Evaluating the Biological Potential in Samples Returned from Planetary Satellites and Small Solar System Bodies: Framework for Decision Making

Task Group on Sample Return from Small Solar System Bodies, National Research Council

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Evaluating the Biological Potential in Samples Returned from Planetary Satellites and Small Solar System Bodies

Framework for Decision Making

Task Group on Sample Return from Small Solar System Bodies
Space Studies Board
Commission on Physical Sciences, Mathematics, and Applications
National Research Council

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Foreword

For the first time since the Apollo program, NASA has specific plans to bring samples to Earth from elsewhere in the solar system. The earliest mission, Stardust, is scheduled to be launched in 1999 and return approximately 7 years later with a collection of cometary and interplanetary material. Other missions in various stages of definition would gather bits from Mars, an asteroid, or the satellites of Jupiter.

Prudence demands giving proper attention to handling extraterrestrial samples so that they pose no risk to Earth's biosphere. At the same time, an unreasonable level of concern could needlessly escalate the cost of sample handling or obviate such missions altogether.

Since Mars is the place most often considered as a possible host of past or present microbial life forms and one from which samples will surely be returned within the next decade, it has received the greatest amount of attention, including a recent study by a task group of the Space Studies Board (National Research Council, 1997, *Mars Sample Return: Issues and Recommendations*, National Academy Press, Washington D.C.). The present report broadens the scope of consideration to encompass the other bodies in the solar system.

The report finds that the degree of caution required in handling material depends on its site of origin. To a high degree of confidence, some returned samples do not need special handling precautions. Others might be in this category, but the degree of confidence is lower. For still others, the samples should be handled with the same degree of containment as would be applied to material from Mars.

In addition, the report considers further research that would inform this issue and reduce areas of uncertainty. Learning how some of Earth's hardier microbes would fare under the extreme conditions of radiation and temperature can help increase our understanding of the sterilization processes that occur naturally in parts of the solar system.

Since NASA has plans to bring Mars rocks back to Earth within a decade, the proper procedures for handling the most suspect samples must be put in place. This report shows that the full machinery of containment will also be required for some material, but certainly not everything, collected in our neighborhood.

Claude R. Canizares, *Chair*
Space Studies Board

Preface

The National Research Council's Space Studies Board provides guidance to NASA on planetary protection, which is the effort to preserve conditions for future biological and organic exploration on planets and other solar system objects and to protect Earth and its biosphere from potential extraterrestrial sources of contamination. In 1997, the Space Studies Board produced the report *Mars Sample Return: Issues and Recommendations*, which assessed the potential for a viable exogenous biological entity to be included in a sample returned to Earth from Mars as well as the potential for large-scale effects if such an entity were inadvertently introduced into Earth's biosphere. The report provides justification for and recommendations on procedures for the quarantine of samples returned from Mars.

Given the prospect of sample return missions from various small solar system bodies in the next decade, NASA then requested that the Board assess the potential for a living entity to be present in or on samples returned from small solar system bodies such as planetary satellites, asteroids, and comets. Guidance from the new study would extend and generalize to other solar system bodies the published advice regarding Mars.

In response to NASA's request, the Space Studies Board convened the Task Group on Sample Return from Small Solar System Bodies to assess the potential for a living entity to be present in or on samples returned from small solar system bodies by addressing the following:

- The potential for a living entity to be contained in or on samples returned from planetary satellites or small solar system bodies, such as asteroids, comets, and meteoroids;
- Detectable differences among small solar system bodies that would affect the above assessment;
- Scientific investigations that need to be conducted to reduce the uncertainty in the above assessment; and
- The potential risk posed by samples returned directly to Earth from spaceflight missions, as compared to the natural influx of material that enters Earth's atmosphere as interplanetary dust particles, meteorites, and other small impactors.

The task group met three times over an 11-month period, reviewed relevant reports, was briefed by representatives from NASA and expert researchers and practitioners on topics related to sample return, and held a workshop to obtain a wide spectrum of perspectives. The task group considered in some detail the following topics:

1. The possibility that, at some time in the past, life originated on a body from which a sample might be taken, or that life was transported there from elsewhere in the solar system;

2. The possibility that life still exists on the body either in active or in reactivatable form; and
3. The potential hazard to terrestrial ecosystems from extraterrestrial life if it exists in a returned sample.

The central concern addressed by the task group in this report is the possibility that samples returned to Earth from small solar bodies might harbor living entities that could harm terrestrial living organisms or disrupt their ecosystems. The primary audience for the task group's report is NASA, those who have a stake in sample return missions and planetary protection, and the public at large.

The task group members wish to thank those individuals who made presentations at the task group meetings, including Sherwood Chang, NASA-Ames; Christopher Chyba, University of Arizona; Ben Clark, Lockheed-Martin; John Cronin, Arizona State University; James Ferris, Rensselaer Polytechnic Institute; Marina Fomenkova, University of California, San Diego; Ted Roush, San Francisco State University; and Perry Stabekis, Lockheed-Martin. Special thanks are given to John Rummel and Michael Meyer for serving as the project's points of contact at NASA and for their presentations to the task group.

Acknowledgment of Reviewers

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 content of the review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their participation in the review of this report:

Rita R. Colwell, University of Maryland;
Ellis Cowling, North Carolina State University;
Michael Gaffey, Rensselaer Polytechnic Institute;
Donald M. Hunten, University of Arizona;
Marsha I. Lester, University of Pennsylvania;
Harry Y. McSween, Jr., University of Tennessee;
Norman R. Pace, University of California, Berkeley;
Everett L. Shock, Washington University; and
John A. Wood, Harvard University.

Although the individuals listed above provided many constructive comments and suggestions, responsibility for the final content of this report rests solely with the authoring task group and the NRC.

Contents

Executive Summary

As advances in the biological and planetary sciences enable a shift from mere observation to active exploration of the solar system, space missions are increasingly likely to collect samples from planetary satellites and small solar system bodies and return them to Earth for study. This is an exciting development that offers the opportunity to search for extraterrestrial life forms and improve understanding of the origin and composition of the solar system. But sample return also involves potential risks that need to be understood and managed properly.

Accordingly, the National Aeronautics and Space Administration (NASA) asked the Space Studies Board of the National Research Council (NRC) to assess the potential for a living entity to be contained in or on samples returned from planetary satellites and other small solar system bodies such as asteroids and comets. In response to NASA's request, the Space Studies Board established the Task Group on Sample Return from Small Solar System Bodies to address the following specific tasks:

- Assess the potential for a living entity to be contained in or on samples returned from planetary satellites or primitive solar system bodies, such as asteroids, comets, and meteoroids;
- Identify detectable differences among small solar system bodies that would affect the above assessment;
- Identify scientific investigations that need to be conducted to reduce the uncertainty in the above assessment; and
- Assess the potential risk posed by samples returned directly to Earth from spaceflight missions, as compared to the natural influx of material that enters Earth's atmosphere as interplanetary dust particles, meteorites, and other small impactors.

Concerns about potential risks from returned extraterrestrial materials are not new, having been raised initially more than three decades ago with the return of lunar samples during the Apollo program. In 1997, the National Research Council revisited these issues for samples returned from Mars and updated previous recommendations (NRC, 1992) for handling returned samples and avoiding planetary cross-contamination (NRC, 1997). This report of the Task Group on Sample Return from Small Solar System Bodies builds on and extends that earlier work.

STUDY APPROACH

Because there is no direct evidence that a living entity evolved or exists on any small solar system body, the task group examined indirect evidence based on data from Earth, meteorites, and the Moon and on astronomical observations of distant objects in an effort to assess whether NASA needs to treat samples returned from small solar system bodies differently from samples returned from Mars. To identify the requirements for the origin and survival of living organisms, the task group examined contemporary views on the range of conditions under which life can originate, the conditions required for the preservation of metabolically active organisms in terrestrial environments, and the somewhat different conditions needed to preserve living organisms in a dormant form. Based on this analysis, the task group identified six parameters (liquid water, energy sources, organic compounds, temperature, radiation intensity, and natural influx to Earth) as relevant to its assessment and formulated the following six questions to help determine how returned samples should be handled.

1. Does the preponderance of scientific evidence indicate that there was never liquid water in or on the target body?
2. Does the preponderance of scientific evidence indicate that metabolically useful energy sources were never present?
3. Does the preponderance of scientific evidence indicate that there was never sufficient organic matter (or CO_2 or carbonates *and* an appropriate source of reducing equivalents)[1] in or on the target body to support life?
4. Does the preponderance of scientific evidence indicate that subsequent to the disappearance of liquid water, the target body has been subjected to extreme temperatures (i.e., >160 °C)?
5. Does the preponderance of scientific evidence indicate that there is or was sufficient radiation for biological sterilization of terrestrial life forms?
6. Does the preponderance of scientific evidence indicate that there has been a natural influx to Earth, e.g., via meteorites, of material equivalent to a sample returned from the target body?

For the purposes of this report, the term "preponderance of scientific evidence" is not used in a legal sense but rather is intended to connote a nonquantitative level of evidence compelling enough to research scientists in the field to support an informed judgment. In applying the questions, the task group drew on existing data on the origin, composition, and environmental conditions (past and present) of each small body or planetary satellite examined and then determined whether the quality and weight of the evidence were convincing enough to allow making judgments and deriving findings. The answers to the questions, taken together, were used by the task group to reach a considered conclusion that the potential for a living entity to be in on a returned sample was either "negligible" or "not negligible." Because of the incomplete current state of knowledge about small solar system bodies, there are no definitive answers to the questions, and so all judgments regarding biological potential are qualitative (not quantitative).

The questions allow for a conservative, case-by-case approach to assessing whether or not special physical and biological isolation and handling of returned samples (containment) would be warranted, taking into account information about the different small bodies, natural influx to Earth of material from small bodies, and the possible nature of putative extraterrestrial life. An answer of "yes" to any question argues against the need for special containment beyond what is needed for scientific purposes. (Sample-handling requirements to support scientific investigations are currently under study by NASA.) For containment procedures to be necessary, an answer of "no" needs to be returned to all six questions. For such samples, strict containment and handling as outlined in Chapter 7 are required.

The task group chose to consider only two possible alternatives for containment and handling of samples returned from small solar system bodies: either (1) strict containment and handling of returned samples as outlined in the Mars report (NRC, 1997) or (2) no special containment beyond what is needed for scientific purposes. The task group ruled out intermediate or compromise procedures involving partial containment. In certain cases (e.g., P- and D-type asteroids) the limitations of the available data led the task group to be less certain, and therefore more conservative, in its assessment of the need for containment.

The following section summarizes the task group's findings with regard to the potential for a living entity to be present in samples returned from select planetary satellites and small solar system bodies. The selection was

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[1] For the purposes of this report, CO_2 or carbonates *and* an appropriate source of reducing equivalents is equivalent to "organic matter" to accommodate chemolithoautotrophs.

based on scientific interest and the likelihood of possible sample return missions to those destinations in the near future. These findings provided the basis for the task group's conclusions and recommendations, which are presented directly afterward.

FINDINGS

Planetary Satellites

Satellites are natural consequences of planetary formation processes. The task group considered the possibility of sample return from the major satellites of the innermost planets. These include the satellite of Earth (the Moon), satellites of Mars (Phobos and Deimos), and selected satellites of Jupiter (Io, Europa, Ganymede, and Callisto). The potential for a living entity to be present in samples returned from the Moon and Io is negligible. The potential for a living entity to be present in samples returned from Phobos, Deimos, and Callisto is extremely low, but the task group could not conclude that it is necessarily zero. Importantly, the task group found that there is a significant potential for a living entity to be present in samples returned from Europa and Ganymede.

Asteroids

Asteroids are the remnants of planetesimals—small primordial bodies from which the planets accumulated. Common asteroid types include undifferentiated, primitive types (C-, B-, and G-types); undifferentiated metamorphosed types (Q- and S-types [ordinary chondrites]); and differentiated types (M-, V-, J-, A-, S- [stony irons], and E-types). Other types of asteroids have been defined, including the common P- and D-types in the outer parts of the asteroid belt, but little is known about their composition and origin. Others are subdivisions of the types listed above, whereas still others are rare, new types, generally seen only among the population of very small asteroids. For undifferentiated, primitive (C-type) asteroids, the potential for a living entity to be contained in returned samples is extremely low, but the task group could not conclude that it is necessarily zero. Because of a fundamental lack of information about P- and D-type asteroids, the potential for a living entity to be present in returned samples cannot be determined and, therefore, was considered conservatively by the task group as possible at this time. For all C-type asteroids, undifferentiated metamorphosed asteroids, and differentiated asteroids, the potential for a living entity to be present in returned samples is extremely low, but the task group could not conclude that it is necessarily zero.

Comets

Comets are believed to have formed in the protoplanetary disk, at distances from the Sun ranging from the distance of proto-Jupiter to far beyond the distance of proto-Neptune. It is unlikely that a living entity could exist on comets, but the possibility cannot be completely ruled out except in a few cases, such as in the outer layers of Oort Cloud comets entering the solar system for the first time. Thus, the potential for a living entity to be present in returned samples from all comets was considered by the task group to be extremely low, but the task group could not conclude that it is necessarily zero.

Cosmic Dust

Because interplanetary dust particles (IDPs) are derived from a variety of sources, including interstellar grains and debris from comets, asteroids, and possibly planetary satellites, IDPs cannot be viewed as a distinct target body. As a result, the assessment approach used in this study does not lend itself readily to IDPs. Instead, the task group considered the potential source(s) of any IDPs that might be returned in samples. For the purposes of this study, IDPs are viewed as originating from either a single identifiable parent body or multiple sources. Particles collected near a particular solar system body are viewed as originating from that body, possibly including grains recently released from that body. Thus, the potential for a living entity to be present in returned samples, and the associated containment requirements, will be the same as those for the parent body. On the other hand, IDPs collected in the interplanetary medium may represent a mixture of dust originating from many parent bodies. Because IDPs in the interstellar medium are exposed to sterilizing doses of radiation, the potential for IDPs to contain viable organisms or a living entity is negligible.

CONCLUSIONS AND RECOMMENDATIONS

Table ES.1 summarizes the task group's assessment of the level of containment and handling warranted for samples returned from the planetary satellites and small solar system bodies examined in this study. Box ES.1 summarizes the requirements that apply to samples for which strict containment and handling are advisable. It is important to note that the task group's recommended approach is provided only as a guide and not as an inflexible protocol for determining whether containment is required. The final decision must be based on the best judgment of the decision makers at the time and, when possible, on experience with samples returned previously from the target bodies.

Containment of Returned Samples

On the basis of available information about the Moon, Io, dynamically new comets (specifically the outer 10 meters), and interplanetary dust particles (sampled from the interplanetary medium, sampled near the Moon or Io,

TABLE ES.1 Summary of Currently Recommended Approach to Handling Samples Returned from Planetary Satellites and Small Solar System Bodies Assessed by the Task Group on Sample Return from Small Solar System Bodies

I No Special Containment and Handling Warranted Beyond What Is Needed for Scientific Purposes		II Strict Containment and Handling Warranted
Ia *High Degree of Confidence*	Ib *Lesser Degree of Confidence*[a]	
The Moon	Phobos	Europa
Io	Deimos	Ganymede
Dynamically new comets[b]	Callisto	P-type asteroids
Interplanetary dust particles[c]	C-type asteroids	D-type asteroids
	Undifferentiated metamorphosed asteroids	Interplanetary dust particles[d]
	Differentiated asteroids	
	All other comets	
	Interplanetary dust particles[e]	

[a] Subcolumn Ib lists those bodies for which confidence in the recommended approach is still high but for which there is insufficient information at present to express it absolutely. This lesser degree of confidence does not mean that containment is warranted for those bodies; rather, it means that continued scrutiny of the issue is warranted for the listed bodies as new data become available. The validity of the task group's conclusion that containment is not warranted for the bodies listed in Ib should be evaluated, on a case-by-case basis, by an appropriately constituted advisory committee in light of the data available at the time that a sample return mission to the body is planned.

[b] Samples from the outer 10 meters of dynamically new comets.

[c] Interplanetary dust particles sampled from the interplanetary medium and from the parent bodies listed in subcolumn Ia.

[d] Interplanetary dust sampled from the parent bodies in column II and collected in a way that would not result in exposure to extreme temperatures.

[e] Interplanetary dust sampled from the parent bodies listed in subcolumn Ib.

BOX ES.1 SUMMARY OF REQUIREMENTS FOR SAMPLES THAT NEED STRICT CONTAINMENT AND HANDLING

All samples returned from planetary satellites and small solar system bodies that must be contained should be treated as potentially hazardous until proven otherwise. As in the 1997 Mars report (NRC, 1997), strict containment is recommended for all pristine sample material, and special handling procedures are needed for samples en route to and on Earth. If sample containment cannot be verified en route to Earth, the sample, and any spacecraft components that may have been exposed to the sample, should either be sterilized or not returned to Earth. Integrity of containment should be maintained through reentry of the spacecraft and transfer of the sample to an appropriate receiving facility. Furthermore, distribution of unsterilized materials returned from small bodies should be controlled and should occur only if rigorous analysis shows that the materials do not present a biological hazard. Finally, the planetary protection measures adopted for the first sample return mission to a small solar system body should not be relaxed for subsequent missions without a thorough scientific review and concurrence by an appropriate independent body.

or sampled in a way that would result in exposure to extreme temperatures), the task group concluded with a high degree of confidence that no special containment is warranted for samples returned from those bodies beyond what is needed for scientific purposes.

Recommendation: Samples returned from the Moon, Io, the outer 10 meters of dynamically new comets, and interplanetary dust particles (from the interplanetary medium, near the Moon, Io, or dynamically new comets), or sampled in a way that would result in exposure to extreme temperatures (e.g., spike heated), should not be contained or handled in a special way beyond what is needed for scientific purposes.

For samples returned from Phobos and Deimos, Callisto, C-type asteroids, undifferentiated metamorphosed asteroids, differentiated asteroids, and comets other than dynamically new comets, the potential for a living entity in or on a returned sample is extremely low, but the task group could not conclude that it is zero. Based on the best available data at the time of this study, the task group concluded that containment is not warranted for samples returned from these bodies or from interplanetary dust particles collected near these bodies. However, this conclusion is less firm than the conclusion for the Moon and Io and should be reexamined at the time of mission planning on a case-by-case basis.

Recommendation: For samples returned from Phobos and Deimos, Callisto, C-type asteroids, undifferentiated metamorphosed asteroids, differentiated asteroids, comets other than dynamically new ones, and interplanetary dust particles sampled near these bodies, a conservative, case-by-case approach should be used to assess the containment and handling requirements. NASA should consult with or establish an advisory committee with expertise in the planetary and biological sciences relevant to such an assessment. The goal of such an assessment should be to use any new, relevant data to evaluate whether containment is still not warranted. This assessment should take into account all available information about the target body, the natural influx to Earth of relevant materials, and the likely nature of any putative living entities. Such an advisory committee should include both NASA and non-NASA experts and should be established as early in the mission planning process as possible.

For samples returned from Europa and Ganymede, the task group concluded that strict containment and handling requirements are warranted. Because the knowledge base for P- and D-type asteroids is highly speculative, the task group concluded conservatively that strict containment and handling requirements are warranted at this time. Strict containment and handling requirements are also warranted for interplanetary dust particles collected near these bodies unless they are sampled in a way that would result in exposure to extreme temperatures, e.g., spike heated.

Recommendation: Based on currently available information, samples returned from Europa, Ganymede, P- and D-type asteroids, and interplanetary dust particles sampled near these bodies should be contained and handled similarly to samples returned from Mars (NRC, 1997). Interplanetary dust particles sampled in a way that would result in exposure to extreme temperatures, e.g., spike heated, should not be contained or handled in a special way beyond what is needed for scientific purposes.

Handling of Returned Samples

For samples that are returned from planetary satellites and small solar system bodies and that warrant containment, the concerns about biohazards or large-scale adverse effects on Earth are similar to those identified earlier for Mars (NRC, 1997). The task group concluded that the risks of pathogenicity from putative life forms are extremely low, because it is highly unlikely that extraterrestrial organisms could have evolved pathogenic traits in the absence of host organisms. However, because there are examples of opportunistic pathogens from terrestrial and aquatic environments that have not co-evolved with their hosts, the risk cannot be described as zero. The recommendations on containment and handling in the Mars report (NRC, 1997) represent a strong basic framework for addressing potential risks associated with returned samples warranting containment.

The microbial species composition of most anaerobic environments on Earth is not known, and consequently it is also not known how the species composition of these anaerobic microbial communities might change over time, what environmental factors might influence these changes, or what the incidence of and successful colonization by new species of microorganisms in these habitats might be. Accordingly, the task group concluded that although there is a low likelihood of a viable anaerobic microorganism surviving transport through space and finding a suitable anaerobic habitat on Earth, growth in a suitable habitat if found might be possible. This conclusion is necessary because of the current lack of information about anaerobic environments on Earth that may be analogous to environments on other solar system bodies, and the likelihood that the metabolic properties of such an extraterrestrial anaerobe would resemble an Earth anaerobe from a similar environment.

For overall evaluation of returned samples that warrant containment, it will be necessary to apply a comprehensive battery of tests combining both life-detection studies and biohazard screening.

Recommendation: Returned samples judged to warrant containment should be quarantined and screened thoroughly for indications of a potential for pathogenicity and ecological disruption, even though the likelihood of adverse biological effects from returned extraterrestrial samples is very low.

Recommendation: NASA should consult with or establish an advisory committee of experts from the scientific community when developing protocols and methods to examine returned samples for indicators of past or present extraterrestrial life forms.

Recommendation: The planetary protection measures adopted for the first sample return mission to a small body whose samples warrant special handling and containment should not be relaxed for subsequent missions without a thorough scientific review and concurrence by an appropriate independent body.

Scientific Investigations to Reduce Uncertainty

Identified by the task group in Chapters 2 through 6 is scientific research that could help to reduce the uncertainty in its assessment of the potential for a living entity to be contained in or on samples returned from planetary satellites and small solar system bodies. Because most of the suggested research topics are general in scope, they are not repeated here. However, one topic is of sufficient importance that it requires emphasis.

Because organisms subjected to sterilizing conditions for a sufficient time period pose no threat to terrestrial ecosystems, it is important to assemble a database on the survival capacity of a wide range of terrestrial organisms under extreme conditions. Despite the existence of a rich literature on the survival of microorganisms exposed to radiation and high temperatures, the studied taxa represent only a small sampling of the microbial diversity known to exist in the biosphere and, in general, have not been taken from extreme environments. Little is known about the radiation and temperature resistance of microorganisms from environments on Earth that have the chemical and physical characteristics likely to be encountered in or on small solar system bodies.

Recommendation: NASA should sponsor research that will lead to a better understanding of the radiation and temperature resistance of microorganisms from environments on Earth that have the chemical and physical characteristics likely to be encountered in or on small solar system bodies. Information on the survival of organisms subjected to long- or short-term ionizing radiation needs to be collected for both metabolically active and dormant stages of diverse groups of microorganisms, including hyperthermophiles, oligotrophic chemoorganotrophs, and chemolithoautotrophs. Likewise, it is important to establish short- and long-term temperature survival curves for similarly broad groups of metabolically active and dormant organisms. In particular, data are required on survival of diverse microorganisms under flash heating (1- to 10-second exposures) to temperatures between 160 °C and 400 °C.

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1

Introduction

As advances in the biological and planetary sciences enable a shift from mere observation to active exploration of the solar system, space missions are increasingly likely to collect samples from planetary satellites and small solar system bodies and return them to Earth for study. NASA plans to return such samples not only during the MUSES-C mission but also during missions proposed for NASA's Discovery program and in possible joint work with the Department of Defense (i.e., Clementine II). Several such missions are possible early in the next century (see Table 1.1). This is an exciting development that offers the opportunity to search for extraterrestrial life forms and improve understanding of the origin and composition of the solar system.

However, sample return also involves potential risks that need to be understood and managed properly. Concerns about potential risks from returned extraterrestrial materials are not new, having been raised initially more than three decades ago with the return of lunar samples during the Apollo program. NASA's planetary protection policy seeks to preserve natural conditions on planets and other bodies in the solar system while also protecting Earth and its biosphere from potential extraterrestrial sources of contamination (Appendix D gives details on current planetary protection requirements).

