of the Europa environment will allow the development of and provide proof-of-concept testing for new technologies required for the exploration of Europa. The use of radar to explore thick glacial ice sheets on Earth is an obvious example of the relevance of this approach. The exploration of the ice-water and ice-rock boundaries on terrestrial ice as an abode for life also may offer valuable lessons in exploration strategy.

COMPLEX recommends that NASA continue its collaborative efforts with other government agencies to explore sub-ice freshwater lakes (such as Antarctica's Lake Vostok) and sub-ice-shelf ocean environments as a means of understanding scientific, technological, and operational issues associated with the exploration of isolated environments.

COMPLEX recommends that peer review be used to select Earth-analog programs and investigators to ensure a significant and appropriate level of participation by all of the relevant scientific communities.

INTERDISCIPLINARY AND INTERAGENCY ISSUES

The exploration of Europa is an interdisciplinary venture, and various aspects of the necessary science and technology background are being investigated at present by federal agencies other than NASA, including the National Science Foundation, the Department of Defense, the Department of Energy, and the National Oceanic and Atmospheric Administration and the Office of Air and Space Commercialization within the Department of Commerce. Some of the Earth-analog studies, for example those in Greenland and Antarctica, will require sensitivity to international agreements and treaties. Additional international issues could arise in connection with the possible biological contamination of Europa by spacecraft from Earth, the potential for back-contamination of Earth if samples from Europa that may contain biologically active materials should ever be returned to Earth, or in launching spacecraft that carry radioisotope thermoelectric generators.

COMPLEX recommends that NASA, to avoid "reinventing the wheel," look to other government agencies to deal with some of the scientific and technological issues and to cooperate with governments of other countries in exploring Earth analogs.

COMPLEX endorses the planetary protection procedures and policies articulated in previous NASA and NRC documents and recommends that appropriate planetary protection measures be determined and implemented on all relevant spacecraft missions.[2]

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