As the primary advisor to NASA for planetary protection policy, the National Research Council's Space Studies Board recently produced *Mars Sample Return: Issues and Recommendations* (NRC, 1997), which assessed the potential for inclusion of a viable exogenous biological entity in a sample returned to Earth from Mars as well as the potential for large-scale effects if such an entity were inadvertently introduced into Earth's biosphere. The report addressed how to protect Earth from possible contamination by putative martian biota and provided justification for and recommendations on procedures for the quarantine of samples returned from Mars.

TABLE 1.1 Sample Return Missions Being Planned

Mission	Destination	Launch (year)	Return (year)
Stardust	Comet Wild 2 and interstellar dust	1999	2006
Genesis	Solar wind	2001	2003
MUSES-C	Asteroid 4660 Nereus	2002	2006

In a similar vein, this report of the Space Studies Board's Task Group on Sample Return from Small Solar System Bodies considers whether samples returned to Earth from small solar system bodies might harbor living entities that could harm terrestrial organisms or disrupt ecosystems.

SCOPE AND APPROACH OF THIS STUDY

Because only self-replicating entities could pose a significant danger to terrestrial organisms and ecosystems,[1] the task group focused on the following topics:

1. The possibility that, at some time in the past, life originated on a body from which a sample might be taken, or that life was transported there from elsewhere in the solar system;
2. The possibility that life still exists on the body either in active or in reactivatable form; and
3. The potential hazard to terrestrial ecosystems from extraterrestrial life if it exists in a returned sample.

Assessing the potential for biological contamination of Earth by organisms present in samples returned from small solar system bodies requires identifying the range of conditions under which life can originate, as well as the environmental extremes that can be tolerated by metabolically active and inactive life forms. Life originates at the transition from a world of minerals and abiotically synthesized organic compounds to one of organic-based self-replicating systems capable of evolving by natural selection. This report recognizes forms of life that are composed of organic compounds and are dependent on organic chemistry; the task group had no relevant information for considering any other forms.

There is no direct evidence indicating that a living entity evolved or exists on small solar system bodies. Therefore, this report examines indirect evidence based on data from Earth, meteorites, other planets, the Sun, and the Moon and on astronomical observations of distant objects in an effort to assess whether NASA needs to treat samples returned from small solar system differently from samples returned from Mars. The quality of the available data varies for each type of small solar system body examined in this report. For example, far more data are available on the structure, composition, and history of the Moon than for any other body. The task group began by reviewing what is known about the origin of life on Earth, the conditions for the preservation of metabolically active organisms in a terrestrial environment, and the somewhat different conditions needed to preserve living organisms in an inactive form. It then attempted to generalize from terrestrial experience and to outline general requirements for the origin and survival of life that would apply on any solar body.

Based on this analysis, the task group identified six parameters (Box 1.1) as relevant to the assessment and arranged these parameters in a rough order of importance, while recognizing that the order might change somewhat depending on the solar system body being assessed.

A key concern of the task group was the identification of returned samples that do not require containment,[2] because containment has important financial and scientific implications for mission planning. Based on the six parameters identified as relevant, the task group formulated a series of questions as a basis for identification of whether or not samples require containment. These questions were used to assess the potential for a biological entity to be present in or on samples returned from planetary satellites, asteroids, comets, and cosmic dust. Based on the answers to these questions, the task group derived findings that it then analyzed with respect to their implications for sample containment and handling. The task group considered only two possible containment and handling requirements: either (1) strict containment and handling as outlined in the Mars report (NRC, 1997) or (2) no special containment beyond what is needed for scientific purposes. (Sample handling requirements to support scientific investigations are currently under study by NASA.) The task group ruled out intermediate or compromise procedures involving partial containment. In certain cases (e.g., P- and D-type asteroids) the limitations of the available data led the task group to be less certain, and therefore more conservative, in its assessment of the need for containment.

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[1] See NRC (1997) for a discussion on the potential for pathogenesis (toxic effects of microorganisms and infectious agents).

[2] The terms "contained" and "containment" are used in this report to indicate physical and biological isolation and handling of returned samples as specified for samples returned from Mars (see NRC, 1997).

BOX 1.1 PARAMETERS RELEVANT TO ASSESSMENT OF THE POTENTIAL FOR PRESENCE OF A BIOLOGICAL ENTITY IN RETURNED SAMPLES

1. *Liquid water:* Liquid water may safely be considered a requirement for life on small solar system bodies, because the chemistry on which life is based must take place in solution, and there is no other plausible solvent.
2. *Energy sources:* A source of energy to support the origin and continuation of life in any environment is a thermodynamic necessity. For extraterrestrial environments, the energy sources are more likely to be geochemical than photosynthetic.
3. *Organic compounds:* Chemical building blocks for organic polymers must be available.
4. *Temperature:* The temperature limits for the survival of metabolically active cells (160 °C) at 1 atm are likely to apply to extraterrestrial organisms also unless their biochemistry does not depend on the formation of amide, ester, or phosphodiester bonds.
5. *Radiation intensity:* Extraterrestrial biopolymers are unlikely to differ greatly from terrestrial biopolymers with respect to radiation sensitivity.
6. *Comparison to natural influx to Earth:* Earth receives a natural influx of material (in the form of dust and meteorites) from other bodies in the solar system. Some material may be delivered in ways that shield it from sterilizing temperatures or radiation.

CURRENT UNDERSTANDING OF ORIGINS, CONTINUANCE, AND SURVIVAL OF TERRESTRIALLIFE FORMS–A SYNOPSIS

Early Earth as a Model for the Origins of Self-replicating Life Forms

The planet Earth is 4.6 billion years old. The first life form appeared more than 3.5 billion years ago (Schidlowski, 1988; Schopf; 1993; Mojzsis et al., 1996) and rapidly evolved to microscopic, relatively simple cells. Over the ensuing years, primitive cells evolved into at least 10 million different species, which represent Earth's existing biological diversity. All organisms, including animals, plants, fungi, and an untold collection of microbial species, have their common ancestral roots within these earliest life forms.

Without exception, life in Earth's biosphere is carbon based and is organized within a phase boundary or membrane that envelops reacting biomolecules. Every documented terrestrial cellular life form is a self-replicating entity that has genetic information in the form of nucleic acid polymers coding for proteins. Biologically active systems require at a minimum liquid water, carbon, nitrogen, phosphate, sulfur, various metals, and a source of energy either in the form of solar radiation or from chemosynthetic processes.

The conditions that nurtured early self-replicating systems and their transition into microbial cells are speculative. In contrast, it is much easier to model the early stages of prebiotic evolution. Origins-of-life experiments have outlined the synthesis of the basic building blocks of life, including amino acids, nucleotides, and simple polypeptides and polynucleotides (Miller, 1992). It is even possible to demonstrate the evolution of nucleic acids in vitro and to select for specific catalytic properties (Doudna and Szostak, 1989; Lohse and Szostak, 1996; Wright and Joyce, 1997). Yet creation of self-sustaining, self-replicating biological entities capable of evolution has not yet been achieved in the laboratory and even if successful would not necessarily mimic how life started on Earth or in other parts of the universe.

For life to originate, the presence of liquid water and a source of utilizable free energy are necessities. Furthermore, life as we know it could not have begun on Earth at temperatures much above 160 °C (Stetter et al., 1990) because of the limited thermal stability of macromolecules and other cell components. The synthesis and polymerization of basic organic building blocks of life on Earth eventually led to self-replicating nucleic acids coding for proteins, but the earliest replicating systems were not necessarily composed of amino acids and nucleotides. If extraterrestrial biosystems exist, their modes of information storage, retrieval, and processing and their enzymatic activity may not be identical to those of biological entities on Earth.

Viability of Microorganisms

Microbes are far more likely than multicellular organisms to retain viability on small solar system bodies because they can adapt to a much wider range of environmental conditions. Single-cell organisms have infiltrated virtually every corner of Earth's biosphere and still constitute the bulk of Earth's biomass. They grow in temperate marine and terrestrial settings, within other microbial or multicellular organisms, in deep subsurface niches, and in extreme environments that would be lethal for other life forms. They often influence geochemical reactions within the biosphere and frequently play key roles in food webs and complex ecosystems.

The physiological state of microorganisms influences their ability to survive extreme environmental conditions (see Table 1.2). For example, organisms with active DNA repair mechanisms or a protective layer of material are more likely to endure exposure to ultraviolet (UV) or ionizing radiation than are cells without equivalent capabilities. Viable microorganisms are either metabolically active (vigorous) or dormant (quiescent). Communities of metabolically active microbes may increase in biomass or simply maintain a constant density by replacing dead cells with new ones. Sometimes metabolic activity is restricted to the repair of macromolecular machinery without cell division. Examples of metabolically active microorganisms include exponentially growing cells, cultures that have reached a stationary phase during which cell division occurs either very slowly or at a rate equivalent to that associated with cell death, and organisms that have shifted from exogenous to endogenous metabolism to survive starvation conditions. Dormant cells are metabolically inactive but are capable of returning to an active state. Examples include spores that are metabolically "frozen," freeze-dried cells, and cells that remain viable at suboptimal or freezing temperatures and/or in a desiccated state.

The distinguishing feature of a dormant versus a dead microorganism is the ability to recover from a quiescent to a metabolically active state. Differentiating dead cells from dormant or nonculturable microorganisms can be difficult. Only as few as 1 to 10 percent of the various kinds of microorganisms from most habitats such as the open ocean have been cultured successfully in the laboratory (Amann et al., 1995); the nutritional and physiological requirements of the vast number of viable but not yet cultured organisms are virtually unknown. Furthermore there is increasing evidence for the existence of consortia of microorganisms composed of taxa that are incapable of independent growth (Mar, 1982; Wolin, 1982; Warikoo et al., 1996; Zhang and Young, 1997), such as the symbionts of marine animals (Haygood and Davidson, 1997).

The inability to culture many of the microorganisms known to exist on Earth is of profound importance in estimating the possibility of microorganisms existing and/or surviving on small solar system bodies. Extremophiles not yet cultured certainly exist on Earth, and the ability of those that have been cultured to survive hostile conditions has already established new limits for the range of environmental conditions that can support viable organisms. Lack of knowledge about extremophiles on Earth is a significant source of uncertainty when assessing the probability of biological contamination of Earth by organisms that may be present in samples returned from small solar system bodies.

Factors That Influence the Survival of Metabolically Active Cells

The most important determinants for long-term survival of metabolically active organisms are the physical and chemical features of their environments, sources of available energy, chemical constituents of nutrients, and cellular processes associated with specific stages of an organism's life cycle.

Temperature extremes and elevated levels of ionizing radiation dictate environmental limits in which organisms cannot survive. Other parameters modulate the response of microorganisms exposed to high temperatures and radiation. The documented range of temperatures at which microbial growth is possible is –10 °C to 113 °C (Blochl et al., 1997; Grossman and Gleitz, 1993; Helmke and Weyland, 1995; Nickerson and Sinskey, 1972; Stetter, 1996), although the absolute limits remain to be determined. Psychrophilic (cold-loving) microorganisms

TABLE 1.2 Microorganisms with Particular Physiological and Nutritional Characteristics

Physiological Characteristic	Description
Temperature	
Psychrophile/facultative psychrophile	Optimal temperature for growth is 15 °C or lower, maximal temperature is approximately 20 °C, and minimal temperature is 0 °C or lower
Psychrotroph	Capable of growing at 5 °C or below, with maximal temperature generally above 25 °C to 30 °C; term in this case is a misnomer because it does not indicate nutritional characteristics
Mesophile	Generally defined by optimal temperature for growth, which is approximately 37 °C; frequently grows in the range from 8 °C to 10 °C and from 45 °C to 50 °C
Thermophile	Grows at 50 °C or above
Hyperthermophile	Grows at 90 °C or above, although optimal temperature for growth is generally above 80 °C; maximal growth of pure cultures occurs between 110 °C and 113 °C, although the maximum (113 °C) may well increase as further research is done
Oxygen	
Aerobe	Capable of using oxygen as a terminal electron acceptor; can tolerate a level of oxygen equivalent to or higher than the 21 percent oxygen present in an air atmosphere and has a strictly respiratory-type metabolism
Anaerobe	Grows in the absence of oxygen; some anaerobes have a fermentative-type metabolism; others may carry out anaerobic respiration in which a terminal electron acceptor other than oxygen is used
Facultative anaerobe	Can grow aerobically or anaerobically—characteristic of a large number of genera of bacteria including coliforms such as *Escherichia coli*
Microaerophile	Capable of oxygen-dependent growth but only at low oxygen levels; cannot grow in the presence of a level of oxygen equivalent to that present in an air atmosphere (21 percent oxygen)
pH	
Acidophile	Grows at pH values less than 2
Alkalophile	Grows at pH values greater than 10
Neutrophile	Grows best at pH values near 7
Salinity	
Halophile	Requires salt for growth: extreme halophiles (all are archaea), 2.5 M to 5 M salt; moderate halophiles, usually low levels of NaCl as well as 15 to 20 percent NaCl
Hydrostatic pressure (100 atmospheres per 1,000-m depth)	
Barophile	Obligate barophiles, no growth at 1 atmosphere of pressure; barotolerant bacteria, growth at 1 atmosphere but also at higher pressures. A number of deep-sea bacteria are called barophilic if they grow optimally under pressure and particularly if they grow optimally at or near their in situ pressure (0.987 atm = 1 bar = 0.1 megapascal [Mpa])
Nutrition	
Autotroph	Uses carbon dioxide as its sole source of carbon
Heterotroph	Unable to use carbon dioxide as its sole source of carbon and requires one or more organic compounds
Chemoorganoheterotroph	Derives energy from chemical compounds and uses organic compounds as a source of electrons
Chemolithoautotroph	Relies on chemical compounds for energy and uses inorganic compounds as a source of electrons Five classes: hydrogen bacteria, iron bacteria, sulfur bacteria, ammonia oxidizers, and nitrite oxidizers. Specific nutritional groups of bacteria that do not clearly fit in this category include obligate methane oxidizers and the carbon monoxide oxidizers. There are also photoorganoheterotrophs and photolithoautotrophs among the anoxigenic photosynthetic bacteria.
Mixotroph	Capable of growing both chemoorganoheterotrophically and chemolithoautotrophically; examples include some of the hydrogen bacteria and some species of *Thiobacillus* (sulfur-oxidizing bacteria)
Oligotroph	Can develop at first cultivation on media containing minimal organic material (1 to 15 micrograms carbon per liter) and grow on such media in subsequent cultivation
Copiotroph	Requires nutrients at levels 100 times those of oligotrophs

are not metabolically active below eutectic freezing points where liquid water is no longer available. A theoretical 160 °C upper limit on growth (at 1 atm pressure) is dictated by the thermal instability of macromolecules, membranes, and other cellular structures, but growth at temperatures even higher cannot be discounted when all environmental parameters (such as high pressure) are considered. Because the upper temperature limit for growth will depend on pressure, and the environments likely to be encountered in sample return missions will be at low rather than high pressure, the theoretical 160 °C upper temperature limit for growth is reasonable.

Unless sequestered within a protective niche, microorganisms associated with small solar system bodies will also be exposed to UV and ionizing radiation. The regions of the electromagnetic spectrum known to cause light-induced damage to microorganisms are the far UV (200 to 290 nm), near UV (290 to 400 nm), and visible light from 400 to 750 nm. Radiation at all of these wavelengths can induce lethal or sublethal damage in microorganisms at various intensities and can inhibit photosynthesis in aquatic environments. Ionizing and UV radiation in the presence of oxygen at high levels can lead to the formation of destructive oxygen radicals. Exposure to electromagnetic radiation at high levels will have a profound effect on any microorganism. The dose at which radiation is lethal or sublethal will depend on intrinsic cellular characteristics such as ability to sporulate, the capacity to synthesize protective pigments, and the efficiency of DNA repair mechanisms, since DNA is the primary site of radiation damage. The mechanisms for repairing radiation damage appear to be similar in all metabolically active organisms, but there is considerable variation in the lethal dose for each taxon.

As documented in the literature to date, the microorganisms most resistant to ionizing radiation are mesophilic and thermophilic *Deinococcus* spp. (Minton, 1994; Mattimore and Battista, 1996; Battista, 1997). These gram-positive, aerobic bacteria are 100 percent resistant to gamma radiation at doses of 4 to 5 kGy,[3] and a significant fraction can survive exposure at a level as high as 20 kGy—a level of ionizing radiation that is more than 100 times greater than the lethal dose for most organisms, including *Escherichia coli* and *Staphylococcus aureus*, and approximately 5 to 20 times the lethal dose for bacterial spores (Clark et al., 1998). Radiation resistance in *Deinococcus* is conferred by a very efficient repair system for double-stranded breaks in the DNA (Minton, 1994) and appears to be related to efficient physiological adaptation to desiccation (Mattimore and Battista, 1996; Battista, 1997). Little is known about the mechanisms of radiation resistance of other groups of microorganisms that live near natural sources of radiation, such as sulfide structures associated with hydrothermal vents (Cheery et al., 1992; Grasty et al., 1988) or anthropogenic reservoirs.

All metabolically active cells require liquid water, but microorganisms vary widely in their ability to grow and survive at different levels of water activity (a_w) and in their tolerance to desiccation, including that arising from increases in solute concentration. The maximum solute concentrations (w/v) permitting microbial growth vary with the specific solute. There are organisms that can grow in solutions that are 90 percent sucrose, 70 percent glycerol, and 30 percent NaCl (Kushner, 1978). The equivalent a_w for each is 0.85, 0.75, and 0.80, respectively. On the other hand, many microorganisms can survive in higher concentrations of solute than will permit growth or can survive in the absence of water (desiccation) (Potts, 1994), and both freeze-drying and use of glycerol solutions have enabled long-term preservation of viable microorganisms. Survival times for prokaryotic microorganisms in the air-dried state range from less than 10 minutes for some gram-negative bacteria on glass slides or in petri dishes, to thousands of years for spores in dried soils and for endolithic bacteria, to possibly millions of years in permafrost (see Potts, 1994, and references therein).

Information on osmotic pressure owing to desiccation or to increases in solute concentrations, such as might occur in fluid inclusions or mineral crystals, is important in assessing the potential for small solar system bodies to harbor viable microorganisms.[4] The osmotic pressure that limits the growth of extremophiles like the archaebacterium

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[3] 1 Gray (Gy) = 100 rads; 1 Gy represents energy absorption of 1 joule per kg.

[4] Osmotic pressure, expressed in units of megapascals (Mpa), atmospheres (atm), and bars (0.1 Mpa equals 1 atm or 1.013 bars), is one of the terms used to define the effects of desiccation due to increases in solute concentration. All of these units are applied to other sources of pressure including hydrostatic (water), lithostatic (rock), and hyperbaric (gas). To put this in perspective, 0.1 Mpa of hydrostatic pressure is equivalent to the pressure in the ocean at a depth of 10 m, and lithostatic pressure is three times the hydrostatic pressure. Although these forms of pressure are important in characterizing the conditions that limit life on Earth, they probably do not significantly affect the growth and survival of microorganisms on small solar system bodies.

Halobacterium, which grows in saturated NaCl (30 percent, and with an a_w of 0.80), is 41 Mpa. *Tychonema* spp. can survive at 400 Mpa—virtually no water (Potts, 1994). Most gram-negative organisms are more fastidious since they cease to grow between 1.5 and 7 Mpa, and bacteria like *Escherichia coli* cannot survive at 51 Mpa (Potts, 1994).

Other environmental factors pose fewer problems, as evidenced by the growth of microorganisms over a range of pH from less than or equal to 1 to greater than or equal to 12 (Horikoshi, 1996; Schleper et al., 1995), at hydrostatic pressures exceeding those at the depth of the deepest ocean trenches (11,000 m) (Jannasch and Taylor, 1984; Yayanos, 1995), on the surfaces and in cracks of rocks, including deep subsurface basalts (Thorseth et al., 1995; Stevens, 1997; Pedersen, 1997), and in the presence of heavy metals at concentrations once believed to be toxic to all life (Wang et al., 1997).

Terrestrial organisms can use the energy of sunlight or the free energy associated with chemical disequilibrium for growth. Solar power for driving biological processes will also be available in many extraterrestrial environments; however, such a source of energy would require surface liquid water and perhaps atmospheres capable of filtering out harmful radiation without blocking beneficial wavelengths. It is highly probable that any metabolically active microorganisms on small solar system bodies would depend on geochemical energy sources, such as reduction by hydrogen, iron (Fe [III]), or ammonia, of various forms of sulfur (including elemental sulfur, polysulfides, and thiosulfate) or Fe (II). Other chemical systems capable of supporting metabolically active cells can be produced by reaction of basaltic rock with geothermally heated water (Baross and Deming, 1995; Liu et al., 1997).

As an alternative to photochemistry or volcanically driven chemistry, low-temperature abiotic reactions can provide an energy source. Recent reports describe microbial communities in deep basaltic rocks that utilize hydrogen formed from the oxidation of Fe (II) in fayalite using water as the electron acceptor (Stevens and McKinley, 1995). The energy from reduced sulfur compounds, Fe (II), and methane is derived from oxidation reactions in which O_2 or nitrate is an electron acceptor. In anaerobic reducing environments, energy might be derived from reduction of CO_2 by H_2 to form methane or through the reduction of elemental sulfur, as is the case with the hyperthermophilic *Thermoproteus* spp. Both of these forms of anaerobic metabolism are present in archaea.

Based on available information, aerobic environments are considered not likely to be present on small solar system bodies. Therefore, the metabolically active microorganisms most likely to occur on small solar system bodies would be anaerobic chemotrophs. The closest terrestrial analogs would include the following:

1. Methanogens ($CO_2 + H_2 \rightarrow CH_4$);
2. Acetogens (H_2, CO_2, CO, HCOOH, CH_3OH, etc. $\rightarrow CH_3COOH$);
3. Iron-reducers (acetate, fatty acids, aromatics + Fe [III] → CO_2 + Fe [II]);
4. Anaerobic methane oxidizers;
5. Heterotrophic, CO_2-fixing sulfur reducers (sulfur, sulfate and thiosulfate); and
6. Fermentors (assuming a source of appropriate carbon substrates formed abiotically or from decomposition of CO_2-fixing microorganisms).

With the exception of acetogens, all of these metabolic groups have been isolated from volcanic or submarine hydrothermal vent environments, and most are either mesophiles or thermophiles.

Appropriate sources of carbon for extraterrestrial growth include low-molecular-weight organic compounds such as amino acids, hydrocarbons, and inorganic volatiles including carbon dioxide, methane, and carbon monoxide. On small solar system bodies with limited concentrations of organics (see, e.g., McCord et al., 1997), these compounds could be used by oligotrophs. In terrestrial settings, oligotrophic organisms typically grow on organic carbon at concentrations of 1 to 15 micrograms per liter (Morgan and Dow, 1986), and marine organisms have been shown to assimilate dissolved amino acids at concentrations of a few micrograms per liter or less (Wheeler et al., 1974). Most are sessile and divide very slowly. Chemolithoautotrophs (organisms that use inorganic forms of energy and carbon) could be the dominant microbial forms in some extraterrestrial environments. The recent description of subterranean lithoautotrophic microbial ecosystems (SLIMEs) in deep subsurface basalts points to a microbial community that is not dependent on organic carbon or energy sources derived from photosynthesis (Stevens and McKinley, 1995). This community subsists on H_2 that is formed from the abiotic interaction of basalt with water. It derives its energy from metals, sulfur, or hydrogen and fixes CO_2. SLIME may be the closest analog for life in the subsurface lithology of Mars and similar solar system bodies.

Limited information is available on the stress tolerance of microorganisms similar to those that might be associated with small solar system bodies. For example, there is no information about the response of chemolithoautotrophs to environmental stress, although there is some indication that anaerobic sulfate-reducing bacteria show high survival efficiency during starvation (Fukui et al., 1996). There is evidence for increased radiation resistance in halobacteria during starvation (Whitelam and Good, 1986). Most reports on the survival of metabolically active microorganisms describe chemoorganoheterotrophs (organisms that use preformed organic compounds). There are also accounts of starvation-survival strategies for aquatic and soil microorganisms that require high levels of organic material for growth. When exposed to conditions of starvation (e.g., for one or more required nutrients) or to low temperatures (e.g., below the minimum temperature for growth), some chemoorganoheterotrophs adapt by decreasing cell size to 0.2 to 0.5 microns, reducing genomes to a single copy, and diminishing concentrations of other macromolecules. At the same time these cells may increase their capacity for high-affinity binding and transport of organic compounds, which allows them to respond rapidly to low levels of organic substrates (Barcina et al., 1997; Kaprelyants et al., 1993; Roszak and Colwell, 1987). Another strategy involves a switch from a surface independent (i.e., suspended) to a sessile life form, which can require morphological changes ushered in by altered cell surface characteristics. A switch from a single polar flagellum for motility to multiple lateral flagella can aid gliding on surfaces prior to attachment. Because of long periods required to test the influence of environmental factors, there are few data on long-term survival of chemoorganotrophs. However, Morita (1986) reported that a marine psychrophilic vibrio was still viable after 2.5 years in the starvation state, and Munroe and Colwell (1996) reported viable but nonculturable cells able to survive for 3 years in synthetic seawater.

Factors That Affect the Survival of Dormant Microorganisms

Dormancy is an effective strategy that allows microorganisms to survive environmental conditions not conducive to active growth. The capacity of many organisms to form cysts or spores allows them to survive greater temperature excursions than those tolerated by vegetative cells, albeit in suspended states of metabolic activity. It is these forms that are likely to survive over extended periods of time, provided that they are protected from the detrimental effects of ionizing radiation. Other microorganisms become dormant in response to environmental change. For example, some species pathogenic to humans become metabolically inactive when exposed to low temperatures but may retain the ability to respond to added substrates. These organisms may be viable in natural settings (Weichart and Kjelleberg, 1996) but nonculturable in the laboratory (Xu et al., 1982; Oliver, 1993). Although metabolically inactive cells cannot correct defects caused by ionizing radiation, the molecular machinery required for such repair can sometimes be reactivated in response to environmental or physiological change.

There are several reports, some controversial, of quiescent eukaryotic and prokaryotic organisms having survived for thousands of years. For example, fungi and *Streptomyces* spp. were isolated from a well-preserved 5,300-year-old human corpse (Haselwandter and Ebner, 1994). According to one account, viable prokaryotic and eukaryotic microorganisms were preserved for 3 million years in arctic and antarctic permafrost (Gilichinsky, 1997). Another report describes cultivation of the spore-forming organism *Bacillus sphaericus* from the abdominal contents of a bee entombed in 25- to 40-million-year-old amber (Cano and Borucki, 1985). However, few microorganisms' survival capabilities have been studied rigorously. This is particularly true for microorganisms that can utilize very low concentrations of organic nutrients or inorganic energy sources and microbes that inhabit the most extreme environments on Earth.

Survival of cellular life forms in a dormant state is enhanced by very low levels of water activity and/or reduced temperatures. Cryo-preservation and freeze-drying are standard means for preserving microorganisms in culture collections. Both are forms of dehydration that suspend enzymatic activities, including the destructive activities of proteases, hydrolases, and nucleases. The survival of cells undergoing drying is dependent on the rate of drying; in general, slow (24-hour) drying is associated with greater survival (Antheunisse et al., 1981). Cryopreservation enhances the likelihood of survival because the Q_{10} effect[5] of enzymatic hydrolysis is reduced and the rates of deleterious chemical reactions are slowed. The major constraint is eutectic freezing. Repeated freeze-thaw cycles are especially deleterious to cellular life because they lead to the rupture of critical membrane and cell wall structure. Once dehydrated, an organism can survive in a nearly total vacuum or, if frozen, can survive in an arrested metabolic state at temperatures below that required to liquefy nitrogen. However, when organisms are metabolically inactive, they no longer have the capacity to repair the devastating effects of exposure to relatively low levels of radiation or damage from the formation of free radicals.

QUESTIONS APPROPRIATE FOR ASSESSING THE BIOLOGICAL POTENTIAL OF SMALL BODIES

As indicated by the task group's review of current data and understanding, life on Earth and the survival of metabolically active cells absolutely require the presence of liquid water, a source of energy that can be tapped by metabolic processes, temperatures that do not exceed ca. 160 °C, carbonaceous material, and shielding from high-intensity or long-term exposure to ionizing radiation or UV flux. Conditions compatible with survival of dormant life forms are less stringent than those required for initiation of life or continuance of metabolically active cells. Some organisms can survive in nearly completely dehydrated states and tolerate higher levels of ionizing radiation even in the complete absence of organic compounds and sources of energy. The survival of microorganisms exposed to ionizing radiation will depend on their location in a solar system body, with those on the surface subject to higher levels of radiation than those within the interior (assuming no internal sources of radiation). Furthermore, metabolically active organisms are more likely to be capable of repairing radiation-induced damage. In most cases, based on the average background radiation levels in space of 10 to 30 rads per year, it is estimated that it would require from 50,000 to 1 million years to inactivate organisms on the surface of solar system bodies and up to 10 million years if the organisms were deep in regolith, e.g., up to 100 cm or more (Clark et al., 1998).

The conditions necessary for the origin of life and the survival of microorganisms on small solar system bodies can be inferred from the terrestrial experience, as outlined in the preceding section. Water may safely be regarded as a necessity for life on small solar system bodies because the chemistry on which life as we know it is based must take place in solution, and there is no other plausible solvent at this time. A source of energy to support the origin and continuation of life in any environment is a thermodynamic necessity. For extraterrestrial environments the energy sources are more likely to be geochemical than photosynthetic. The temperature limit of 160 °C for survival of metabolically active cells may not be exceeded by extraterrestrial organisms unless their biochemistry does not depend on the formation of amide, ester, or phosphodiester bonds or unless protective mechanisms exist that are not yet understood. Chemical building blocks for organic polymers must be available, and the "biopolymers" are assumed not to differ greatly from terrestrial biopolymers in their sensitivity to radiation.

The microbial species composition of most anaerobic environments on Earth is not known, and so it is also not known how the species composition of these anaerobic microbial communities might change over time, what environmental factors might influence any changes, or how frequently and successfully these habitats might be colonized by new species of microorganisms. Accordingly, the task group concluded that although there is a low likelihood of a viable anaerobic microorganism surviving transport through space and finding a suitable anaerobic habitat on Earth, growth in a suitable habitat if found might be possible. This conclusion is necessary because of our current lack of information about anaerobic environments on Earth that may be analogous to environments on other solar bodies, and the likelihood that the metabolic properties of such an extraterrestrial anaerobe would resemble an Earth anaerobe from a similar environment.

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[5] The Q_{10} effect is the effect of a change in temperature (°C or K) on biochemical and physiological reaction rates. Generally it indicates a doubling of the reaction velocity for every 10-degree rise in temperature and is expressed as Q_{10} = velocity (T degrees + 10 degrees)/velocity (T degrees).

To aid in identifying whether or not samples returned from a range of small solar system bodies require containment, the task group formulated the following series of questions:

1. Does the preponderance of scientific evidence indicate that there was never liquid water in or on the target body?
2. Does the preponderance of scientific evidence indicate that metabolically useful energy sources were never present?
3. Does the preponderance of scientific evidence indicate that there was never sufficient organic matter (or CO_2 or carbonates *and* and appropriate source of reducing equivalents)[6] in or on the target body to support life?
4. Does the preponderance of scientific evidence indicate that subsequent to the disappearance of liquid water, the target body has been subjected to extreme temperatures (i.e., >160 °C)?
5. Does the preponderance of scientific evidence indicate that there is or was sufficient radiation for biological sterilization of terrestrial life forms?
6. Does the preponderance of scientific evidence indicate that there has been a natural influx to Earth, e.g., via meteorites, of material equivalent to a sample returned from the target body?

For the purposes of this report, the term "preponderance of scientific evidence" is not used in a legal sense but rather is intended to connote a nonquantitative level of evidence compelling enough to research scientists in the field to support an informed judgment. In applying the questions, the task group drew on existing data on the origin, composition, and environmental conditions (past and present) of each small body or planetary satellite examined and then determined whether the quality and weight of the evidence were convincing enough to allow making judgments and deriving findings. The answers to the questions, taken together, were used by the task group to reach a considered conclusion that the potential for a living entity to be in or on a returned sample was either "negligible" or "not negligible." Because of the incomplete current state of knowledge about small solar system bodies, there are no definitive answers to the questions, and so all judgments regarding biological potential are qualitative (not quantitative).

Figure 1.1 shows the relationship of these questions and how they are answered to the task group's assessment of the need for sample containment. The questions allow a conservative, case-by-case approach, taking into account information about the different kinds of small solar system bodies, the natural influx to Earth of various relevant materials such as meteorites or interplanetary dust particles, and the possible nature of putative extraterrestrial life. An answer of "yes" to any question argues against the need for special containment beyond what is needed for scientific purposes. For containment procedures to be necessary, an answer of "no" must be returned to all the questions. For such samples, strict containment and handling as outlined in Chapter 7 are required.

CONTENT AND ORGANIZATION OF THIS REPORT

Chapter 2 discusses the natural influx to Earth of material from small solar system bodies and the exchange of material between solar system bodies other than Earth. Chapter 3 describes the origin, composition, and environmental conditions (both past and present) of planetary satellites, specifically those inside the orbit of Jupiter (Europa, Io, Ganymede, Callisto, and the Moon) as well as Phobos and Demos, the satellites of Mars. An assessment of the potential for a living entity to be present in returned samples and suggested scientific investigations to reduce the uncertainty in the assessment are presented. Chapters 4, 5, and 6 present similar analyses for asteroids (including a discussion of the connection between asteroids and meteorites), comets (large and small), and dust, respectively. Chapter 7 synthesizes relevant information from the NRC report *Mars Sample Return: Issues and Recommendations* (NRC, 1997) pertaining to potential risks and handling of returned samples and addresses biohazard and life detection concerns relative to small solar system bodies. Chapter 8 presents the task

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[6] For the purposes of this report, CO_2 or carbonates *and* an appropriate source of reducing equivalents is equivalent to "organic matter" to accommodate chemolithoautotrophs.

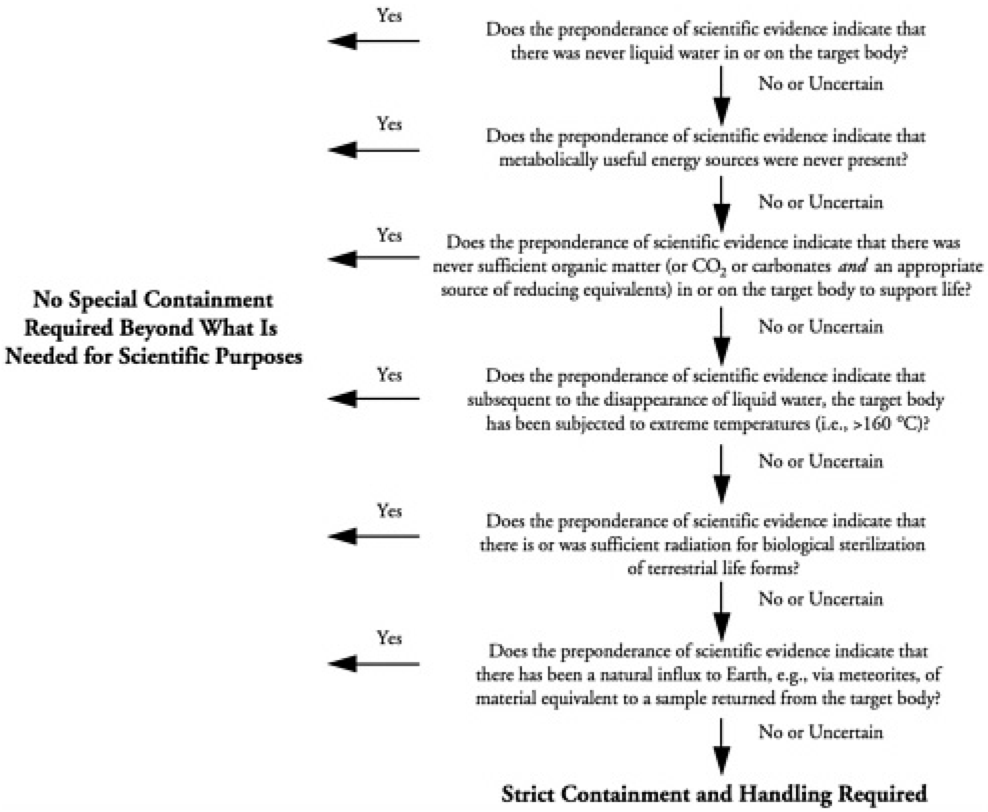

FIGURE 1.1 Relationship of the task group's criteria for assessing biological potential to its assessment of the need for sample containment.
The terms "contained" and "containment" are used in this report to indicate physical and biological isolation and handling of returned samples as specified for samples returned from Mars (see NRC, 1997). For the purposes of this report, the term "preponderance of scientific evidence" is not used in a legal sense but rather is intended to connote a nonquantitative level of evidence compelling enough to research scientists in the field to support an informed judgment.

group's conclusions and recommendations. The appendixes include biographies of the task group members (Appendix A), the letter of request received from NASA (Appendix B), some references to related topics not discussed in the body of the report (Appendix C), information on planetary protection policies in NASA and the International Council of Scientific Unions' Committee on Space Research (COSPAR) (Appendix D), and a glossary (Appendix E).

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2

Natural Influx and Cross-Contamination

Solar system bodies are not isolated from each other. Earth, for example, encounters a suite of objects—interplanetary dust particles (IDPs) and small bodies commonly referred to as the interplanetary debris complex. These bodies range from fine dust that is delivered continuously to objects several tens of kilometers in size or larger, including comets and Earth-approaching asteroids, which impact very rarely. This chapter discusses the natural influx of extraterrestrial material to Earth and cross-contamination of planetary satellites and small solar system bodies.

To understand the potential dangers of returning samples from solar system bodies to Earth, it is vital to assess the material delivered to Earth by entirely natural processes. As a starting point, the task group assumed that the natural influx of objects to Earth is not hazardous, from the perspective of biological contamination. Much research supports the common perception that, except during very rare impact catastrophes (e.g., at the Cretaceous-Tertiary boundary), the evolution of life on our planet is explained by interactions among terrestrial species and changing environmental conditions without any external, cosmic biogenic agents. To the degree that sample return from missions to small bodies mimics even in a modest way the copious natural influx of interplanetary debris, it seems reasonable to assume that such samples are not potentially dangerous; this is the view that was adopted by the task group. For proposed missions to small solar system bodies that would return samples not introduced to Earth naturally, further analysis is needed before requirements for containment are considered.

NATURAL INFLUX TO EARTH

Most of the material that has struck Earth during the nearly 4 billion years since the Late Heavy Bombardment has come in the form of rare impacts by large bodies (comets and asteroids). These bodies range from 100 meters to tens of kilometers in diameter and strike Earth infrequently (i.e., less than once a century to as rarely as once every 100 million years for objects larger than 10 km). They contribute, on average, 10 times the amount of material that has been estimated for the more constant influx of material from smaller bodies (Ceplecha, 1997), which is estimated at 2×10^{10} g/yr. The rare impact of large bodies could have devastating consequences for life on Earth (Alvarez et al., 1980; Chapman and Morrison, 1994), potentially dwarfing the threat from any biological contamination. The material from these bodies has never been analyzed for the presence of life forms because such impacts have not been witnessed. Objects of this size are not considered further in this report.

The cross section of the interplanetary debris complex is dominated by the smallest particles.[1] While the dominant mass is in objects exceeding 10^{14} kg, there are significant excesses in mass of particles ranging roughly

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[1] The numbers of particles that constitute the interplanetary debris complex roughly follow a differential power law in diameter with an exponent of about -3.5 (which is also a theoretically derived exponent for a population of colliding objects in collisional equilibrium).

from 10^{-9} to 10^{-7} kg, 10^{-4} to 10^{-3} kg, and, especially 10^{5} to 10^{7} kg (Ceplecha, 1997). The processes that govern the production and losses of material within the interplanetary debris complex, including redistribution of material among the bodies and the planets that are sources of meteorites, depend on these characteristics of the size distribution.

Associated with the size distribution of particles and objects in the interplanetary debris complex are characteristic lifetimes against collisional destruction. In general, the smaller a particle, the shorter the time it lasts before being destroyed or physically removed from the system. In a biological context, an important criterion is whether material within a body is protected from solar and galactic cosmic rays. Generally speaking, the interiors of bodies larger than approximately 1 meter may be shielded for appreciable periods. However, in some cases (e.g., cometary dust liberated from a comet that is very near Earth) the lifetimes of very small particles before impact may be short enough to preclude sterilization of potential biological entities by radiation.

In general, the meteoroids and dust in the interplanetary debris complex are short-lived. Large objects move according to Keplerian and chaotic orbital dynamics, affected by perturbations from distant, massive bodies. Once in Earth-crossing orbits, they last for time periods (e.g., 10^{6} to 10^{7} years) that are very short compared with the age of the solar system before encountering a planet, impacting the Sun, or being ejected from the solar system primarily by Jupiter's gravity. Particles meters in size and smaller are pushed around by the solar wind and radiation forces (e.g., Yarkovsky effects) and are swept up by the Sun and the terrestrial planets or else driven beyond the terrestrial planet zone (Burns, 1987).

All of these short-lived objects must be resupplied from long-lived "parent bodies" that have survived in "storage locations." Large comets and asteroids, and still larger planets and planetary satellites, serve as parent bodies for such materials so long as they are away from regions with high impact rates or are in stable orbits that do not cross the orbits of other planets and thus serve as reservoirs of fresh material. Their smaller cousins may also serve as parent bodies provided that they have been stored in locations, such as the Oort Cloud, where the volume density and velocities of other objects are low enough that collisions are rare and less destructive. The chief locations of parent bodies that contribute to the interplanetary debris complex are the main asteroid belt, located between 2.2 and 3.2 AU from the Sun; the Trojan asteroids, at 5 AU; the Kuiper Belt (and associated Scattered Disk), ranging out several tens of astronomical units beyond Neptune's orbit; the Oort Cloud, a spherical halo of comets weakly gravitationally bound to the distant Sun and extending part way to the nearest stars; and the major planets and satellites of the solar system.

The smaller debris is resupplied from these parent bodies predominantly by exogenic and endogenic processes. First, hypervelocity impacts among the components of the interplanetary debris complex or impacts of asteroids and comets onto the surfaces of planets and satellites produce sprays of ejected material from the target bodies (dust, boulders, and so on), which launch the debris away from the impact point, some fraction of it often exceeding the target's escape velocity. Second, active processes on bodies (especially sublimation of ices near comet surfaces that carries away surficial grains, but also powerful volcanic processes on bodies like Io) drive fine material away from the parent object, thus incorporating it into the interplanetary debris complex.

This chapter assesses the parent objects and the modes of delivery to Earth of material produced by these processes, prior to its being removed from the interplanetary debris complex by processes of (primarily collisional) physical destruction or dynamical removal from the complex. Inasmuch as interplanetary debris encounters other planetary bodies and other bodies within the interplanetary debris complex, effectively "contaminating" them, material received on—or brought back to—Earth from one body may contain material originally derived from another body.

Analysis of lunar soils suggests that a small percentage are of extralunar origin, as small meteoroids become incorporated into the lunar regolith. In addition, meteorites have occasional (but not extremely rare) visible fragments of other meteorite types embedded within them, implying that relatively intact lithic fragments from one parent object can be delivered as a result of sampling a different parent body (Zolensky et al., 1996). Cross-contamination is not universal. It may be difficult or impossible to derive by natural processes materials contained deep within large bodies, located deep within the gravity fields of large planets, or associated with bodies far from Earth and in orbits that are not easily converted into Earth-crossing orbits. It may be that such materials do not reach "any" of the other bodies that reach Earth. These issues are addressed below.

PROCESSES OF DELIVERY FROM DIVERSE PARENT BODIES

The dominant sources of materials in the interplanetary debris complex near Earth are the inner half of the asteroid belt, the Kuiper Belt, and the Oort Cloud. Collisions among main-belt asteroids, at typical velocities of 5 km/s, generate ejecta that becomes part of the interplanetary debris complex. Large particles that cannot be moved by radiation forces can be delivered to Earth via chaotic dynamical processes after they are collisionally ejected into one of several commensurabilities (e.g., orbits having periods related to Jupiter's orbital period by simple fractions, like the 3:1 commensurability recognized as one of the so-called Kirkwood gaps in the distribution of asteroid semi major axes) and so-called secular resonances. The asteroidal size distribution is such that the production of most of the fragments is episodic and sporadic, as shown by spikes in histograms of cosmic-ray exposure that are used to estimate the ages of meteorites. Objects that are converted so as to have elongated planet-crossing orbits become short-lived, because if they do not strike a planet, their orbits are apt to be further perturbed so that they strike the Sun or are ejected from the solar system on a time scale of a few million years. If such an object's aphelion (the point on an elliptical orbit farthest from the Sun) remains in the asteroid belt, the object continues to suffer collisional fragmentation, further populating the smaller-mass ranges of the interplanetary debris complex. It is believed that most meteorites are derived from the asteroids (in the asteroid belt), as are their near-Earth-object relatives. Examination of meteorites reveals the degree to which the asteroidal rocks have been damaged by impacts. While small fractions of impact ejecta are melted or vaporized, and any biological entities in those portions consequently destroyed, most meteoritic material is relatively undamaged, having been derived from the periphery of impact craters or from ejecta from crater interiors that nevertheless escaped heavy shock or melting. It is doubted that meteorites are derived in any appreciable numbers from beyond 2.8 AU (the 5:2 commensurability with Jupiter).

Kuiper Belt comets may also be a population of collisional fragments (Davis and Farinella, 1996), like the asteroids, although this is not certain; Oort Cloud comets are much more likely to have escaped collisional fragmentation. During their short times in the inner solar system, comets from both storage locations become active as their volatiles are warmed by the sunlight from which they have been protected since formation. The activity liberates copious quantities of cometary dust, which manifests itself as a component of cometary comae and tails and as meteors in the night sky. It is very uncertain, however, if cometary processes liberate much larger fragments. Debris larger than radar wavelengths has been detected near some comets, but pieces of comets meters to tens of meters in size are generally unobservable, especially once they are devolatilized. Comets are observed to split, sometimes due to tidal forces (as in the case of Comet Shoemaker-Levy 9, whose fragments subsequently struck Jupiter in 1994) but often for no apparent reason, contributing to the perspective that comets are inherently weak. Little if any cometary material survives passage through Earth's atmosphere as meteorites, and it is difficult to calibrate the size distribution of cometary fragments from meteoric phenomena alone. Therefore, while most of the observational evidence about the contribution of cometary materials to Earth concerns cometary dust (and the rare impact by an intact comet nucleus), there is the possibility that significant cometary material is contributed by objects of intermediate sizes.

During the period that comets are near the Sun and active (i.e, generating comae and tails), their activity is far more important than are collisions with asteroids in liberating cometary materials. However, short-period comets (derived primarily from the Kuiper Belt) last long after their visible activity becomes dormant as they lose their volatiles, and they eventually "die." It is estimated that a few tens-of-percent of Earth-approaching asteroids are dead or dormant comets (Wetherill, 1988). These objects presumably suffer collisional interactions with main-belt asteroids, leading to cratering and fragmentation, just as small asteroids that originated in the asteroid belt do.

Materials from larger objects, like the Moon and Mars, can also be derived by impact cratering, despite the fact that such surface materials are trapped deep within the planetary gravity fields. Such high-velocity planetary ejecta can join the interplanetary debris complex and be subject to further collisions and dynamical evolution. Obviously, the forces required to excavate material from a planet at escape velocity might be expected to modify it physically (e.g., by shock heating, melting, vaporization) more than in the case of asteroids. But it is now understood, and demonstrated by the traits of lunar and martian meteorites, that modest-sized (meter-scale) fragments can be excavated with minimal physical damage. Conceivably, even larger fragments could be excavated, portions of which might remain similarly undamaged. Most samples from planetary surfaces must be excavated in rare, large cratering events and do not result from the more frequent bombardment by smaller projectiles. Certainly this must be true for excavation of materials from the surfaces of planets with substantial atmospheres (e.g., Venus); given the long durations between such large impacts and the short survival time of any material excavated from Venus, it is very unlikely that any contemporaneous meteorites are being derived from Venus.

Earth itself could be a source of material migrating around interplanetary space; most tektites are derived from large impacts that produce craters (e.g., the Ries basin in Germany) exceeding 10 km in diameter; such events happen only once every few hundred thousand years. Still larger impacts are required to blow away a portion of Earth's atmosphere and eject major amounts of Earth material at escape velocity.

Although ions probably derived from Io have been detected away from Jupiter, it is very unlikely that meteorites can be derived from the galilean satellites. The difficulties of excavating materials from bodies as large as the Moon and Mars apply to them, as well, but are augmented by the fact that much greater velocities must be achieved to escape Jupiter's enormous gravity. Somewhat analogous difficulties exist for excavation from the satellites of Mars. Although the satellites are small, and cratering ejecta is readily lofted into Mars orbit, much larger velocities would have to be achieved for material from Phobos or Deimos to escape Mars's gravitational well and enter independent heliocentric orbits and join the interplanetary debris complex. If Phobos and Deimos are, as they may well be, gravelly or rubbly bodies, ejecta velocities may be too low to reach Mars escape velocity because loosely consolidated bodies absorb energy more efficiently than compact bodies through reduction of porosity. Thus, that energy is not available to accelerate the ejecta out of Mars's gravitational well.

The last stage of natural delivery of extraterrestrial materials to Earth is penetration through the atmosphere and impact or airborne settling onto the ground or ocean. The effects of such delivery depend on the impact velocity (and angle), the size of the projectile, and the nature of the projectile material. To objects sufficiently large and/or strong, Earth's atmosphere presents little resistance. Asteroids larger than roughly 100 m in diameter and comets larger than several hundred meters penetrate the atmosphere and strike the ground (or ocean) at hypervelocities, resulting in an explosion crater. Smaller objects may explode or burn up in the atmosphere. Iron objects are generally strong enough so that major chunks survive atmospheric penetration; most terrestrial impact craters the size of Meteor Crater and smaller are formed by iron projectiles. A fraction of interplanetary dust particles, preferentially those arriving at lower velocities (see Chapter 6), survive atmospheric penetration relatively intact and settle to Earth.

A typical meteorite that lands on Earth is the remnant of a somewhat larger preatmospheric mass, whose exterior has ablated away. Meteorites exhibit an external "fusion crust" of heated, melted material that did not quite ablate away. They land on Earth relatively gently, at terminal velocity. The interior of a meteorite is likely to be unaffected by its arrival on Earth; it is generally cold, there having been inadequate time for the brief heat pulse from its exterior to penetrate. Thus, in spite of the superficially violent mode of delivery, most interplanetary objects that strike Earth (both some small interplanetary dust particles and most meteorite-sized and larger projectiles) do so in a mode that would fail to sterilize or otherwise destroy many biological materials.

CROSS-CONTAMINATION

The question of interplanetary delivery of materials has recently been analyzed by Gladman et al. (1996). It is evident, based on current, evolving understanding of impact and dynamical processes, that there is appreciable mixing of materials among solar system bodies. In addition, there is considerable evidence for cross-contamination. Many meteorites, for example, contain sizeable (e.g., centimeter-scale) clasts (small, identifiable portions of a rock) of materials from foreign parent bodies; although such xenoliths constitute a tiny fraction (e.g., less than 1 percent) of meteorite mass (Zolensky et al., 1996), that would be enough to be important in the context of biological contamination. Similarly, a small percentage of the lunar regolith is believed to be composed of primarily carbonaceous chondritic material derived from infalling exogenic projectiles and dust. Martian and lunar meteorites, which constitute less than 0.2 percent of meteorites recovered from Antarctica, are mentioned above.

It is probable that cross-contamination among objects augments the variety of parent bodies represented in what reaches Earth by natural influx. For example, while outer-belt asteroids cannot be dynamically converted into Earth-crossing orbits, such objects in moderately eccentric orbits do collide with asteroids in the inner asteroid belt, which do communicate with Earth. One could imagine a chain of contamination providing an access route for materials from virtually any body—e.g., ejecta from Europa is encountered by a comet passing through the Jupiter system, which ultimately crashes on the Moon; then such material gets to Earth by excavation in a lunar cratering impact. Obviously, as in this example, the probabilities of occurrence of most multichain contamination routes drop geometrically toward zero, but cannot be totally ruled out in principle. However, to the degree that the apparent safety of the natural influx is relied upon to declare a body safe for sample return, it must be realized that the episodic nature of cross-contamination and delivery processes probably means that exactly zero percent (not just a very small percentage) of material impacting Earth during a finite time (e.g., a century) can be expected to come via such multichain routes. Only the tiniest particles might escape this generalization, and any biological materials are rapidly sterilized by radiation in such small particles.

SUMMARY

Earth receives from other bodies in the solar system abundant material that is ejected from such bodies and delivered to the surface of Earth. Because of cross-contamination, small but significant fractions of the delivered materials could have been formed originally on bodies from which Earth does not receive meteorites directly. However, there are some bodies, as well as places on other bodies, from which material would be so difficult to obtain, or would arrive so infrequently, that it is unlikely that Earth has received samples during our lifetimes, even if such material is delivered on rare occasions. For some planetary satellites and small bodies, the uncertainty associated with cross-contamination reduced the degree of confidence in the inherent safety of a sample returned from such bodies.

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3

Planetary Satellites Inside Jupiter's Orbit

Satellites are natural consequences of planetary formation processes. They can form in place around planets via condensation and agglomeration of material from circumplanetary gas and dust disks. Such disks may be an integral part of the development of large gaseous planets like Jupiter from the solar nebula. Natural satellites can also develop from shorter-lived disks produced by large impacts on a growing planet; such a process may have produced Earth's Moon. Some satellites may be captured objects—i.e., objects that formed elsewhere in the solar system but were captured into orbit around a planet by aerodynamic drag forces generated by passage through an extended early planetary atmosphere.

Planetary satellites vary widely with respect to their post-formation geologic histories, ranging from quiescent bodies that have been subjected to little since their formation (except for impacts), to volcanic bodies that continue vigorous activity to the present. They also vary widely in their endowment of H_2O, ranging from objects with no discernible water to objects that are more than 50 percent H_2O by mass. Aspects of a satellite's formation, subsequent geologic history, and water endowment must all be considered carefully when evaluating the object's biological potential.

ORIGIN, COMPOSITION, AND ENVIRONMENTAL CONDITIONS OF SATELLITES EXAMINED

The Moon

Of all the planetary satellites considered in this chapter, the easiest to assess from a planetary protection perspective is the Moon. Lunar meteorites have been delivered to Earth throughout its history, and several hundred kilograms of lunar samples were returned to Earth deliberately during the Apollo program. Both crews and samples from Apollo 11, 12, and 14 were subjected to an elaborate quarantine and testing regime at the Lunar Receiving Laboratory to ensure that no harmful organisms were introduced to Earth's biosphere by returning astronauts, spacecraft, or extraterrestrial material (Allton et al., 1998).[1] Quarantine was ended after Apollo 14

NOTE: The planetary satellites examined in this study were selected based on scientific interest and the likelihood of possible sample return missions in the near future.

[1] One of the reviewers for this report observed that the quarantine procedure for the Apollo missions appeared to be compromised when the command module was opened while retrieving the crew at sea.

because all the protocol requirements had been met, and samples were certified as safe by the Interagency Committee on Back Contamination. [2] Subsequently, the distribution of Apollo lunar samples came under the purview of a scientific advisory committee whose main concern was scientific preservation of samples. Since release from quarantine, there has been no restriction of sample distribution based on concerns about back contamination or planetary protection. There have been no discernible adverse consequences for researchers or for Earth's ecosystem as a result of this policy. Moreover, no evidence of lunar life has been found in any of the samples. The task group's discussion of the Moon is therefore cursory.

The Moon is a large rocky body with a history dominated by impacts and volcanism. The most recent significant volcanism took place approximately 2.5 Gyr ago. There have been a number of hypotheses of lunar origin, including co-accretion with Earth, dynamically induced fission from the growing Earth, or capture from some other region of the solar system. However, the hypothesis that appears most consistent with all the available data is that the Moon accreted from debris that was excavated from Earth's mantle by a giant impact very early in Earth's history (Hartmann and Davis, 1975). One consequence of its apparently violent origin is that the Moon is highly depleted in volatiles. There is no perceptible water in lunar rocks and no geologic evidence for the former presence of liquid water at or near the lunar surface. The potential for hydrothermal systems at any point in lunar history therefore appears small.

It has been hypothesized that ice may exist near the lunar polar regions (Arnold, 1979), built up as a consequence of cometary impacts on the Moon. Most H_2O molecules released during cometary impact events would ultimately escape to space because of high daytime lunar surface temperatures. However, a small fraction could come into contact with cold, permanently shadowed regions on the floors of lunar craters, becoming permanently trapped there. Bistatic radar results from the Clementine mission have been interpreted as providing some evidence for lunar polar ice (Nozette et al., 1996), although Earth-based radar results have called these conclusions into question (Stacy et al., 1997). More recently, results from the Lunar Prospector mission have provided strong evidence for the existence of at least modest amounts of lunar polar ice. The discovery has little biological significance, however. Lunar polar ice passes directly from solid to vapor upon impact, and back to solid upon condensation, never existing in the liquid phase.

As noted above, many samples of lunar rocks and soils were returned to Earth by the U.S. Apollo and Soviet Luna programs. None have been found to contain any evidence of past or present lunar biological activity.

The Satellites of Mars

Phobos and Deimos, the two natural satellites of Mars, are small, irregularly shaped rocky objects. With maximum dimensions of 27 km (Phobos) and 15 km (Deimos), they are more similar in size and shape to asteroids than to the other much larger planetary satellites discussed in this chapter.

Phobos and Deimos are notoriously difficult objects to observe from Earth. Spacecraft observations clearly show that they have very low albedos (about 0.05). Mariner 9 and Viking spacecraft spectrophotometric data from 200 to 700 nm show few features other than a dropoff in reflectance shortward of about 400 nm (Pang et al., 1978). These data are broadly consistent with a composition similar to those of undifferentiated carbonaceous meteorites and asteroids. This interpretation is equivocal, however, based as it is on a lack of observable spectral features. Ground-based near-infrared (IR) spectra obtained for Deimos out to 3 μm show a match that is closest to the C-type and P-type asteroids (Bell et al., 1993; Murchie and Erard, 1996).

The densities of the martian satellites have been constrained by spacecraft flybys to be approximately 2.2 ± 0.5 g/cm^3 for Phobos and approximately 1.7 ± 0.5 g/cm^3 for Deimos (Duxbury and Callahan, 1982). These low densities are reminiscent of the C-type asteroid Ceres. The densities probably cannot be taken as good indicators of composition, however, owing both to their large uncertainties (i.e., ± 0.5 g/cm^3) and to the possibility that the satellites have significant internal porosities.

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[2] The Interagency Committee on Back Contamination was established by NASA in 1966, in cooperation with the U.S. Public Health Service, the Departments of Agriculture and the Interior, and the National Academy of Sciences to advise NASA on measures necessary for the prevention of contamination by lunar samples returned to Earth.

Images of Phobos and Deimos show a geologic evolution that has been dominated by impacts. Craters are the primary morphologic features on both satellites. These craters show a variety of forms, but this variety appears to arise primarily from the degree to which the craters have been degraded by or filled with ejecta from subsequent impacts (Thomas et al., 1992). Individual impact ejecta blocks have been observed on both satellites; morphologic evidence suggests that crater ejecta has been transported both ballistically and by downslope motion (Thomas and Veverka, 1980). The most complex geologic features on the satellites are sets of subparallel topographic grooves on Phobos, but the bulk of the geologic evidence indicates that even these are simply a consequence of fracturing produced by Phobos' large Stickney impact (Thomas et al., 1979), perhaps modulated by tides. Spacecraft images therefore show no clear evidence for any geologic activity other than as a result of cratering within the martian satellites.

The presence of Stickney suggests the possibility that Phobos and/or Deimos may have been catastrophically disrupted, and reassembled in Mars orbit, by one or more even larger impacts. The degree to which such events reorganized the satellites' original structure, and the timing of such events, are difficult to evaluate. It is important to recognize, however, that the presence of Phobos and Deimos in orbit near Mars results in much more effective reaccumulation of debris and mantling by a thick regolith than would be true for asteroids of equivalent size in heliocentric orbit.

The origin of Phobos and Deimos is unclear. Both lie in orbits that are low in inclination and nearly circular. Because of their apparent spectral similarity to primitive asteroids, it has been suggested that one or both may be captured objects that formed in the outer portion of the asteroid belt (Hunten, 1979; Lambeck, 1979; Cazenave et al., 1980). However, a capture-based origin presents serious dynamical difficulties (Burns, 1992). The present orbit of Deimos poses the most serious problem. Solid-body tidal interactions between Phobos and Mars have caused substantial evolution of Phobos' orbit from its "original" one (e.g., Burns, 1977). Indeed, this orbital acceleration of Phobos will cause it to impact Mars in the geologically near future. Phobos' orbit therefore in principle could have undergone some significant evolution from an initial capture orbit (which presumably would have been far more elliptical). Deimos, however, lies far enough from Mars that it has undergone essentially no orbital change due to tidal interactions over its history. Its present near-circular, near-equatorial orbit is hardly a likely one for any plausible capture mechanism.

Even for Phobos there are significant dynamical arguments against a capture origin. In order to have evolved from an early postcapture orbit of significant inclination and eccentricity to its present one, the orbit of Phobos is very likely to have crossed that of Deimos for a significant period (Burns, 1992). A destructive collision with Deimos would therefore have been difficult to avoid. Considering these dynamical arguments, a more likely scenario may be that Phobos and Deimos co-formed with Mars and are composed of undifferentiated material left over from the martian formation process.

Overall, the limited spectral data and poorly determined densities of Phobos and Deimos are broadly consistent with their being similar to C-type or P- and D-type asteroids. The dynamical arguments discussed above are not easily reconciled with this interpretation, however, since such asteroids are most commonly found in the outer portions of the main belt. Taken together, then, the available data do not allow for a definitive answer about the compositions and internal histories of the martian satellites other than that they may have been broadly similar to those of similar-sized asteroids of carbonaceous, undifferentiated, and/or unknown composition.

It is not known whether or not there was ever any liquid water or hydrothermal activity within Phobos and Deimos. There is no evidence to support the idea, but the uncertainty regarding the bodies' composition does not exclude the possibility. If any aqueous activity ever did take place within Phobos, it clearly would have been very early in the objects' histories, during the brief interval when the thermal effects of short-lived radionuclides like ^{26}Al were being felt.

As is discussed in more detail in Chapter 4, the upper meters of an asteroid are subjected to continuous bombardment by galactic cosmic rays and solar flare protons. In addition, all portions of an asteroid are subjected to the radiation produced by long-term decay of natural radionuclides such as U, K, and Th. The only plausible exception would be an object with void spaces that were filled with ice containing biological materials and that, by virtue of ice's lack of radionuclides, shielded these materials from radiation.

Phobos and Deimos are dark and lie considerably closer to the Sun than do most typical P- and D-type asteroids. They are therefore warm objects, and typical subsurface temperatures are far too high for ice to persist for long periods, at least in near-surface environments. It is unlikely that ice-filled voids are present today within the upper reaches of Phobos and Deimos that are accessible to sample return missions. However, given the evident large-scale cratering on these satellites, and the possibility of past reorganization of interior materials by catastrophic disruption and reassembly, it is conceivable that materials long-protected from natural radioactivity might be available for sampling.

Because any biological materials would have to date from Phobos' and Deimos' earliest histories, the effects of radiation would be substantial in most cases. Considering just the radiation produced at all locations within the satellites by chondritic abundances of U, K, and Th, the time to accumulate a total dose of 18 Mrad (sufficient to eliminate the most radiation-resistant microorganisms known) is 900 million years. For the upper few meters of the satellites the situation is considerably more severe. A total dose of 18 Mrad is produced at a depth of 1.5 m by galactic cosmic rays and solar flare protons in just 15 million years. The radiation levels are sufficient to inactivate any organisms in or on the satellites, except in rare cases where regolith processes have moved any long-protected materials from depth to within range of sampling techniques. It is possible that the processes of disruption/reassembly and regolith turnover have been so efficient that Phobos and Deimos have been devolatilized for aeons and all materials will have been bathed in lethal radiation, rendering them harmless.

The most plausible way for biological material not formed within the bodies themselves to reach the surface of Phobos or Deimos would be in materials ejected from Mars as a result of impacts on the planet's surface. It is clear that some small fraction of ejecta from impacts on Mars are transferred to the planet's satellites. Three factors, however, reduce concern about the possibility of hazards from this source of contamination: (1) any martian material sampled from the satellites would have arrived there as a result of random impacts, not from the special environments that might be sampled by dedicated sample return missions to Mars itself; (2) Viking data have demonstrated that the surface and near-surface of Mars are hostile to biological materials; and (3) SNC meteorites, sampled by random impacts, have not been found to be hazardous on Earth.

The Galilean Satellites of Jupiter

The four galilean satellites are large objects in low-inclination, low-eccentricity orbits around Jupiter. Their substantial size and the regularity of their orbits provide evidence that they formed via condensation and agglomeration from a primordial circumjovian nebula. A major uncertainty regarding their formation is the gas density in the nebula at the time that accretion took place. Plausible hypotheses range from essentially gas-free scenarios (e.g., Safronov et al., 1986) to ones in which gas densities were high enough that gas drag was a dominant dynamical process (e.g., Hayashi et al., 1985). Regardless of the gas/solid ratio during accretion, however, the present bulk compositions of the satellites must to some degree reflect the pressure and temperature conditions in the material orbiting Jupiter at the time that condensation occurred.

Simple consideration of the condensation sequence of materials from a circumjovian nebula of solar composition suggests that the galilean satellites' "original" (i.e., post-accretional) composition was some mixture of H_2O ice and roughly chondritic-composition non-icy material (Lewis, 1971, 1972). Other ices are not expected to have been present in substantial quantities owing to insufficiently low temperatures. In the presence of a radial temperature gradient in the circumjovian nebula, the ratio of icy to non-icy condensed material would have depended on the distance of formation from Jupiter. This scenario is supported by the progression in the densities of the galilean satellites, which decrease regularly with increasing distance from Jupiter. The satellites may be thought of most simply, then, as chondritic/silicate bodies in bulk composition, with substantially varying additional endowments of H_2O.

The satellites' densities indicate just how substantial the variation in H_2O endowment is. Io's density is about 3.5 g/cm^3, consistent with a rocky or rock-metal composition that is lacking even in water of hydration. Europa's density is about 3.0 g/cm^3, consistent either with hydrated silicates or with dehydrated silicates and a substantial quantity of free H_2O. Ganymede and Callisto have densities of about 1.9 and 1.8 g/cm^3, respectively, indicating bulk compositions that approach 50 percent H_2O by mass.

The satellites also show an enormous degree of variability in the extent of geologic activity they have undergone since their formation (Smith et al., 1979a,b). Callisto has a heavily cratered surface that provides evidence for little or no internal activity. Ganymede exhibits two distinct types of geologic terrain: dark, heavily cratered terrain that is similar to Callisto's (though with somewhat lower crater density), and brighter, younger "grooved terrain" that has undergone intense tectonic deformation. Europa's surface is bright and icy, with extreme tectonism and a crater density far lower than anything found on Ganymede. Io has no impact craters, and there is evidence of widespread, ongoing volcanic activity.

Several factors may help account for the observed variability in geologic history among the galilean satellites. Among them, the most important is probably the variability of tidal heating. The three inner galilean satellites, Io, Europa, and Ganymede, currently participate in a Laplace orbital resonance (a commensurability in their mean motions that causes repeated alignments of the satellites at identical points in their orbits). The mutual gravitational perturbations of the satellites upon one another sum as a consequence of these alignments to produce significant orbital eccentricities. The eccentricities in turn can lead to significant heating. Satellites close to their primary body can exhibit significant tidal deformation. The size of a satellite's tidal bulge varies with distance from the primary body. In addition, for a synchronously rotating satellite in an eccentric orbit, the orientation of the bulge varies with orbital phase. Both variations cause flexure of the satellite, dissipating strain energy as heat.

This tidal heating is a very strong function of mean orbital radius. A consequence of this strong dependence is that Io is subjected to overwhelming tidal heating that powers its volcanism. Europa may undergo just enough heating to allow liquid water to exist beneath its surface, and Ganymede's tidal heating could have been geologically significant only during possible former periods of higher orbital eccentricity. Callisto is unlikely ever to have undergone significant tidal heating.

The galilean satellites are therefore an extremely diverse group of objects in terms of their endowment of H_2O, the fraction of that H_2O that has been liquid, and the quantity of liquid that could have reached the surface. The variability in their biological potential is correspondingly large.

Io

Io is the innermost of the galilean satellites. It has a radius of more than 1,800 km, making it slightly larger than the Moon, and has a density of approximately 3.5 g/cm^3, indicating a composition dominated by rock and possibly metal.

Io is the most volcanically active known body in the solar system. Its volcanism is the result of intense tidal heating (Peale et al., 1979; McEwen et al., 1998). The volcanism takes a number of forms. The most dramatic are gas-driven eruptions that produce spectacular eruptive plumes that reach heights as great as 300 km above the surface (Strom et al., 1979). The plumes apparently develop when volatile material, either SO_2 (Smith et al., 1979c) or S (Reynolds et al., 1980), comes into contact with hot silicates, vaporizing energetically. Other volcanic eruptions produce surface flows that exhibit the familiar morphology of low-viscosity lavas, but that show colors ranging from black through various shades of orange, greenish-yellow, and white. The coloration is similar in some respects to that of quenched high-temperature allotropes of sulfur (Sagan, 1979), leading to the suggestion that the flows are composed predominantly of sulfur. Solid sulfur is too weak to support much of the topography exhibited by the flow units, however (Clow and Carr, 1980), and so a more plausible explanation may be that basaltic volcanism dominates, with coloration added by a small admixture or coating of sulfur and sulfur compounds.

Given the high level of volcanic activity on Io, it is abundantly clear that the geothermal energy that would have been needed to drive hydrothermal activity there is present. What appears to be lacking, however, is water. No spectroscopic evidence for H_2O has been found on Io. Instead, the dominant volatiles on Io appear to be sulfur compounds. Allotropes of elemental sulfur may be responsible for some of Io's coloration, as noted above. SO_2 has been clearly shown to be present via infrared spectroscopy (e.g., Nash, 1983; Howell et al., 1984). Abundant sulfur and oxygen ions are present in the jovian magnetosphere, with Io identified as the source (Bagenal and Sullivan, 1981). Io is also associated with a Jupiter-encircling torus of neutral atomic Na, K, O, and S (Brown et al., 1983), derived from magnetospheric interactions with Io's surface materials. Nowhere, however, is there evidence for H_2O.

From a biological perspective, another important point regarding Io is that the radiation environment to which it is subjected is more intense than that of any other large solid body in the solar system. Jupiter has a powerful magnetosphere, and charged particles trapped in the magnetosphere continually bombard Io's surface at high flux levels and with high energy. This radiation would serve as a powerful inhibitor of biological activity at the surface of Io. This radiation would be less intense (but not zero) for the other jovian satellites. Finally, because essentially all of the material at the surface of Io is volcanic, a good case can be made that all accessible material on the satellite has been heated at some point in time to temperatures too high for organic molecules to be preserved.

Overall, the prospects for biological activity at and below Io's surface appear extremely poor. While abundant biologically useful energy is present, there is no evidence for H_2O ice at the surface, and no evidence for the former presence of solid or liquid H_2O beneath the surface.

Europa

Europa is one of the most interesting objects in the solar system. Its radius of about 1,600 km makes it slightly smaller than the Moon. It has a density of about 3.0 g/cm^3, meaning that it is probably mostly silicate and metal by mass but may also contain a significant endowment of a lower-density material, probably H_2O. Its surface composition is known from infrared spectroscopy to be dominated by H_2O ice (Pilcher et al., 1972). Ultraviolet spectroscopic data also suggest that a small amount of sulfur is present; this sulfur was probably implanted from the jovian magnetosphere, with Io as its original source (Lane et al., 1981).

The thickness of Europa's H_2O-rich outer region may be substantial. If the density of the non-icy component is the same as that of Io, then this thickness is at least 100 km. Recent Galileo determinations have suggested that Europa's degree of central condensation could be still greater than this, and the thickness of the H_2O region correspondingly larger (Anderson et al., 1997).

A crucial question from a biological standpoint is whether or not any of the subsurface H_2O on Europa is liquid. Europa participates in the same three-body Laplace orbital resonance as Io, and as a result is also subjected to tidal heating. However, the heating is much less intense. For homogeneous tidal heating, the heating rate decreases as the sixth power of the orbital radius, other factors being equal. Tidal heating therefore has not been the dominating factor in the evolution of Europa to the extent that it has on Io.

Unfortunately, the extent to which tidal heating has affected Europa's interior is poorly understood. The reason for this is that tidal heating calculations depend on several uncertain material parameters. The most important of these are the flexural rigidity and the specific tidal dissipation function of the satellite's materials. While uncertainties in these parameters are comparatively unimportant on Io due to the overwhelmingly large magnitude of the heating there, they are important in evaluating Europa's evolution.

Another major source of uncertainty has to do with the long-term rheological properties of Europa's ice and their variation with depth. Heat can of course be transported within Europa's icy crustal materials by conduction. Under certain circumstances, however, it can also be transported by solid-state convection. Factors favoring convection include low viscosity, a large base-to-top temperature difference, and a large icy layer thickness. Convection can be a much more efficient heat transport mechanism than conduction, and so whether or not a model predicts that liquid exists beneath Europa's surface can depend in large part on whether or not convective instability is predicted. This is in turn related to the poorly known relationship between ice viscosity and temperature over convective time scales and strain rates.

As a consequence of these various sources of uncertainty, the subsurface structure of Europa is poorly known. Some calculations have suggested that tidal heating has been sufficient to melt most of the H_2O within Europa and to keep it molten to the present (e.g., Cassen et al., 1979; Squyres et al., 1983; Ojakangas and Stevenson, 1989). In such models, the tidal heating and rheological parameters are such that solid-state convection does not occur, and tidal heating is able to maintain a thin ice crust over a thick liquid layer. If this is the case, Europa has a rock-metal interior, a thick "ocean" of liquid water, and a relatively thin outer shell of H_2O ice. Other models make parameter choices that reduce tidal heating and/or emphasize the importance of solid-state convection in the ice as an effective agent of heat transport, and conclude that the ice surrounding Europa's rock-metal interior is completely frozen (e.g., Cassen et al., 1980; Ross and Schubert, 1987). Plausible intermediate possibilities involve a thin layer of water beneath a thick ice cover, an ice cover of irregular thickness, or water that is present only in small localized regions.

The photogeologic evidence for liquid water under Europa's ice cover is significant but equivocal. Europa's impact crater density is very low, indicating geologically recent resurfacing (Smith et al., 1979b; Carr et al., 1998). The mechanism by which this resurfacing has occurred, however, is unclear. Surface extrusions of either liquid or warm, mobile ice may have been significant. A major role could also have been played by simple viscous relaxation of topography.

There is also substantial evidence for crustal deformation on Europa. The satellite's surface is laced with an intricate pattern of fractures, ridges, and other lineations, ranging in size from tens of kilometers wide and more than 1,000 km long down to the smallest scale seen in Voyager and Galileo images. Two lines of evidence suggest that only a very thin near-surface region behaved in a brittle fashion as this tectonism took place. One is the narrow widths of most grooves and ridges, which are consistent with brittle deformation being limited to the upper 1 km or so (e.g., Golombek and Banerdt, 1989). The other is the substantial evidence that small blocks of crustal material have rotated and translated laterally with respect to one another, moving over easily deformed material that lies immediately below (e.g., Schenk and McKinnon, 1988). Whatever lies just below Europa's surface clearly is therefore substantially softer and more mobile than cold ice.

High-resolution Galileo images have further fueled speculation that liquid water could be present within Europa. The most dramatic of these clearly show local regions that have been disrupted by material rising up from beneath Europa's surface. Crustal blocks in some cases have been "rafted" by this material, fragmenting, rotating, and translating with respect to one another. The Galileo images show this crustal disruption to be widespread, geologically young (perhaps as recent as 10 million years), and involving fluid-like behavior within a few kilometers of the surface. It is impossible to determine from the imaging data alone if this activity involved liquid water or solid-state convection of ice (Carr et al., 1998; Pappalardo et al., 1998a). The gravity data from several encounters suggest a layer of water or water ice from 100 to 200 km thick (Anderson et al., 1997).

Reynolds et al. (1983) considered the possibility that significant biologically useful energy could be released in Europa's putative ocean. Europa's surface experiences substantial insolation. However, even under the most optimistic assumptions about the frequency of ice fracturing and the transparency of refrozen materials, only a trivial amount of sunlight can penetrate into subsurface liquid. Hydrothermal energy, however, could be another matter. Radionuclides in Europa's silicates produce heat, and radiogenic heating is augmented by tidal energy dissipation in the silicate-metal interior. It is not clear whether or not this rate of heat production has been sufficient to allow magmatic activity to persist within Europa to the present. The rate of heat production is significantly greater than it is for the Moon, which is not volcanically active at the present, and significantly less than it is for Earth, which is active. However, the higher heating rates in the past were clearly sufficient to have produced magmatic activity in Europa's silicates at some point. This argument is reinforced by the discovery by Galileo of Europa's high degree of central condensation and the likelihood that it has an iron core (Anderson et al., 1997). The interaction of magmatism in Europa's rocky material with the H_2O immediately above it could have led to the development of local hydrothermal systems within Europa whether the overlying H_2O was dominantly liquid or not.

While much remains to be learned about Europa, several factors relevant to its biological potential are clear. One is that hydrothermal systems are likely to have operated within a few hundred kilometers of Europa's surface at some point in its history. Another is that material from beneath the surface has reached the surface in the geologically recent past. When these factors are considered together, it is clear that Europa is an important object from the standpoint of exobiology. Of all the solar system bodies other than Earth, only Mars appears to have a potential for past or present life that is comparable to Europa's. Indeed, investigation of Europa's biological potential forms much of the rationale for continued investigation of the satellite.

In future exploration of Europa, a premium will be placed on sampling resurfaced regions that may contain materials brought up recently from deep below Europa's surface. Spectral data from Galileo indicate the possibility of salts included in the surface ice of Europa (McCord et al., 1998). Such materials could carry the chemical signature of subsurface hydrothermal activity. If recent hydrothermal systems on Europa have supported life, they could also carry frozen evidence of such life.

Ganymede

Ganymede is the largest of the galilean satellites, and the largest satellite in the solar system. With a radius of some 2,600 km, it is larger than the planet Mercury. Ganymede's density is about 1.9 g/cm^3, meaning that it is probably roughly 50 percent H_2O by mass. Infrared spectroscopy demonstrates that H_2O ice constitutes a major fraction of Ganymede's surface material (Johnson and Pilcher, 1977). Galileo data have shown Ganymede to have a moment of inertia consistent with a large degree of central condensation (Anderson et al., 1996a). Combined with the finding of an intrinsic magnetic field (Kivelson et al., 1996; Schubert et al., 1996), it appears likely that Ganymede has a metallic core, silicate mantle, and outer ice shell several hundred of kilometers thick. Without the ice, Ganymede would resemble Io (Anderson et al., 1996b).

A major factor that must be considered when examining the geologic evolution of Ganymede's interior is the complex phase diagram of H_2O (e.g., Shoemaker et al., 1982). Ice has a number of different crystalline forms, or polymorphs, that are stable over different temperature and pressure ranges. The familiar form, ice I, is stable at Ganymede's surface. However, at depths of hundreds of kilometers within the satellite, polymorphs other than ice I will be present. These polymorphs all have densities significantly greater than those of ice I. Ices VI and VII, possibly important deep within the satellite at various times in its history, also have elevated melting temperatures.

The various polymorphs also have substantially differing rheological properties. This factor, plus the heats of phase transformation among the various polymorphs, can act to resist solid-state convection across phase boundaries. Convection across phase boundaries is unlikely to have been inhibited at all times, however, and deep through-going solid-state convection cells could have existed during some periods in Ganymede's history (Schubert et al., 1981). Liquid water is unlikely to be present in significant quantities in Ganymede today, due both to the heat-transporting efficiency of solid-state convection and to the very low current rate of tidal heating.

Ganymede's surface shows substantial evidence for geologic activity early in its history (Smith et al., 1979a,b). Some parts of Ganymede are relatively dark and heavily created, suggesting that they are composed of ancient mixtures of ice and silicates that have been subjected to little geologic activity other than impact cratering. Among the most intriguing geologic features in these old terrains are the "crater palimpsests" (Smith et al., 1979b). These are circular features of very little relief that are apparently vestiges of large ancient impacts. Their mechanism of formation has not been firmly established. However, one plausible model is that ancient impacts that penetrated through Ganymede's cold outer crustal regions allowed warm, mobile, and buoyant subsurface ice to be extruded to the surface, spreading outward to form the circular palimpsest deposits (Thomas and Squyres, 1990). Coupled with the possibility of deep through-going solid-state convection, this model opens the possibility that ice from very deep within Ganymede was extruded to the surface during palimpsest formation.

Other regions of Ganymede are brighter and less heavily cratered. Evidence for tectonism in these regions of "grooved terrain" is widespread. The tectonism appears to have been dominantly extensional, producing a geometrically complex arrangement of grooves that are probably the surface expression of grabens and other fault-fracture features (e.g., Shoemaker et al., 1982). A variety of explanations have been offered for this tectonism, all related to subsurface phase changes among the various forms of H_2O possible in the deep interior (e.g., Squyres, 1980; Shoemaker et al., 1982; Kirk and Stevenson, 1983).

While the crater density in the grooved terrain tends to be lower than that in the darker terrain, the dominant mechanism of resurfacing is unclear. Following the Voyager mission, interpretations of Ganymede's bright terrain focused largely on the role of "cryovolcanism"—extrusion of liquid water or warm, mobile ice to Ganymede's surface. The prevailing hypothesis at that time was that the bands of bright terrain represented broad, down-dropped grabens that had been filled in with cryovolcanic deposits (e.g., Parmentier et al., 1982). In fact, extrusion of liquid rather than warm ice seemed plausible, given the lack of any observed viscous flow features in the Voyager images.

Recent Galileo images have called into question the idea of cryovolcanism in Ganymede's grooved terrain. High-resolution images of the Uruk Sulcus region in particular have showed such intense deformation at small scales that the destruction of preexisting craters there seems attributable entirely to tectonism (Belton et al., 1996; Pappalardo et al., 1998b). While it is tempting to extrapolate this conclusion to the rest of Ganymede, the limited spatial distribution of the high-resolution Galileo coverage makes this impossible. At this point, then, the satellite-wide role of cryovolcanism in the resurfacing of grooved terrain remains uncertain.

Because Ganymede's rocky-metallic interior lies so far below the surface, little study has been performed on its detailed evolution. However, if Ganymede is fully differentiated, then the size of its non-icy interior is comparable to that of Europa's. This being the case, there is also a distinct possibility that magmatic activity has occurred there. In fact, Galileo's discovery of Ganymede's intrinsic magnetic field leaves open the possibility that deep magmatic activity in Ganymede could persist to the present (Kivelson et al., 1996). It is therefore likely that hydrothermal activity has taken place at Ganymede's silicate-ice boundary, albeit many hundreds of kilometers beneath the satellite's surface.

Ganymede's biological potential is probably lower than that of Europa. Hydrothermal activity near the silicate-ice boundary could have occurred through at least some of the satellite's history, and through-going convection in the ice layer could have transported frozen hydrothermal fluids to near-surface regions. Whether or not subsurface material was extruded to the surface in formation of the grooved terrain is doubtful, but it remains a possibility. Such extrusion is certainly a possibility in the case of the crater palimpsests. Cryovolcanic deposits at the surface of Ganymede, if they exist, are likely to be hundreds of millions to billions of years old, and many hundreds of kilometers removed from any potential hydrothermal sites.

Callisto

Callisto is similar to Ganymede in its size (radius of approximately 2,400 km) and density (approximately 1.8 g/cm^3). This similarity makes it difficult to explain why the satellites are so different in appearance. In contrast to Ganymede, Callisto shows negligible evidence for resurfacing or tectonism (Smith et al., 1979a,b). Instead, the satellite's history has been dominated nearly completely by impacts. All of the major geologic features seen in both Voyager and Galileo images can be explained in terms of impact-related processes. This applies even to sets of subparallel furrows, which are due to faulting but which are clearly concentric with features of major impacts and caused by them (McKinnon and Melosh, 1980).

The general lack of nonimpact processes on Callisto does not rule out the possibility that subsurface material has risen to the surface in some locations. Although distinct crater palimpsests like those on Ganymede are not generally observed, it is clear that large impacts have caused excavations to substantial depths in the satellite. The largest impact scars do not retain deep crater-like topography, and so have clearly undergone postimpact modification that has included upward viscous flow of materials that were originally deep below the surface. The floors of the largest impact scars could therefore contain materials that were once many tens of kilometers beneath the satellite's surface.

Galileo gravity data show that although Callisto is somewhat differentiated, it is much less so than Ganymede (Anderson et al., 1996a). The lack of a magnetic signature also distinguishes it from Ganymede (Khurana et al., 1997). If correct, this finding may mean that early heating of Callisto was less severe than that for Ganymede, so that heat transport processes (probably including deep solid-state convection) were more able to keep pace with heat production and help to inhibit differentiation. This finding is consistent with the lack of tectonism on Callisto, since the ice-ice phase changes associated with differentiation can produce substantial surface extension and tectonism (Squyres, 1980).

Callisto's apparent lesser degree of differentiation, and particularly its minimal resurfacing and tectonism, are significant from a biological perspective. These findings imply that silicates, rather than being concentrated near the satellite's center as they are in Ganymede, may be distributed more nearly uniformly throughout it. If a rocky or rocky-metallic interior is poorly developed within Callisto, silicate magmatism and hydrothermal activity are less likely to have taken place there.

One conceivable mechanism by which biological materials could have reached the surface of Callisto would be transfer by ejecta from an impact on another body in the Jupiter system, like Europa, that has some biological potential. However, such material would constitute such a trivial volume of Callisto's surface material that the odds of sampling it would be negligible. This applies to the other planetary satellites as well.

POTENTIAL FOR A LIVING ENTITY TO BE IN OR ON SAMPLES RETURNED FROMPLANETARY SATELLITES

For samples returned from the seven planetary satellites discussed above, the answers to the questions posed in Chapters 1 and 2 can be summarized as follows.

1. Does the preponderance of scientific evidence[3] indicate that there was never liquid water in or on the target body?

   The evidence indicates that there was never liquid water on the Moon and Io. For Phobos and Deimos, there is no evidence that liquid water ever existed, but owing to uncertainty about the bodies' composition, the possibility cannot be excluded. There is evidence for the potential for liquid water on Europa and, to a lesser extent, on Ganymede and Callisto.
2. Does the preponderance of scientific evidence indicate that metabolically useful energy sources were never present?

   Biologically useful energy may be present on Io. It is likely that hydrothermal systems operated within a few hundred kilometers of Europa's surface at some point in its history and that material from beneath the surface has reached the surface in the geologically recent past. Because Callisto is apparently less differentiated than Ganymede, for example, a biologically useful energy source is much less likely on Callisto than on Ganymede but is still possible.
3. Does the preponderance of scientific evidence indicate that there was never sufficient organic matter (or CO_2 or carbonates *and* an appropriate source of reducing equivalents)[4] in or on the target body to support life?

   Because of the lack of data, it is uncertain that there was never sufficient organic matter (or CO_2 or carbonates and an appropriate source of reducing equivalents) in or on the planetary satellites discussed in this chapter.
4. Does the preponderance of scientific evidence indicate that subsequent to the disappearance of liquid water, the target body has been subjected to extreme temperatures (i.e., >160 °C)?

   Because of its volcanism, Io is likely to have been subjected to sterilizing temperatures. It is as yet undetermined whether sterilizing temperatures were reached for the other six planetary satellites discussed in this chapter.
5. Does the preponderance of scientific evidence indicate that there is or was sufficient radiation for biological sterilization of terrestrial life forms?

   The effects of galactic cosmic rays, solar flare protons, and radiation from natural radionuclides on Phobos and Deimos have been substantial and are sufficient for biological sterilization of the satellites. Io is subjected to intense sterilizing radiation from Jupiter's magnetosphere.
6. Does the preponderance of scientific evidence indicate the natural influx to Earth, e.g., via meteorites, of material equivalent to a sample returned from the target body?

   Because of the lack of data, it is uncertain whether there has been natural influx to Earth of material from the planetary satellites examined in this chapter.

This direct evidence, along with the absence of indirect evidence for recent or past liquid water on the Moon, indicates that the potential for a living entity to be present in samples returned is negligible. Phobos and Deimos

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[3] For the purposes of this report, the term "preponderance of scientific evidence" is not used in a legal sense but rather is intended to connote a nonquantitative level of evidence compelling enough to research scientists in the field to support an informed judgment.

[4] For the purposes of this report, CO_2 or carbonates *and* an appropriate source of reducing equivalents is equivalent to "organic matter" to accommodate chemolithoautotrophs.

have been radiation-sterilized by natural radioactive sources and are too warm and too fractured to enable life-protecting ice to persist in interior pockets, and so the potential for a living entity to be present in returned samples is negligible. However, Phobos and Deimos could be subject to cross-contamination by ejecta from Mars. It is uncertain whether such material would constitute such a trivial volume of the surface of Phobos or Deimos that the odds of sampling it would be negligible. The potential for a living entity to be present in samples returned from Io is negligible because of the lack of water in any form and the additional sterilizing influence of jovian magnetospheric bombardment on near-surface materials. There is evidence of liquid water beneath the icy crust of Europa, first surmised from Voyager data and reinforced by Galileo data. A readily available energy source (i.e., heat) may be present because of the Laplace orbital resonance relationship among Io, Europa, and Ganymede. Accordingly, the task group found that there is a potential for a living entity to be present in samples returned from Europa. Similarly, the task group found that there is a potential for a living entity to be present in samples returned from Ganymede. Because Callisto lacks an adequate source of energy to melt ice today and because there is no direct evidence that Callisto contained liquid water in the past, the potential for a living entity to be present in or on a returned sample is extremely low, but the task group could not conclude that it is zero. Callisto could be subject to cross-contamination by ejecta from another body in the Jupiter system (e.g., Europa) that has some biological potential. However, such material would constitute such a trivial volume of Callisto's surface material that the odds of sampling it would be negligible.

On the basis of available information about the Moon and Io, the task group concluded with a high degree of confidence that no special containment is warranted for samples returned from those bodies beyond what is needed for scientific purposes. For samples returned from Europa and Ganymede, the task group concluded that strict containment and handling requirements are warranted. For samples returned from Phobos, Deimos, and Callisto, the potential for a living entity in a returned sample is uncertain because of potential cross-contamination. While the task group concluded that containment is not warranted for samples returned from Phobos, Deimos, and Callisto, these conclusions are less firm than that for the Moon and Io. These conclusions need to be reexamined on a case-by-case basis when missions to these bodies are planned.

SCIENTIFIC INVESTIGATIONS TO REDUCE THE UNCERTAINTY IN THE ASSESSMENTOF PLANETARY SATELLITES

Outlined below are investigations that would help to improve some of the uncertainty associated with assessment of the biological potential of some of the planetary satellites inside Jupiter's orbit before samples are returned.

Phobos and Deimos

Compositional remote sensing of Phobos and Deimos (e.g., x-ray and gamma-ray analysis for elemental chemistry, infrared analysis for mineralogy) could help to show whether these objects are primitive, undifferentiated bodies (perhaps akin to P- and D-type asteroids) or whether they are more evolved bodies with a correspondingly lower biological potential. Additionally, it would be especially useful in this context to analyze Phobos and Deimos for the presence of organic matter.

Europa

Europa is the focus of an intensive, ongoing investigation by the Galileo spacecraft. Unless compelling evidence is found that Europa does not now have, and never had, liquid water, special containment procedures will be needed until the question of the existence of a Europan biota is answered definitively by a sample return or in situ mission. Orbital geophysical sensing of several sorts (imaging, laser/Doppler geodesy, radar sounding) has the potential to resolve the question of whether or not there is a global "ocean" of liquid water beneath Europa's icy surface. If compelling evidence were found for subsurface liquid, remote and in situ determinations of the composition of recently resurfaced regions could provide information about the nature of that liquid.

Ganymede

Ganymede is also the focus of an ongoing investigation by the Galileo spacecraft. It seems likely that a sample return or in situ mission would be mounted to Europa before a mission to Ganymede. Improved determinations of Ganymede's moment of inertia could help to determine the extent to which the satellite is differentiated, and compositional remote sensing might provide evidence of whether or not liquid was involved in any of Ganymede's resurfacing.

Callisto

One of the primary arguments against use of special containment procedures for samples from Callisto is that the satellite appears to be largely or even completely undifferentiated. Improved determinations of Callisto's moment of inertia could verify this interpretation and thereby strengthen this case.

SUMMARY

The task group considered the possibility of sample return from the major satellites of the innermost five planets. These include the satellite of the Earth (the Moon), satellites of Mars (Phobos and Deimos), and satellites of Jupiter (Io, Europa, Ganymede, and Callisto). Many samples of lunar rocks and soils were returned to Earth by the U.S. Apollo and Soviet Luna programs. None has been found to contain any evidence of past or present lunar biological activity. Because of this direct evidence, and because there is no indirect evidence for recent or past liquid water on the Moon, the potential for a living entity to be present in returned samples is negligible. For samples returned from Phobos and Deimos the potential for a living entity in a returned sample is considered to be very low, but it cannot be expressed definitely because of possible cross-contamination from Mars. Although containment is unlikely to be required for samples returned from these bodies, this conclusion is less firm than that for the Moon and Io. There are no special containment procedures warranted for samples returned from Io, which is volcanically active, lacks liquid water, and has been heat sterilized (i.e., at temperatures greater than 160 °C). Although the task group does not recommend special containment procedures for samples returned from Callisto, its assessment depends on preliminary evidence suggesting that liquid water was not present in the past or present environment, but this assessment is less certain than, for example, that for Io or the Moon.

Unlike samples from the Moon and Io, samples returned from Europa should be contained. The evidence for a liquid water ocean beneath the icy crust, first surmised from Voyager data and reinforced by Galileo data, coupled with a readily available energy source from its role in the Laplace orbital resonance relationship, makes Europa a prime target in the search for extraterrestrial life. Likewise, strict containment and handling procedures are required for samples returned from Ganymede. While there is no evidence for liquid water beneath the icy crust at present, it cannot be ruled out that liquid water once existed, if only at great depth. Evidence for possible whole-satellite convection, coupled with a readily available energy source from its role in the Laplace orbital resonance relationship, also makes Ganymede a target in the search for extraterrestrial life

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4

Asteroids and Meteorites

Asteroids, like comets, are the remnant population of planetesimals—those small primordial bodies from which the planets accumulated. Common asteroid types are described in Table 4.1. Generally, the asteroids considered are those that are relic planetesimals formed in and beyond the asteroid belt (which is located between 2.2 and 3.2 AU from the Sun), as far away from the Sun as the Trojans, which orbit at Jupiter's distance. Those formed in more distant locations are usually called, or at least thought of as, comets. This chapter examines the origin, composition, and environmental conditions of three major classes of asteroids: undifferentiated, primitive (C-type) asteroids; undifferentiated metamorphosed asteroids; and differentiated asteroids.

The historical definitions of asteroids relate to the absence or presence of "cometary activity," which requires volatile compounds (especially water ice) near or at the surface of the object. Watson et al. (1963) showed that water ice readily sublimates in periods of time short compared with the age of the solar system out to Jupiter's distance. Therefore, objects made of a primordial mixture of ices and refractories formed at asteroidal distances from the Sun may be expected to have lost surficial ices and be dormant "asteroids," whereas objects deflected into the inner solar system from much more remote storage locations (the Kuiper Belt, Scattered Disk, and Oort Cloud) retain such volatiles on or near their surfaces and show "cometary" activity (comae and tails) until they have lived for some thousands of years in the inner solar system.

While, for this reason, absence of near-surface volatiles does not guarantee an absence of volatiles at depth within asteroids, other factors determine whether or not asteroids have or have had appreciable quantities of volatiles. Inside some solar distance, volatiles may never have condensed within planetesimals. It remains a matter of conjecture and current research where this boundary existed (e.g., was Earth formed "wet" [e.g., Dreibus and Wänke, 1987] or were all of its volatiles derived from late-accreting planetesimals [Chyba, 1987], e.g., comets, from much farther out?). In addition, subsequent thermal evolution—perhaps dependent on body size and/or distance from the Sun—undoubtedly dried out some asteroids; perhaps it dried out most asteroids. Other processes (e.g., efficient megaregolithic overturn of rubble-pile asteroids by repeated collisions) might also have allowed volatiles to sublimate. Spectral reflectance studies and other remote-sensing techniques show that some asteroids likely are composed of a dry suite of minerals (e.g., metallic bodies). Although it is conjectural, most researchers would not be surprised if many asteroids from the middle of the asteroid belt out to the Trojans were to look briefly like comets following rare catastrophic, disrupting collisions, which would expose buried volatiles. (A minority but significant fraction of objects called asteroids, especially those in Earth-approaching orbits, may be dormant or dead comets.)

For nearly two centuries, it has seemed reasonable to the scientific community that meteorites might come from asteroids. But as late as the 1970s, there were no known physical mechanisms for transporting asteroid fragments to Earth. For instance, collisions sufficient to produce such drastic orbital changes would instead vaporize the asteroidal material. The problem is now solved, except for the details (Wisdom, 1985). Throughout the asteroid belt, there are zones where resonant gravitational perturbations by planets, primarily Jupiter and Saturn, form dynamically chaotic zones. When inter-asteroidal collisions near the boundaries of these zones send fragments into them, orbital eccentricities are rapidly increased and the fragments cross the orbits of the other planets—including Earth's. Fragments reach Earth primarily from the inner parts of the asteroid belt, especially near the 3:1 commensurability with Jupiter (those in the outer belt reach Jupiter first and are generally ejected from the solar system). Earth-crossing asteroids often continue to have aphelia in the asteroid belt, and thus they continue to suffer collisions with main-belt asteroids. The smaller fragments that encounter Earth as meteorites result from a multi-generational collisional cascade and come both directly from the resonances in the main belt and from cratering and collisions involving Earth-crossing asteroids.

A few meteorites are from the Moon and Mars (Warren, 1994). Some meteorites may be from comets (Campins, 1997) or from more distant asteroids, but none have so far been identified as likely candidates, and there are physical reasons that mitigate against that (the high velocity and weak strength of comets result in upper atmospheric disintegration of incoming cometary meteoroids; efficient dynamical mechanisms for delivering asteroidal debris from regions beyond the 5:2 resonance have not been identified). The collisional cascade also generates finer materials as small as interplanetary dust, which is transported by Poynting-Robertson drag and other radiation forces (Burns et al., 1979). The relative contribution of comets and asteroids to particles of various sizes in the interplanetary dust complex is not well known, but both sources contribute a significant fraction (Bradley et al., 1988).

TABLE 4.1 Common Asteroid Types

Type	Reflectance Spectrum	Meteoritic Analog(s)
Undifferentiated C-like types		
C	Very low albedo, flat longward of 0.4 µm absorption band in UV and sometimes near 3 µm	Carbonaceous chondrites
B	Low albedo; C-like but brighter, more neutral	Carbonaceous chondrites
G	Low albedo; C-like but brighter, strong UV	Carbonaceous chondrites
Undifferentiated metamorphosed types		
Q	Moderate albedo, strong absorption near 1 µm and 2 µm	Ordinary chondrites
S	Moderate albedo, reddish in visible, weak to moderate absorption near 1 µm and 2 µm	Ordinary chondrites
Differentiated types		
M	Moderate albedo, slightly reddish linear slope	Irons
V, J	High albedo, like S-types but stronger and additional absorptions	HED basaltic achondrites
A	High albedo, strong absorptions due to olivine	Brachinites
S	Moderate albedo, reddish in visible, weak to moderate absorption near 1 µm 2 µm	Stony-irons, achondrites (?)
E	High albedo, flat or slightly reddish	Aubrites (?)
Others		
P	Very low albedo, slightly reddish linear slope	None
D	Very low albedo, reddish linear slope	None

NOTE: Other asteroid types have been defined that are not included in this table, e.g., F-types. Some are subdivisions of the types listed. Others are rare, new types, generally seen only among the population of very small asteroids. Some classified asteroids may be atypical of their class (e.g., M-types with 3 µm absorption features) or may have different meteorite analogs, pending availability of better data (e.g., M-types not surveyed by radar for high radar reflectivity could have undifferentiated enstatite chondrites as a meteorite analog).

The early history of asteroids is shrouded in uncertainty. It is believed that a planet never accreted in the asteroid belt because of the influence of massive Jupiter. Certainly, the inclinations and eccentricities of asteroid orbits today mean that asteroids typically collide at velocities of 5 km/sec, which results in cratering and catastrophic fragmentation, not accretion. Yet for growth to the sizes of the larger asteroids (hundreds to nearly 1,000 km in diameter), velocities must once have been much lower, as in other planetary accretion zones. There are large gaps in the distribution of asteroids where planetesimals once must have existed but no longer do, owing to resonant perturbations by Jupiter (these include not only the Kirkwood commensurability gaps within the asteroid belt, but also the so-called secular resonances, and the vast volumes of space beyond 3.2 AU where asteroids are now rare and were presumably cleared out early in solar system history). Perhaps collisions (and close gravitational encounters, if they were big enough) by those now-vanished bodies and others in Jupiter's accretion zone (Jupiter-scattered planetesimals) pumped up the velocities of the remaining main-belt asteroids. Alternatively, jovian resonances, which migrated through the asteroidal region during the late stages of Jupiter's growth, may have done so while asteroidal planetesimals were accreting, clearing out and/or pumping up the velocities of many asteroids (Ruzmaikina et al., 1989). The asteroids are also depleted by collisional fragmentation, but recent research suggests (but not yet definitively) that collisions are inefficient at disrupting asteroids (Asphaug et al., 1998) and probably did not play more than a minor role in reducing the original planet's-worth of mass in the asteroidal region to the roughly 0.01 percent that remains today.

Whatever the precise scenario for asteroids' origin, the asteroid population has been roughly what it is like today for at least 4 billion years, with the largest bodies never much larger than the 950-km Ceres. The asteroids have been gradually evolving by collisions ever since. Sufficiently energetic collisions break asteroids into pieces, imparting the fragments with velocities that exceed escape velocity so that they go into similar but separate heliocentric orbits (groups of asteroids in similar orbits are called "families"). A majority of collisions, however, lack the energy to disrupt an asteroid, yet are more than sufficient to shatter its constituent rocky materials. Therefore, most asteroids (at least those larger than a few kilometers in diameter) are expected to be shattered into gravitationally bound "rubble piles" (Melosh and Ryan, 1997). Exceptions may be the much stronger remnant metallic cores of differentiated bodies (i.e., bodies that once melted to the degree that metal sank into their cores and the least-dense silicates erupted onto their surfaces as lava).

It should be noted that the size distribution of asteroids is such that most of the mass (hence collisional kinetic energy of impacts) is in the largest objects. Thus the greatest damage is done on the largest spatial scales, resulting in coarse rubble, analogous to the lunar megaregolith. While surficial regoliths exist on the larger asteroids, which may be analogous to the fine-grained lunar regolith, asteroid interiors are not "gardened" at fine scales but rather are jumbled about. Therefore, while a significant fraction of meteorites have portions that contain solar wind gases and cosmic-ray tracks, indicating that they were once, for a brief period, near the surface of their parent body, much of the other material within asteroids must be expected to have never been close enough to the surface to be sterilized by cosmic rays, despite the collisional jumbling.

Meteorites bear witness to the collisional processes. Many are rocks (referred to as breccias) whose properties reflect the collisions that break, shatter, and weld together the asteroidal rocks. While localized melting sometimes occurs, melting has affected only a tiny fraction of meteoritic materials and has probably never been sufficient to differentiate all, or even a substantial part, of any asteroid (Keil et al., 1997). There is evidence that some asteroids were heated to very high temperatures (see below), but it all happened very early in their history, perhaps by the decay of ^{26}Al within the first million years or so.

Even the remaining asteroidal parent bodies of meteorites show evidence of high temperatures. Not only were some asteroids melted to the point of geochemical differentiation (forming metallic cores, mantles, and basaltic crusts), but many others were also metamorphosed at temperatures only a few hundred degrees shy of melting (McSween et al., 1988), and even many of the most primitive, least evolved asteroids show signs of early high temperatures. For instance, most carbonaceous chondritic meteorites experienced extensive aqueous alteration early in their parent body's history (Zolensky and McSween, 1988). However, present-day asteroids are too small to have had, or to have maintained, hot regions after the early period of formation. (The only meteorites known with young formation ages are now understood to come from Mars.) Asteroids are occasionally dislodged into orbits that approach the Sun, which would heat them; however, such bodies are likely to be destroyed within a few million years of such orbital change (e.g., by diving into the Sun or crashing into a planet). There is simply no viable scenario for maintaining warm temperatures within an asteroid over solar system history.

Most meteorites found on the surface of Earth come from meter-scale bodies that have been liberated from larger bodies (whether in Earth-approaching orbits or in the main asteroid belt) within the last hundreds of thousands to hundreds of millions of years. Such meteorites might often be expected to be sterilized by radiation, depending on how long they have orbited the Sun as small, independent bodies. At rare intervals (thousands to many millions of years), it is possible for Earth to be impacted by very large bodies, which are hundreds of meters to kilometers in size or larger (e.g., Gehrels, 1994). Such objects are unaffected by Earth's atmosphere, and the projectile material is vaporized, melted, or otherwise severely damaged upon impact with Earth's surface, in ways probably inimical to the survival of life that might be contained within them. At intermediate sizes and frequencies of impact, however, there are bodies meters to tens of meters in size that impact Earth quite frequently and may deliver materials, which were never subjected to cosmic radiation, fairly gently to the surface of Earth (at terminal velocity).

In the discussion of different types of asteroids and meteorites in this chapter, it is assumed that there exists a fraction of asteroidal materials that were never subjected to a lethal dose of cosmic radiation and thus, may contain dormant life. However, the possibility remains that natural radiation from long-lived radionuclides may be sufficient to have sterilized remnant life even in the buried, shielded portions of asteroids (see Chapter 1; also Clark et al., 1998). If this is the case, then many of the potentially hazardous situations discussed have been precluded. The task group notes that most asteroids contain nonvolatile material of roughly cosmic composition at small spatial scales and that their interiors would have been uniformly subjected to such low-level radiation. The exception would be portions of strongly differentiated objects that are strongly depleted in radioactive elements or portions of undifferentiated objects that contain pockets of ice.

The association between asteroids of different types and various kinds of meteorites has been determined incompletely and not without controversy. The following general summaries should be sufficient for the purpose of this report. Because of the collisional mixing process among asteroids, which results in the presence of a small percentage of lithic fragments (xenoliths) from other bodies, almost any asteroid might be expected to contain a small component of another type (see Chapter 2). This factor is *not* considered in what follows, which considers only the indigenous materials of the different types of asteroids and meteorite parent bodies.

UNDIFFERENTIATED, PRIMITIVE (C-TYPE) ASTEROIDS

C-type asteroids are very black objects, typically reflecting only 3 to 5 percent of incident sunlight. They have reflectance spectra that are relatively neutral in color throughout the visible and near-infrared, except for a prominent absorption feature (present in only some of them) near 3 µm, owing primarily to water of hydration (Jones et al., 1990). These features are roughly typical of laboratory spectra of carbonaceous chondritic meteorites (Feierberg et al., 1981). There are minor discrepancies in matching meteorite and asteroid spectra, and also minor variations among asteroid spectra that have resulted in additional classes of asteroids (G- and B-types are lumped in with the C-type asteroids).

Although it is not rigorously proved, it is likely that the C-type asteroids (which are overwhelmingly the most abundant type in the main belt, especially the middle and outer parts) are represented in various meteorite collections[1] by carbonaceous chondrites (Feierberg et al., 1981). The sampling of such asteroids by carbonaceous meteorites is likely to be biased toward those near middle-belt resonances (like the 3:1) rather than from outer belt asteroids; moreover, it is likely that the vast majority of carbonaceous chondrites come from fewer than 10 C-type parent bodies, although minor representation of a much vaster sample is likely. Because the relevant spectral reflectance data lack many of the pronounced absorption features that are diagnostic of composition, the comparison

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[1] C-type asteroids are likely to be represented in meteorite collections by petrologic type 1 and 2 carbonaceous chondrites. The type-1 and type-2 carbonaceous chondrites are the aqueously altered meteorites as represented by the CM2 Murchison and CI1 Orgueil. The type-3 carbonaceous chondrites such as CM3 Allende have only very minor aqueous alterations. Based on spectral criteria, type-3 carbonaceous chondrites might be classified as S-type asteroids (Gaffey et al., 1993a,b).

between carbonaceous chondritic meteorites and C-type asteroids is less robust than that for some other spectral types.

Most C-type asteroids observed today are probably fragments from collisions among earlier generations of somewhat larger asteroids, although the actual size distribution in the primordial asteroid belt is uncertain. The properties of carbonaceous chondrites suggest that the diameters of their parent objects are on the order of 100 km, but significantly larger objects cannot be ruled out. Note that the largest C-type today, Ceres, is nearly 1,000 km in diameter.

Based on meteoritic evidence, C-type asteroids were accreted from dust, whose chemical composition was close to that of average protosolar-system material for the nonvolatile elements, plus volatile material in the form of water ice (and possibly even more volatile ices) and organic matter (Bunch and Chang, 1980). The chemical and physical form of that organic matter is unknown, but at least some was probably present as molecular fragments within ice mantles coating dust grains, such structures being predicted to form in dense interstellar clouds such as that which gave birth to the solar system (Greenberg, 1984). In this sense, C-type asteroids may be similar in composition to the nonvolatile fraction of comets.

Carbonaceous-chondrite petrology reveals that at least some C-type asteroids were heated to above the melting point of water ice shortly after accretion (Zolensky and McSween, 1988). The heating agent is not known but may have been the decay of freshly synthesized ^{26}Al and/or ^{60}Fe, or possibly inductive heating caused by a strong early solar wind. The resulting liquid water may have been eventually lost to space but, at least in the larger asteroids, remained for long enough to produce a secondary, hydrated lithology from the primary anhydrous silicates, oxides, sulfides, and metal originally accreted by the asteroid (Zolensky and McSween, 1988). The liquid water also reacted with the primary organic matter, producing the crop of secondary organic compounds found in carbonaceous chondrites today (Kerridge, 1993). The duration of aqueous activity is unknown; theoretical estimates range up to 10^8 years, but not longer (Grimm and McSween, 1993).

Some C-type asteroids actually show spectral evidence for hydrated minerals on their surfaces, whereas others do not. It is not clear whether those that do not show the water of hydration feature were dehydrated at moderately high temperatures, or if they were never warmed to the melting point of ice (or never incorporated water) in the first place.

Undifferentiated asteroids, especially those C-types rich in organics and that exhibit evidence of warm temperatures giving rise to aqueous alteration, are plausible candidate environments for the origin and sustenance of life. However, as explained above, these conditions lasted only for a transient period of time near the beginning of planetary history. Despite numerous false alarms, no convincing evidence for ancient organisms has ever been found in carbonaceous meteorites. However, it is clear that conditions for the origin of life—namely, presence of liquid water, organic matter, trace elements, and an energy gradient—were at least transiently met on some, possibly most, C-type asteroids.[2] The extent to which the population of meteoritic organic compounds matched that needed for production of a self-replicating system is not currently known, but with that caveat, there appear to be no grounds for concluding that emergence of life in a C-type asteroid was precluded. However, the epoch of liquid water must have ended more than 4 Gyr ago (Grimm and McSween, 1993), and so the question is whether or not any life that was formed could have survived. Clearly, as argued above for all asteroids, portions of C-type asteroids have been shielded from external cosmic radiation. Within the interiors of such bodies, there is a low level of radioactivity from long-lived radionuclides that probably would sterilize dormant entities surrounded by nonvolatile material of cosmic composition. But material embedded in pockets of ice, which may well exist within some C-, P-, and D-type asteroids, could have been protected from much of that radiation, and so there is the prospect that dormant life may have survived for the ensuing aeons.

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[2] Numerous carbonaceous chondrites have been found to contain organic compounds, some of which were apparently synthesized directly on the parent body during a period when aqueous conditions existed (Cronin and Chang, 1992). However, there is no evidence that prebiotic chemistry advanced beyond the synthesis of some of the monomeric molecules thought to be important in the origin of life. There is a rich history of claims of finding evidence of life in a variety of meteorites (see Appendix C), but these indications have all eventually been found to be either artifacts or the result of terrestrial contamination. Thus, although meteorites containing extraterrestrial organic compounds have fallen on Earth throughout its history, there is no evidence that this process has ever inoculated Earth with any extinct or extant organisms.

It is likely that Earth receives considerable cosmic dust from C-type asteroids, but this material has probably been sterilized during its transport time to Earth, although very rarely—much more rarely than for comets—dust might land on Earth very shortly after its liberation from an unsterilized portion of an Earth-crossing C-type asteroid. The dominant delivery mechanism of potentially unsterilized C-type material is by meteorites and by the infrequent impact of larger C-type projectiles.

In addition to C-types, there are P- and D-types located predominantly near and beyond the outer edge of the main asteroid belt (D-types predominate among the Trojans, at Jupiter's distance from the Sun). There appear to be no meteoritic analogs for these asteroid types, consistent with their virtual absence in the inner parts of the asteroid belt for which dynamical transport processes have been identified. On the other hand, it is probable that rare fragments of P- and D-type asteroids occasionally reach Earth. It is assumed that P- and D-types are even more primitive than C-types, although this concept is difficult to test. Conceivably their colors have more to do with the state of their surfaces (owing to greater distance from the Sun, lesser collisional environment) than to their interior compositions. For purposes of this report, it is reasonable to consider P- and D-type asteroids as being similar to C-types. But caution is warranted as their nature is truly only a matter of speculation. Given that it is also not proven that a significant portion of P- and D-type material reaches Earth as part of the apparently nonhazardous natural influx, uncontained sample return from such objects should proceed only after some of the unknowns have been resolved.

UNDIFFERENTIATED, METAMORPHOSED ASTEROIDS

Undifferentiated, metamorphosed asteroids are those that were heated to temperatures of less than 1,000 K so that minerals did not segregate in a macroscopic way, but are also dehydrated (if ever hydrated in the first place) and were probably subject to temperatures at which biological materials could not survive. The most common meteorites on Earth, the ordinary chondrites, are fragments of such asteroids. These meteorites are known to be undifferentiated because their bulk elemental compositions are similar to the nonvolatile elements in the solar system (e.g., Wasson, 1985).

There has been a long-standing dispute about which main-belt asteroids to associate with these common meteorites (Chapman, 1996). In all probability, some of the S-type asteroids (the most abundant asteroid type in the inner third of the asteroid belt) are undifferentiated but metamorphosed objects analogous to ordinary chondrites, although a few researchers deny this. Other S-types may be examples of differentiated asteroids of various kinds (see below). In general, the spectra of S-types show more diagnostic absorption features than do spectra of C-types. Their slightly reddish spectra show the clear presence of such silicate minerals as olivine and pyroxene. Relying solely on spectral reflectance data, however, it is not always possible to decide unambiguously whether an asteroid observed telescopically has experienced global differentiation or not. In addition to the minerals olivine and pyroxene, the reddish slope of the spectra suggests the presence of metallic iron; together, these minerals constitute the dominant materials in undifferentiated ordinary chondrites. However, the same minerals are also found, in different proportions, in certain differentiated meteorites, and in addition the observed asteroid spectra do not exactly match those obtained in the laboratory from ordinary-chondrite specimens. Because the ordinary chondrites are the most abundant variety of meteorite falling on Earth today, which argues in favor of an abundant type of parent asteroid, it is commonly, though not universally, believed that the spectral differences between ordinary chondrites and some S-type asteroids are due to "space-weathering" of the asteroid surfaces, and that the ordinary chondrites are, in fact, derived from asteroids of spectral type-S (Wetherill and Chapman, 1988).

This issue will be further addressed by the Near Earth Asteroid Rendezvous (NEAR) mission, but in the interim it seems reasonable for present purposes to equate S-type asteroids with ordinary chondritic material, since those S-types that are actually differentiated asteroids have natures, and have undergone histories, even less hospitable to life. After all, the ordinary chondrites come from some main-belt asteroids, even if they are rare, and the mineralogy that the ordinary chondrites have in common imposes quite firm constraints on their prebiotic chemical history.

Based on their chemical and isotopic compositions, known chondrites, other than carbonaceous chondrites, are derived from at least a half dozen undifferentiated asteroids (Rubin, 1997). Even though they show no evidence for igneous differentiation, most ordinary chondrites exhibit the effects of prolonged heating to temperatures sufficient to cause metamorphism and even, in some cases, incipient partial melting. It is generally believed (McSween et al., 1988) that this metamorphism was caused by internal heating of the asteroidal parent bodies, perhaps by decay of recently synthesized radionuclides such as ^{26}Al or ^{60}Fe, and that the most severely heated chondrites resided at the greatest depth within such an asteroid. Those ordinary chondrites that exhibit evidence for thermal metamorphism contain neither detectable organic matter nor hydrated minerals, so that two of the criteria for origin of life are not met. However, a small number of ordinary chondrites, known as unequilibrated ordinary chondrites (UOCs), show minimal evidence for metamorphism and in a few cases contain evidence for modest degrees of aqueous alteration (Alexander et al., 1989) and traces of organic matter (Yang and Epstein, 1983). Thus, some UOCs strictly satisfy the criteria for emergence of life, but the amount of water was apparently very limited (it may have been vapor rather than liquid), and there is no evidence for the kind of complex organic chemistry needed for development of self-replicating systems. Consequently, it seems highly unlikely that life could have originated on a UOC parent asteroid and, by extension, on any undifferentiated but metamorphosed, i.e., S-type, asteroid.

As mentioned above, the NEAR mission should help to resolve the question of whether ordinary chondrites are derived from S-type asteroids, thereby reducing that element of uncertainty, but otherwise, barring the fall of a UOC unusually rich in organics and hydrated minerals, it is unlikely that our understanding of the biological potential of undifferentiated asteroids is likely to improve in the foreseeable future, except through sample-return missions.

DIFFERENTIATED ASTEROIDS

Differentiated asteroids are inferred to be objects, or fragments of objects, that were once heated to the point of partial melting and geochemical segregation of materials. Vesta is a classic example of a largely intact differentiated body. As demonstrated by McCord et al. (1970), Vesta is covered with basalts (represented on Earth by the so-called HED basaltic achondritic meteorites). It is presumed (and, to some degree, observed [see Binzel et al., 1997]) that the basaltic crust overlies an olivine mantle on Vesta. Presumably Vesta has an iron core.

While Vesta is apparently unique as an intact, differentiated asteroid, many other asteroids look like pieces of a smashed-up Vesta, or fragments of smaller differentiated bodies. These include some so-called M-type bodies (the largest of which is 250-km-diameter 16 Psyche) that are apparently iron cores, or fragments of cores, from the interiors of preexisting bodies like Vesta; ambiguous inferences of metallic composition from spectral reflectance studies are confirmed, in a few instances, by high (metallic) reflectances of radar echoes (Ostro, 1993). There are other classes of asteroids, including small objects (V- and J-class) that may be fragments of Vesta's crust (Binzel and Xu, 1993), the monomineralic (olivine-rich) A-type asteroids, and the E-type asteroids (iron-poor enstatite) that probably represent mantles or crusts of such differentiated bodies. Their spectra are certainly not compatible with being undifferentiated. In addition, as described in the previous section, some (or even most) S-types may be differentiated bodies, as well.

Generally speaking, the various kinds of metallic, stony-iron, and achondritic stony meteorites are believed to be derived from these, and analogous, kinds of asteroids, generally located in the inner to middle parts of the asteroid belt. In general, these materials have been subjected to long-term heating well above 1,000 K, and water has not been present. They seem to be even less likely to harbor biological materials than are the undifferentiated but metamorphosed asteroids discussed in the previous section.

Until recently, some meteorites classified as achondrites were known to have had a much more complex history, including young ages, and evidence of being derived from unusually large asteroids (not identified in space) where ongoing environments conducive to life could not be ruled out. These achondrites, the so-called SNC meteorites, are now understood to come from Mars—a very large "asteroid," indeed, and beyond the purview of this report. As with Mars (and Earth), differentiation in and of itself does not preclude possible biological activity. It cannot be totally ruled out that there were other large asteroidal objects, not now being sampled by the ever-growing suite of collected meteorites, that might have had conditions leading to the origin and presence of life. However, remnants of any such objects are evidently very uncommon among meteorites striking Earth today.

POTENTIAL FOR A LIVING ENTITY TO BE IN OR ON SAMPLES RETURNED FROMASTEROIDS

There are a few researchers who maintain that meteorites are only a very selective sample of the asteroids and, indeed, that the proportions of extraterrestrial materials striking Earth vary dramatically with time (Halliday et al., 1990). While these ideas are not widely supported, it is prudent to remain aware that generalities deduced from studies of meteorites and the likely associations of certain meteorite types with common asteroid types may not strictly apply to any particular asteroid. With this caveat, it can generally be stated that sample return from asteroids of the types sampled by the known meteorites evidently presents no known biological threat. Furthermore, both the differentiated and the undifferentiated-but-metamorphosed asteroids (e.g., M-, S-, V-, J-, and Q-types) have histories that appear to preclude the origin of life in the first place. For C-types to harbor dangerous biological materials (not so far identified in C-type meteorites), that material must have survived aeons since conditions suitable for replication ended.

While P- and D-type asteroids (and perhaps other rare, anomalous asteroid types) may be presumed to have histories similar to those of the C-types (and other types) discussed above, the asteroid population is evidently diverse and some mysteries remain. Thus, uncontained sample return from such unusual and/or unsampled bodies would have to await further investigation of their properties.

For many asteroids, the requirements for life to have emerged (presence of liquid water, organic matter, and a usable energy source) were probably met very early in their history. Although the known meteorites derived from such asteroids reveal no evidence of biological activity, those meteorites cannot be regarded as having sampled the entire population of such asteroids. Similarly, although the natural meteorite influx has apparently had no deleterious effect on terrestrial biology, it is not certain that samples of every asteroid type have fallen on Earth. Furthermore, although natural radioactivity present within the asteroidal/meteoritic material would have been adequate to sterilize any dormant organisms possibly present within the lithic fraction of such objects, if pockets of relatively pure water ice were to exist within an asteroid of this type, attenuation of the natural radiation field within that ice could in principle have permitted survival of putative dormant organisms.

Based on the task group's current knowledge of the origin and composition of asteroids, the answers to the assessment questions employed in this study are as follows:

1. Does the preponderance of scientific evidence[3] indicate that there was never liquid water in or on the target body?

   There is unequivocal evidence for liquid water active within at least some C-type asteroids approximately 4.5 Gyr ago. A minor fraction of S-type asteroids may have experienced a transient episode of aqueous activity, but the great majority of S-types have never seen liquid water. Liquid water can also be ruled out for M-, V-, and E-type asteroids. For P- and D-type asteroids there is no evidence one way or the other regarding the presence of liquid water.
2. Does the preponderance of scientific evidence indicate that metabolically useful energy sources were never present?

   There is no evidence one way or another regarding the presence of metabolically useful energy sources in other asteroid types.
3. Does the preponderance of scientific evidence indicate that there was never sufficient organic matter (or CO_2 or carbonates *and* an appropriate source of reducing equivalents)[4] in or on the target body to support life?

   In most asteroids (especially C-types), there was some (or even an abundance) of organic matter. In others, especially the metamorphosed and differentiated asteroids, there was not.

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[3] For the purposes of this report, the term "preponderance of scientific evidence" is not used in a legal sense but rather is intended to connote a nonquantitative level of evidence compelling enough to research scientists in the field to support an informed judgment.

[4] For the purposes of this report, CO_2 or carbonates *and* an appropriate source of reducing equivalents is equivalent to "organic matter" to accommodate chemolithoautotrophs.

4. Does the preponderance of scientific evidence indicate that subsequent to the disappearance of liquid water, the target body has been subjected to extreme temperatures (i.e., >160 °C)?

   There is meteoritic evidence that some C-type asteroids have experienced temperatures above 160 °C following aqueous activity, but a substantial fraction have not been so heated. In general, there has been no source of sterilizing heat to raise the temperatures of most asteroid materials since primordial epochs, except for the localized heating due to impacts.
5. Does the preponderance of scientific evidence indicate that there is or was sufficient radiation for biological sterilization of terrestrial life forms?

   The interiors of undifferentiated asteroids would have experienced sterilizing doses of radiation from the decay of natural radionuclides during the 4.5 Gyr since cessation of aqueous activity. (The exception is the possibility that localized pockets of ice might have shielded some materials from such radiation within C-type, but not metamorphosed, asteroids.) While sources of radioactivity may be diminished within portions of differentiated asteroids, the previous history of these bodies precludes the origin of life within them in any case.
6. Does the preponderance of scientific evidence indicate the natural influx to Earth, e.g., via meteorites, of material equivalent to a sample returned from the target body?

   Meteorites and interplanetary dust particles (IDPs) have delivered samples of many asteroids to Earth. Some of those meteorites (although virtually no IDPs) would have been protected from sterilizing doses of radiation from galactic and solar cosmic rays while in transit to Earth. Therefore, some C-type material certainly regularly arrives on Earth unsterilized and has not been observed to have adverse effects. Whether or not the C-type material so received is representative of a particular target body, however, is uncertain.

Very little is known about P- and D-type asteroids. It is plausible that they are like C-type asteroids and dormant comets derived from the Jupiter zone. But caution is warranted as their nature is truly only a matter of speculation. Because of this lack of information, the potential for a living entity to be present in returned samples cannot be determined and, therefore, is considered conservatively by the task group as possible at this time. Another reason for caution is that very few P- and D-type asteroids are in orbits that can readily deliver materials to Earth, and most (like the Trojans) are in orbits so distant and so dominated by Jupiter's gravity that they are precluded from communicating directly with Earth, and so the natural influx of P- and D-type materials is very small or, most likely, zero.

Undifferentiated, metamorphosed asteroids as well as most differentiated asteroids[5] are dry and have been heated to very high temperatures. A minor fraction of S-type asteroids may have experienced a transient episode of aqueous activity, but the great majority of S-types have never been exposed to liquid water. Like C-type asteroids, S-types would have experienced sterilizing doses of radiation from decay of natural radionuclides during the 4.5 Gyr since cessation of any aqueous activity. Thus, for S-type asteroids and other non-C/P/D-like asteroid types, the potential for a living entity to be present in returned samples is negligible. However, there is clear evidence in meteorites that substantial cross-contamination of material from one asteroid to another has occurred. It is uncertain whether such material would constitute such a trivial volume of the surface material on asteroids that the odds of sampling it would be negligible.

Because the knowledge base for P- and D-type asteroids is highly speculative, the task group concluded conservatively that strict containment and handling requirements are warranted at this time. For samples returned from C-type asteroids, undifferentiated metamorphosed asteroids, and differentiated asteroids, the potential for a living entity in a returned sample is extremely low, but the task group could not conclude that it is demonstrably zero. Based on the best available data at the time of its study, the task group concluded that containment is not warranted for samples returned from these bodies. However, this conclusion is less firm than the task group's same conclusion for the Moon, Io and certain IDPs and should be reexamined at the time of mission planning on a case-by-case basis.

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[5] Phyllosilicate veins have been described in ureilites.

For differentiated asteroids, despite the high temperatures that brought about differentiation of these bodies, there is no evidence that liquid water was present for the development of life. Liquid water can also be ruled out for M-, V-, and E-type asteroids, and so the potential for a living entity to be present in samples returned from these asteroids is similarly negligible. However, there is clear evidence in meteorites that substantial cross-contamination of material from one asteroid to another has occurred. Differentiated asteroids are known to be subject to cross-contamination, although it is uncertain whether such material would constitute such a trivial volume of the surface material on asteroids that the odds of sampling it would be negligible. Although the task group concluded that containment is not warranted for returned samples from differentiated asteroids, this conclusion is less firm that for the Moon and Io and should be reexamined at the time of mission planning on a case-by-case basis.

SCIENTIFIC INVESTIGATIONS TO REDUCE THE UNCERTAINTY IN THE ASSESSMENTOF ASTEROIDS

Given the possibility that many types of asteroids harbored environments suitable for the origin and sustenance of life early in their history, the chief questions that can readily be addressed by further research fall in two areas: (1) assessing the environments during subsequent aeons that may or may not have permitted dormant life to survive and (2) assessing questions concerning the association between meteorites that have been well studied on Earth (and represent material delivered by the natural influx to Earth) and specific asteroid types and specific asteroids that may be visited by spacecraft.

Although microorganisms could be readily protected from sterilizing external radiation sources if they were deeply buried, the task group's analyses suggest that the natural decay of long-lived radionuclides, in proportions represented by cosmic abundances, are roughly near the (uncertain) threshold levels of potential survivability in a dormant state (Clark et al., 1998). It would help to reduce uncertainty if the actual variety of radiation levels experienced within small bodies could be better assessed. A variety of heterogeneities within small bodies have been hypothesized (large pockets of ice within voids in a "rubblized" asteroid, degrees of local segregation of radioactive materials away from others that might increase the range of dosages within a body, and so on). Various spacecraft experiments in the vicinities of small bodies could help to better assess large-scale internal porosities and heterogeneities. In addition, studies of meteorites directed toward assessing the ranges of exposure to radiation due to small-scale heterogeneities would narrow current uncertainties.

In assessing the necessity to engineer containment for a sample return mission to a particular body, it is important to learn more about two questions: (1) To what degree do existing varieties of meteorites represent the range of materials likely to be present on asteroids of the "type" or "types" of asteroids believed to be parent bodies for those meteorites?, and (2) To what degree of certainty is it known that the particular target asteroid (of a known type) is like typical asteroids of that type? The validity of approaching a particular target based on the understanding developed from meteoritical studies depends on addressing these questions.

The problem of association of meteorite types with asteroid types is an evolving multidisciplinary study, involving ground- and space-based remote sensing studies of asteroids; laboratory analysis of meteorite mineralogy; laboratory experimentation on issues like space-weathering processes, which affect interpretation of reflectance spectra; theoretical studies of the collisional and dynamical physical processes that liberate meteorites from their parent bodies and deliver them to Earth; and so on. A relatively new way of studying asteroids is by spacecraft flyby and rendezvous, which employs techniques not previously applied to asteroids (spatially resolved spectral reflectance maps, x-ray and gamma-ray mapping, and others) but which can be expected to be applied to only a modest number of asteroids in the foreseeable future. Thus, continued application of telescopic studies to a broader variety of asteroids must continue. Improved ground-based radar studies should dramatically enhance our understanding of the distribution of metal among asteroids. Although there are no narrow, focused lines of research that promise immediate, dramatic advances, a broad-based research program on asteroids and meteorites and on the processes that affect them should continue to narrow our uncertainties about associations among asteroids and meteorites.

The question of whether a particular asteroid (which itself may well not have been sampled by the recent natural influx onto Earth) is like meteoritic material associated with its asteroidal type can best be addressed by a precursor mission or a mission phase to a sample return mission, that enhances our detailed knowledge about that body's composition and heterogeneity in ways analogous to the goals of the NEAR mission studies of Eros. Such investigations are likely to confirm (or deny) that a potential target body for sample return in fact resembles what we believe we know about the body from Earth-based data. Such precursor studies may not be necessary for bodies whose associations with meteorite types are quite clear (e.g., the association of Vesta with HED, or HED-like, meteorites), whereas they should be required for bodies (e.g., P- and D-type asteroids) whose association with known meteorite types is obscure.

SUMMARY

For samples returned from C-type asteroids, undifferentiated metamorphosed asteroids, and differentiated asteroids, the potential for a living entity in a returned sample is extremely low, but the task group could not conclude that it is zero. Based on the best available data at the time of its study, the task group concluded that containment is not warranted for samples returned from these bodies. However, this conclusion is less firm than it is for the Moon, Io, and some IDPs and should be reexamined at the time of mission planning on a case-by-case basis. Because the knowledge base for P- and D-type asteroids is highly speculative, the task group concluded conservatively that strict containment and handling requirements are warranted at this time.

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5

Comets

ORIGIN

Place of Formation

Our best understanding of the origin of comets is that they formed in the protoplanetary disk, at distances from the Sun ranging from the distance of proto-Jupiter to far beyond the distance of proto-Neptune. It is generally agreed that the planetesimals that accreted to form Uranus and Neptune, and probably also the cores of Jupiter and Saturn, were identical to comets. The only difference between those planetesimals and comets is circumstantial; i.e., some were captured into the planets and some were not. Although interstellar comets—comets that originally formed around other stars and were subsequently ejected from those stellar systems—are generally predicted to exist, it is certain that none of the comets for which orbits have been determined is interstellar. They all are members of our own solar system and have been for the 4.5×10^9 years of its existence.

Nebular Processes and Accretion

Cometary formation is not well understood, but it certainly includes the following processes. Some interstellar grains, probably only microscopic ones that formed long before the Sun's progenitor molecular cloud contracted to form the Sun, were carried directly into the protoplanetary disk and incorporated in comets. Other grains condensed from vapor as the material of the Sun's progenitor cloud was carried to higher densities and pressures. Much of the material generally thought of as rocky, such as silicate grains, may have been in solid form prior to the formation of the protoplanetary disk. More volatile species, from ordinary water ice down through very volatile species such as CO, may have provided their ices either by condensation from the vapor or from preexisting interstellar grains. This is one of the open questions in cometary research. Since models of the protoplanetary disk predict that the temperature decreases with distance from the protosun, the relative abundances of the volatile species in icy grains undoubtedly varied with distance from the protosun. A key feature of all theories for the formation of planets is that the density of the gaseous, protoplanetary disk is too low to form planets. The solid grains, whether preexisting or condensed from the vapor, are not held up by the pressure of the gas, and they sink rapidly to the mid-plane of the protoplanetary disk. This step is crucial in making the density high enough that the grains will encounter each other frequently. Initially the grains grow by aggregation or agglomeration in which the grains run into each other and stick to each other, at rates determined entirely by geometric cross sections and velocities, the sticking occurring primarily by molecular forces. When the grains become sufficiently large, gravitational attraction assists with both collecting and binding the grains and the process becomes known as accretion. When the grains become macroscopic, the accretion can be modeled more easily, and many investigators have studied the various mechanisms that lead to growth from macroscopic grains to planetesimals. The role of resonances and the ability of resonances to lead to characteristic sizes of planetesimals have been investigated with inconclusive results by many people. The current state of the art in this modeling is the work by Weidenschilling (1997), who finds that resonances are unimportant but predicts characteristic sizes on the order of 100 meters, the size at which the planetesimal has a sufficiently large ratio of mass to cross section that it decouples from the effects of gaseous drag.

Gravitational Scattering

The planetesimals that have grown large enough to escape the effects of gaseous drag can be modeled with purely gravitational physics. The results are somewhat sensitive to the assumed starting conditions, but in the vicinity of Jupiter and Saturn most planetesimals are either incorporated into Jupiter and Saturn or ejected entirely from the solar system by encounters with those bodies. In the vicinity of Uranus and Neptune, many planetesimals are still captured into the two planets or ejected from the solar system, but there is also a significant likelihood of a gentle ejection from the planetary region outward for thousands of astronomical units, i.e., to distances that are a significant fraction of interstellar distances, where the planetesimals are still gravitationally bound to the protosun in a very extended disk. Comprehensive models have not been calculated, but the studies thus far indicate that this is the dominant source of comets in the Oort Cloud.

Since the relative numbers of planetesimals at the distances of the different giant protoplanets are not well known, the relative contributions to the Oort Cloud from various regions of the protoplanetary disk also are not well known. The efficiency is much higher near proto-Uranus and proto-Neptune than near proto-Jupiter and proto-Saturn, but it is unclear whether higher relative numbers of planetesimals near proto-Jupiter and proto-Saturn might have counteracted this effect. As originally explained by Oort (1950), many dynamical simulations have shown that the effects of passing stars, galactic tides, and passages through molecular clouds convert this disk into a roughly spherical distribution that is now know as the Oort Cloud. Beyond Neptune, the process of formation of planetesimals proceeded more slowly owing to the lower densities and lower velocities. The formation of a planet was inhibited because the slow accretion to planetesimals used up all the material before one planetesimal became large enough that its gravitational cross section greatly exceeded its geometrical cross section and approached the scale of the mean separation between planetesimals. Most of these planetesimals are still present today in what is now called the Kuiper Belt, although the inner parts of this belt, say from 40 to 50 AU, have been considerably depleted by subsequent planetary perturbations.

The time scale for formation of large (tens of kilometers) comets in the Uranus-Neptune region is on the order of 10^6 years, that for ejection to the Oort disk is probably up to an order of magnitude longer, and the time scale to convert the Oort Cloud from a disk to a sphere is on the order of 10^9 years. It should be noted that one expects mixing of planetesimals from one part of the protoplanetary disk to another during the stage at which the planets accrete, although the simulations are not yet accurate enough to determine how much mixing occurs. Today the orbits of comets in both the Kuiper Belt and the Oort Cloud are nearly circular, with orbital periods in the Oort Cloud being the longest at about 10^6 years.

The comets that are seen today in the inner solar system have been delivered from both the Oort Cloud and the Kuiper Belt much more recently than the epoch of formation. Comets entering the inner solar system for the first time from the Oort Cloud can be recognized with high confidence from their orbits, the orbit having been perturbed by some passing star or possibly by a chance encounter between two comets. On the basis of an analysis of their orbits, it is possible to identify those comets that more likely came from the Oort Cloud and ones that more likely came from the Kuiper Belt, but for any individual comet we cannot be sure from which of these two reservoirs it came. Researchers also know of seven Centaurs, bodies orbiting roughly between Jupiter and Neptune, one of which is known to show cometary outgassing. These are transition objects between short-period comets and Kuiper Belt objects, although again researchers do not know confidently in individual cases whether the Centaur is arriving from the Kuiper Belt or is being ejected back toward the Kuiper Belt.

Early Heating and Melting

An important issue is whether the formation process allowed any significant internal heating. In the inner solar system, the combination of release of gravitational energy and radioactive decay leads to significant internal heating, at least for the larger bodies. For small bodies, up to the size of the largest known comet (Chiron), the accretion process is gentle enough that no significant accretional heating should occur, at least not sufficient to melt the interior ice on a large scale. Similarly, the long-lived radioisotopes that provide a large part of the outward heat flux from Earth today are insufficient to melt the interior of a small body; they would melt bodies on the order of 1,000 km and larger. On the other hand, short-lived radioisotopes, particularly ^{26}Al, have often been invoked as sources of heating that would have been sufficient to melt the interior of a cometary nucleus if the comets formed within a few half-lives of the creation of these radioisotopes in a nearby nova or supernova. Whether this happened or not is still unclear, and experts argue both sides of the case.

The highest concentrations of ^{26}Al are seen in calcium-aluminum inclusions (CAIs), high-temperature condensates that were among the first things to condense in the inner solar system. These concentrations are an order of magnitude higher (relative to the stable ^{27}Al) than expected from production rates in supernovae, which in fact are balanced (at least to within factors of a few) with the observed gamma rays in the interstellar medium (Timmes et al., 1995). Calculations by Prialnik and Podolak (1995; see also Yabushita, 1993; Grimm and McSween, 1989) show clearly that, with reasonable assumptions about the ratio of refractories to ice, and with an initial abundance of ^{26}Al that is well below that found in CAIs, and even below the excess produced in supernovae, the interiors of solid cometary nuclei only 20 km in radius will be substantially melted. On the other hand, they also find that if the nucleus is porous, the process of sublimation, vapor transport, and recondensation is so efficient at carrying heat away that even much larger comets will never melt, and in fact will usually not substantially exceed the temperature at which amorphous ice crystallizes exothermically (typically in the range from 100 to 150 K). The question of whether or not cometary nuclei melted, therefore, reduces to two other questions: What was the porosity of cometary nuclei initially? and, What was the distribution of ^{26}Al at the place (s) and time(s) of formation of cometary nuclei?

MacPherson et al. (1995) argue from the variations within individual grains of chondritic meteorites that the grains had long histories in the protosolar nebula before they were incorporated into planetesimals, during which time reprocessing of grain material occurred (ending after many half-lives of ^{26}Al in the formation of chondrules from some of the grains that might otherwise have been CAIs), and that the ^{26}Al decayed away within the grains but before accretion of planetesimals. Wood (1996), on the other hand, has argued that drag effects would lead to short dynamical lifetimes of grains falling into the Sun and that chondrule formation would have been far easier in the first million years of the nebula than later, thus concluding that most of the ^{26}Al must have decayed after accretion. Whichever viewpoint one takes, the arguments refer to the situation at the asteroid belt. Independent of evidence for extreme heterogeneity in the abundance of ^{26}Al on small spatial scales, there is good evidence for a non-uniform distribution of ^{26}Al, or at the very least for non-uniform heating in response to the decay of ^{26}Al, as a gradient across the asteroid belt. For example, Grimm and McSween (1993) argue that the systematic variation of asteroidal taxonomy with heliocentric distance is due to the increase of the accretional time scale with heliocentric distance such that the outer parts of the asteroid belt accreted after most of the ^{26}Al had decayed. Although the greater density of solids in the protoplanetary disk just outside the ice boundary (between the asteroid belt and Jupiter) would enhance accretion relative to the rate just inside the boundary, it is clear that accretion would proceed more slowly in the regions in which the comets primarily accreted than in the asteroid belt where the chondritic parent bodies accreted.

Evidence cited below in the subsection on chemical composition argues against the differentiation that would have occurred with global melting since highly evolved comets show chemical composition similar to that of comets newly arrived from the Oort Cloud. Furthermore, one of the widely discussed mechanisms for driving outbursts of comets, particularly at large distances from the Sun, is the exothermic crystallization of water ice. If cometary nuclei had substantially melted, there could not be any significant reservoir of amorphous ice. In fact, Prialnik et al. (1987) find the evidence for amorphous ice sufficiently strong that they use this to argue that the comets must have formed after the ^{26}Al decayed. Finally, it is noted that according to the best estimates the density of cometary nuclei is on the order of 0.3 g/cm^3. Although this number is very poorly determined and applicable primarily to evolved cometary nuclei, it clearly suggests a high porosity that would effectively inhibit melting even in the presence of ^{26}Al. There is also no empirical evidence favoring the existence of excess ^{26}Al in comets, nor is there any evidence for differentiation beyond that expected from vapor transport through porous ice. Therefore, it is concluded that it is very likely, although not firmly proven, that cometary nuclei never melted.

COMPOSITION

Physical Characteristics

When most comets are observed from Earth, the brightness of the coma, the gas and dust driven from the nucleus by sublimation, often overwhelms the brightness of the nucleus. Thus far, direct images are available of only one cometary nucleus, 1P/Halley, as well as a direct measurement via a stellar occultation of the size of one more, P/Chiron, which is actually a Centaur, and fairly reliable indirect measurements of the sizes of a handful more. In addition, granting the assumption that the reflectivity of the nucleus is known (actually a bad assumption), there are another dozen or two comets for which nuclear sizes have been determined. The radii so determined range from about 300 m to 90 km (for P/Chiron) (Meech, 1997) with radii of a few kilometers being the most common. Brandt et al. (1996a,b) have argued that this is purely a selection effect in discovering comets and that the predominant size is really much smaller than this. The recent comet Hale-Bopp, one of our more spectacular visitors in several decades, is thought to have a nucleus with a radius of about 20 km, although this number is uncertain by a factor of two. The smaller comets appear to be typically prolate, with axial ratios on the order of 2:1. The larger comets, P/Chiron and P/Schwassmann-Wachmann 1, show little variation in brightness as they rotate and are therefore generally thought to be spherical. It is unclear whether this difference (1) is a random fluctuation from small-number statistics, or (2) reflects a different origin (such as formation by fragmentation of larger, spherical nuclei to make smaller, irregular ones), or (3) reflects a different evolutionary history (such as outgassing near the Sun with seasonal and rotational effects leading to mass-loss preferentially from certain areas), or (4) is due to the greater importance of gravitation in shaping the larger bodies (an analogous transition to spherical shapes for asteroids occurs at a larger size and is thought to reflect the importance of gravity).

The known Kuiper Belt objects and Centaurs, if they have reflectivities similar to those of known cometary nuclei, are all much larger than the known cometary nuclei. Other than Pluto, the known Kuiper Belt objects are all still too small to have been heated by the long-lived radiogenic species. It is not possible at this time to say confidently whether the size distribution of comets in the inner solar system reflects the size distribution of the bodies in the Kuiper Belt and in the Oort Cloud. One expects that the loss of mass as short-period comets pass near the Sun, typically on the order of 1 m of material per perihelion passage, should lead to shrinkage of the nuclei, but the size of the net effect is tied up closely with models for the evolution of comets discussed below. The irradiation by galactic cosmic rays is less than that for comets in the Oort Cloud due to shielding by the heliosphere. There may still be sufficient radiation to break every chemical bond in the outermost layer, but the issue has not been studied because comets arriving in the inner solar system "for the first time" from the Kuiper belt, unlike those originating from the Oort Cloud, have not been observed. Collisional evolution is likely to have fragmented some large bodies in the Kuiper Belt, but collisions are expected to be negligible in the Oort Cloud.

The key characteristic of cometary nuclei is the outgassing, the observation of which provides the empirical definition used by the International Astronomical Union (IAU) to distinguish a comet from an asteroid. Ice in the cometary nucleus sublimes directly to the vapor phase, perhaps at the surface if ice is exposed but more likely from a subsurface layer of ice. The vapor expands rapidly into the vacuum of space, dragging grains ("dust") from the surface as it goes. The pictures of comet 1P/Halley (Keller et al., 1986) show jets of dust which make it clear that, at least for this one comet, the release of dust is concentrated in a relatively few active areas covering a modest fraction (15 percent) of the total surface. It is not directly known whether the gas also is released only from these active areas or whether the gas only drags dust from the surface in these areas. The pictures of Halley do not have sufficient resolution to address the question of whether ice in the active regions is subliming at the surface as opposed to subliming at a modest depth and percolating through a mantle. Comparison of observed water outgassing rates with sizes of nuclei, where known, and use of a theoretical model for the sublimation suggest that most comets, although there are exceptions, are inactive over most of their surface. Such a comparison does predict that Halley should be outgassing water over roughly 15 percent of its surface, quite comparable to the active fraction observed for dust. Many comets appear on this basis to be active over less than 1 percent of their surface (A'Hearn et al., 1995). This result is generally interpreted to mean that a mantle has built up on the surface which has choked off the sublimation by sealing in the gas, although it is unclear whether simple, consolidated rubble is involved as opposed to some type of material that is sealed by bonding.

The interior of cometary nuclei is almost totally unstudied observationally or experimentally, which is of course one of the reasons for returning samples. It is clear that the material of some, and probably all, cometary nuclei is structurally weak, the upper limit to the tensile strength of P/Shoemaker-Levy 9 before disruption being 10^4 dyn/cm^2 (Sekanina, 1995), i.e., orders of magnitude lower than the tensile strength of ice, which in turn has a tensile strength far below that of rock. The only estimates of the density of cometary nuclei are based on models for the nongravitational acceleration that are rather poorly constrained. The best estimates are that the bulk density of some short-period comets is on the order of 0.3 g/cm^3 (e.g., Rickman, 1991), which implies a highly porous structure, but some would argue that the uncertainty associated with this number could be as large as an order of magnitude in either direction. It is also unclear whether the inferred porosity refers to the mixture of rock and ice in the nucleus or instead is dominated by the depletion of ice by sublimation from a large fraction of a nucleus which originally had much lower porosity. Nevertheless, it seems likely that cometary nuclei, even before depletion of the ice by sublimation, are porous bodies with low density and strength.

Chemical Composition

Because there has never yet been any in situ sampling of a cometary nucleus, and since remote sensing of cometary nuclei has never yet shown definitively any identifiable spectral signature (there are reports of such detections but none that would be considered definitive), current knowledge of the composition of cometary nuclei comes entirely from studies of the coma—by remote sensing for many comets and by in situ measurements for only comet Halley (missions to fly through comets P/Giacobini-Zinner and P/Grigg-Skjellerup returned minimal information relevant to nuclear composition). It is therefore convenient to separate the discussion into substances that are volatile at 1 to 2 AU from the Sun and substances that are not.

The volatiles are clearly dominated by water, although it is unclear whether the ice in cometary nuclei is predominantly amorphous or crystalline. Theory predicts that ice deposited at very low temperatures should be amorphous, and the transition from amorphous to crystalline ice, which is exothermic, has often been invoked as the cause of outbursts in comes. As noted elsewhere, it is not known whether ice is exposed at the surface of nuclei or is exclusively in subsurface layers.

Our knowledge of the abundances of more complex molecules has been increasing dramatically in recent years, beginning with the in situ measurements at comet Halley just over 10 years ago and advancing since then in parallel with the advances in infrared and millimeter-wave technology at each newly discovered bright comet. Table 5.1 lists the known molecules in comets, some of which are thought to be present as parent molecules in the nucleus whereas others are thought, for example, to be the result of destruction of more complex parent molecules after release from the nucleus. These include many organic molecules that can be formed abiotically in the interstellar medium. A major research interest at present is trying to sort out which of these molecules might have been preserved from the interstellar medium and which, e.g., because of different abundance ratios, must have been formed by chemical processes in the protoplanetary disk. These other volatiles probably sum to no more than 20 percent water based on abundances measured thus far. The results from the ion and neutral mass spectrometers on the missions to comet Halley show unambiguously that larger, presumably complex, molecules are present in the outflowing gas, but the exact composition is not known. There have been suggestions of a variety of polymerized species (e.g., Huebner et al., 1987), but no such species have been unambiguously identified.

The interpretation of these volatile species is complex and subject to selection effects. Three examples show the complexity. The intensive observations of relative abundances in comet Hale-Bopp (Biver et al., 1997) provide the first strong evidence that previous perihelion passages have differentiated the near-surface ices. This means that individual observations are not necessarily representative. The mechanism for this differentiation is qualitatively understood, having been predicted more than a decade earlier, and it involves vapor transfer through porous materials rather than melting. Several groups have studied this phenomenon over more than a decade, and the effects are typically important over mantle depths on the order of meters, except for the release of trapped gases in the crystallization of amorphous ice which can be important at much larger depths. Comparison of easy-to-measure species in very many comets has shown that there are systematic differences among comets: A'Hearn et al. (1995) showed that the carbon-chain radicals, C_2 and C_3, are strongly depleted relative to the average in a subset of comets. Although the deficit is correlated with various parameters, the best interpretation is that these species are depleted in a large fraction of the comets that originally came from the Kuiper Belt but not in those that came from the Oort Cloud, thus suggesting a chemical boundary somewhere in the Kuiper Belt such that comets formed outside that boundary do not contain as much of the (unknown) parent molecules of C_2 and C_3. On the other hand, A'Hearn et al. (1995) also showed that the abundances of these, of CN, and of NH show no correlation with any dynamical parameters that statistically indicate the number of perihelion passages a comet has undergone. Since material on the order of meters is lost during each perihelion passage, the material from dynamically old comets is being released from deep in the interior of the original comet. The lack of any correlated differences suggests that global differentiation through widespread melting did not occur, despite arguments (Fomenkova et al., 1992) that some individual grains in comet Halley show signs of being differentiated.

TABLE 5.1 Chemical Species Observed in Comets

Volatile Atoms	Refractory Atoms	Diatomics	Triatomics	Polyatomics	Ions	Isotopic Variants
H	Na	CH	H_2O	H_2CO	H_2O^+	HDO
C	Mg	C_2	CO_2	NH_3	CHO^+	HDO
N	K	CN	NH_2	CH_3CN	CH^+	$H^{13}CN$
O	Al	CO	HCN	CH_3OH	CO^+	^{13}CN
S	Ca	CS	C_3	C_2H_2	$CO_2{}^+$	$^{13}C^{12}C$
He	Si	NH	HCO?	CH_4	$N_2{}^+$	$H^{13}CN$
	Ti	OH	H_2S	C_2H_6	OH^+	$HC^{15}N$
	V	S_2	HNC	H_2CS	O^+	$HC^{15}N$
	Cr	SO	OCS	HNCO	C^+	$C^{34}S$
	Mn		SO_2	HC_3N		
	Fe			HCOOH		
	Co			CH_3OCHO		
	Ni					
	Cu					

Finally, it is noted that the species normally thought of as volatile are now known to come, at least in part, from more complex molecules that are only marginally volatile. The best defined example is that of CO, which amounted to roughly 15 percent water in Halley. It is now clear from the in situ studies (Meier et al., 1993) that only a small percentage of CO is actually derived as a parent molecule, i.e., from frozen CO in the nucleus. The remainder results primarily from the dissociation of formaldehyde, H_2CO, which is itself derived from a much more complex molecule that is probably a polymerized organic compound that is solid when released from the nucleus and that gradually warms in the coma until it vaporizes.

Refractory species in comets are much less well understood than are the volatiles. From remote sensing it is known that many comets contain silicates, although the exact composition of these silicates is unknown in most cases. In some comets, with no obvious correlation to history or formation, the silicates are known to include crystalline olivine, but in other comets this is clearly not present. It is also known that there are refractory grains, or possibly very large molecules, containing C-H bonds. The in situ measurements at Halley revealed the presence of three classes of refractory grains—silicates of various sorts, CHON (composed predominantly of C, H, O, and

N), and mixed (silicates + CHON) (Jessberger and Kissel, 1991). Only the atomic compositions of these grains are known, and not the molecular or crystalline composition. Even the atomic composition is not known with high precision. The CHON grains presumably are composed of refractory organic molecules and may be, at least in part, the grains that provide the extended source of H_2CO and CO discussed above.

Combining the atomic abundances in both the volatiles and the refractories, the overall abundances match the solar abundances reasonably well, except for the very volatile species—nitrogen, hydrogen, and the noble gases. Nitrogen forms relatively few compounds, and so most of it would likely be in the very volatile N_2, while hydrogen is so much more abundant than anything else in the Sun that its most abundant compound must be the very volatile H_2. This suggests that most of the material in comets is accounted for in a way that is consistent with condensation of ices in a very cold place. In general, it is concluded that comets certainly contain abundant, simple, organic molecules and that there is probably a large suite of complex organic molecules in comets.

PAST AND PRESENT ENVIRONMENTAL CONDITIONS

In outlining the environmental history of comets, it is convenient to separate Oort Cloud comets from Kuiper Belt comets. A comet in the Oort Cloud for 4.5 Gyr has been irradiated continuously by galactic cosmic rays without any shielding by the heliosphere. This irradiation is sufficient to break every chemical bond in the outer 10 meters or so of cometary material (depth depending on density), as has been known for many years (e.g., Moore et al., 1983). Laboratory experiments show that this irradiation leads to formation of a variety of highly volatile species, including many free radicals, and the irradiation has therefore been widely invoked to explain the anomalous photometric behavior of comets arriving for the first time from the Oort Cloud, wherein they are apparently actively releasing material at very large heliocentric distances, long before they are first discovered. The temperature of these comets in the Oort Cloud is on the order of 10 K; occasional nearby supernovae transiently heat the outer layers to perhaps 30 to 40 K (Stern and Shull, 1988). As the comet approaches the inner solar system for the first time, part of the heavily irradiated layer is stripped off by explosive sublimation of the supervolatiles created by the irradiation, but laboratory experiments also show that at least in thin samples a sticky residue of "yellow stuff" or "brown stuff" always remains, even up to room temperatures. The extent to which the heavily irradiated layer is removed is thus unclear, but it is very unlikely that it is totally removed. The comet is also warmed as it approaches the Sun for the first time, but the time scale of this warming is such that as the comet rounds perihelion the heating does not have time to penetrate very deeply. Although estimates of the thermal conductivity and heat capacity vary by orders of magnitude, a typical estimate has the thermal wave (the heat pulse up to hundreds of degrees) penetrating to a depth comparable to the amount of material released during the perihelion passage.

As an Oort Cloud comet is captured by planetary perturbations into orbits of shorter and shorter period, decreasing in steps from millions of years to, for example, the 75-year period of Halley, the accumulation of many thermal waves (each lasting a few months only) allows the heating to penetrate more deeply. The equilibrium temperature that would be reached at the center of Halley's nucleus after an infinite number of perihelion passages is roughly 130 K, but the estimates of thermal inertia (a combination of conductivity and heat capacity) are so wide ranging that it is not possible to know at this stage how close the interior has come to reaching that temperature. Kouchi et al. (1992), for example, have argued that the thermal conductivity is so low that the center of Halley, and of all short-period comets for that matter, is still at the temperature the material had in its original place of formation and that the thermal waves have accumulated only to depths of meters. The surface layers of a comet at 1 AU from the Sun, however, are routinely heated to temperatures on the order of 300 K at every perihelion passage. For a comet like P/Halley, this periodic heating certainly occurs hundreds of times, and it could easily be thousands of times. Note that the total since the first heating, however, is very short compared to the age of the solar system, probably less than 10^7 years and certainly less than 10^8 years. It is on this time scale that a comet will be ejected entirely from the solar system or will collide with a planet. Prior to collision with a planet, the typical comet from the Oort Cloud has probably undergone no collisions except with microscopic grains of interplanetary dust. The short-period comets that have undergone this history are, at least statistically, identified from their present orbital characteristics as Halley-family comets.

The evolution of comets from the Kuiper Belt is somewhat different. Whereas the comets from the Oort Cloud evolve toward short-period comets primarily by lowering the aphelion distance, the comets from the Kuiper Belt, with orbits of much lower eccentricity, tend to lower the perihelion and aphelion distances together. This leads to smaller extremes in the temperature fluctuations, but in other respects the evolution is similar. The comets in the Kuiper Belt start out with equilibrium temperatures of several tens of Kelvins, warmer than the equilibrium temperature in the Oort Cloud, but still very cold. Because the density of objects in the Kuiper Belt is higher than that of objects in the Oort Cloud and because the relative velocities are also higher, collisions can occur in the Kuiper Belt. In contrast to the asteroid belt, where the densities are comparable but the relative velocities are higher, the collisions in the Kuiper Belt are relatively gentle. The effect of the collisions depends on the unknown size distribution of objects in the Kuiper Belt, but reasonable simulations (Davis and Farinella, 1997) suggest that the collisions may have created regoliths of meters on Kuiper Belt objects (KBOs); whether there have been body-shattering collisions, as in the asteroid belt, is still unclear.

A KBO is captured, initially by planetary perturbations or by chance KBO gravitational scattering and later exclusively by planetary perturbations, into successively smaller orbits. As with Oort Cloud comets, the process is a random walk in energy so that the decrease in orbital size is not monotonic. Unlike the situation for Oort Cloud comets, however, the process for KBOs typically involves successive steps in which perihelion or aphelion is close to the orbit of one of the giant planets, this thereby imposing a sort of quantification on the evolution that is different from that of Oort Cloud comets, for which the evolution is more truly random. The thermal wave at perihelion is just like that for Oort Cloud comets, heating the surface to a heliocentric-distance-dependent value on the order of 200 to 300 K for a period of months once every orbital period. Because the eccentricities are lower, the amplitude of the thermal wave is smaller; that is, the minimum temperature at aphelion is higher, and this presumably allows the interior regions to approach equilibrium faster than for an Oort Cloud comet, although Kouchi et al. (1992) have argued that even comets from the Kuiper Belt retain their primordial temperatures at their centers. The short-period comets that underwent this history are, at least statistically, identified from their present orbital characteristics as belonging to the Jupiter family. Because of the random fluctuations in cometary orbital evolution, it is not yet possible to determine with confidence the origin of any single comet or even to derive reliable estimates of the fraction of Jupiter-family comets that might be interlopers from the Oort Cloud, or conversely the fraction of Halley-family comets that might be interlopers from the Kuiper Belt. Fractions as large as 10 percent are plausible.

DELIVERY OF SAMPLES TO EARTH

It is generally agreed that Earth has received samples of comets. The size distribution of comets and of near-Earth asteroids suggests that large impacts, such as the Chicxulub crater in the Yucatan, have been caused predominantly by comets (E. Shoemaker, U.S. Geological Survey, private communication, 1996), and estimates of collision rates on various bodies (Weissman, 1994) similarly suggest that comets are a significant, but uncertain, contributor to the impact flux on Earth. Meteorites from asteroids lose material by ablation as they penetrate Earth's atmosphere, but the interiors remain cool. The passage of a large cometary body through Earth's atmosphere is much less understood. Calculations by Chyba et al. (1990) and Chyba and Sagan (1992) suggest that some cometary material is preserved intact in impacts of 1- to 100-m cometary nuclei, but the calculations are equivocal.

Comets are also a significant contributor to interplanetary dust, both the large "dust" in meteor showers and the small dust that may be more than 50 percent cometary, of which a small but not negligible fraction arrives at Earth's surface without having undergone heating above 160 °C. Our sampling of stratospheric dust is insufficient to unambiguously separate cometary dust from asteroidal dust. Statistically, the particles that have been strongly heated on entry are probably cometary and those that are weakly heated are asteroidal, but there are also likely to be cometary particles in the weakly heated group and, although less common, asteroidal particles in the strongly heated group.

The samples that have been delivered to Earth are subject to selection effects. The samples delivered as interplanetary dust are selectively the grains that are small enough to have been lifted off the cometary nucleus by the outflowing gas. The samples that are delivered in large impacts are systematically from a larger, but not well-determined, range of sizes. If they came from fragmentation of KBO-sized bodies, they should represent both the surfaces and the interiors of these bodies. If, on the other hand, they are part of a continuous size distribution at formation, they probably started not much larger and represent a certain segment of the size distribution, perhaps too small for early radioisotope heating to matter but still large enough to survive entry through the atmosphere.

Interestingly, the impact or even the near miss of a large cometary nucleus is invariably accompanied by the arrival of large amounts of dust that had been released from the comet within the days immediately prior to the impact. Dust at sizes of up to 10 or even 100 μm thus rains down intermittently on Earth with little or no heating. The classically cited case is the passage of Earth through the tail of comet Halley in 1910. Weissman (1990) has estimated that a 10-km crater is formed by a comet hitting Earth every 10^5 years and, for typical impact velocities, this corresponds to a 0.5-km comet. While such a large impact may heat the entire mass of incoming material to above sterilization temperatures, it is more important to consider the near misses. The ratio of the number of passages of Earth through the coma of a comet to the number of impacts of a comet onto Earth is roughly the ratio of the cross section of the coma to the cross section of Earth. If the coma has a radius of 10^6 km, this ratio of cross sections is 10^4. In other words, Earth passes through the coma of 10^4 comets for every cometary nucleus that hits Earth—once every several tens of years. Comet IRAS-Araki-Alcock in 1983 was marginally close enough for Earth to be considered inside the coma, but comet Lexell in the 18th century was certainly close enough, and, as noted above, Earth passed through the tail of Halley's comet in 1910.

It is estimated that a typical 0.5-km comet will have a water release rate of 10^{27} molecules per second and a dust release rate of 2×10^4 g/s. If Earth passes through the coma at 10^5 km from the nucleus, it will encounter a dust column of 0.1 g/km^2, and at 10^6 km it will encounter 0.01 g/km^2. With simple scaling and ignoring factors of a few for focusing effects, the former will occur roughly every 10^{3} years and the latter on the order of every 10 years. The anecdotal cases cited above suggest that these numbers may be somewhat high, but not by more than an order of magnitude, and probably are consistent within small-number statistical fluctuations. The implication is that the total material swept up by Earth is on the order of 0.1 tons per year. Although this is less than the dust provided by direct infall from the interplanetary medium, this material from the coma is all recently released from the nucleus. If only a fraction of the debris in the coma (limited to sizes <50 μm) of only a small fraction of the comets approaching Earth (those with very small relative velocities) succeeds in reaching the surface of Earth without being heated to >160 °C, significant amounts of recently released, unsterilized dust from comets have been received over time. However, this is episodic, and it seems unlikely, for example, that such an event has occurred in the last several hundred years (the encounter velocity of comet Lexell was 20 km/s). Taking into account this dust coupled with the likelihood of preserved material from 1- to 100-m impactors (the rate of which is very uncertain), it is clear that Earth has received episodically, over time, unsterilized cometary material.

POTENTIAL FOR A LIVING ENTITY TO BE IN OR ON SAMPLES RETURNED FROMCOMETS

Current understanding of cometary nuclei indicates that they probably never exhibited the conditions under which life is thought to have evolved on Earth. The one possible exception would be early heating, in the first few million years after formation, by now-extinct sources of radioactivity. If that process was important, and as discussed above this is unlikely, then comets might have contained liquid water in significant amounts for significant periods of time. This is the only accepted scenario in which comets would have contained liquid water, a prerequisite for the formation of life.

Some cometary environments would clearly destroy life. In particular, the irradiation by galactic cosmic rays of most bodies outside the heliosphere, particularly including Oort Cloud comets, would destroy any preexisting life in the outermost tens of meters, and the temperatures are so low that life could not form. The low temperatures of comets in the Kuiper Belt would not allow life to form, although it is not known whether preexisting life could survive. The short interval of heating in perihelion passages of long-period comets is not sufficient to allow formation of life. The Centaurs, which are transition objects between the Kuiper Belt objects and Jupiter-family, short-period comets, are warm enough that some very volatile ices vaporize. Chiron was very active at aphelion (17 AU) prior to its actual discovery (Bus et al., 1998), but the generally accepted view is that cometary material is sufficiently porous that the volatile substances escape as vapor rather than remaining trapped as a liquid.

The task group's conclusions regarding the potential for life on comets are summarized as follows in its answers to the key issues raised in Chapters 1 and 2.

1. Does the preponderance of scientific evidence[1] indicate that there was never liquid water in or on the target body?
   The scientific evidence regarding all scales of cometary bodies that have been studied indicates that there was never liquid water in cometary nuclei.
2. Does the preponderance of scientific evidence indicate that metabolically useful energy sources were never present?
   Although free radicals and other unequilibrated chemical products could exist in the presence of liquid water for a short time, it is uncertain whether they could serve as metabolically useful energy sources.
3. Does the preponderance of scientific evidence indicate that there was never sufficient organic matter (or CO_2 or carbonates *and* an appropriate source of reducing equivalents)[2] in or on the target body to support life?
   There was and still is a large quantity of organic material present in cometary nuclei.
4. Does the preponderance of scientific evidence indicate that subsequent to the disappearance of liquid water, the target body has been subjected to extreme temperatures (i.e., >160 °C)?
   Evidence suggests that, except at the very surface layers, cometary nuclei were never heated to sterilization temperatures.
5. Does the preponderance of scientific evidence indicate that there is or was sufficient radiation for biological sterilization of terrestrial life forms?
   For dynamically new comets (e.g., those from the Ort Cloud), the outer 10 meters have probably received sterilizing doses of radiation. The best estimates of the radiation environment of the deep interior indicate that the time for sterilizing doses of radiation is of the same order of magnitude as the age of the solar system. Thus, it cannot be concluded that the deep interior of all comets is radiation sterilized by cosmic radiation. For short-period comets, any irradiated material is entirely lost during each perihelion passage, so that the newly exposed material at the surface may not be subject to sterilizing doses of radiation.
6. Does the preponderance of scientific evidence indicate the natural influx to Earth, e.g., via meteorites, of material equivalent to a sample returned from the target body?
   Evidence suggests that unsterilized cometary dust has been delivered episodically to the surface of Earth.

It is unlikely that a living entity could exist on comets, but the possibility cannot be completely ruled out except in a few cases, such as in the outer layers of Oort Cloud comets entering the solar system for the first time. Thus, the potential for a living entity to be present in samples returned from all comets is considered to be extremely low, but the task group cannot conclude that it is necessarily zero. Although the task group concluded that containment is unlikely to be required for samples returned from these bodies, this conclusion is less firm than that for the Moon, Io, and some IDPs. This conclusion needs be reexamined on a case-by-case basis at the time that missions to these bodies are planned.

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[1] For the purposes of this report, the term "preponderance of scientific evidence" is not used in a legal sense but rather is intended to connote a nonquantitative level of evidence compelling enough to research scientists in the field to support an informed judgment.

[2] For the purposes of this report, CO_2 or carbonates *and* an appropriate source of reducing equivalents is equivalent to "organic matter" to accommodate chemolithoautotrophs.

SCIENTIFIC INVESTIGATIONS TO REDUCE THE UNCERTAINTY IN THE ASSESSMENTOF COMETS

The key questions regarding the potential for life on comets are whether liquid water was ever present and what the thermal evolution of comets was. Searches for variations of abundances from one comet to another, correlated with the size of the comet or with its dynamical history, could increase our understanding about whether global differentiation occurred. Yet, this is a lengthy process, because the number of comets observable at any given time is small and the effects of global differentiation must be separated from effects owing to place of formation and near-surface differentiation on recent previous perihelion passages.

Alternative searches for global differentiation could involve in situ sampling to very large depths. Currently projected in situ sampling on the Rosetta and DS4/Champollion missions will reach only the near-surface layers, although the CONSERT experiment on Rosetta will provide some tomographic sampling of certain properties of the interior. These missions will be very important in separating the near-surface differentiation from the global differentiation and thus simplifying the interpretation of the data from remote sensing, but they will not sample deeply enough, other than with CONSERT, to address global differentiation and in fact are not likely to reach sufficient depth to completely determine the near-surface, recent differentiation. Missions that would more directly sample the deep interior of a cometary nucleus would be extremely valuable in addressing whether liquid water was ever present.

Missions that return dust samples from comets to Earth will assist in determining whether or not liquid water was present on very local scales on cometary nuclei, although this depends on understanding both how much the minerals are metamorphosed on capture and how minerals metamorphose on time scales up to millions of years in the presence of water vapor. The study of ^{26}Al in cometary grains will be important in understanding how much ^{26}Al was present but will not alone determine whether the ^{26}Al was present after the body became large enough to trap heat and melt water. That question could be addressed only by looking at the hydration of other minerals, for example, by identifying clay minerals.

Detailed mapping from spacecraft of the gravitational field of cometary nuclei could lead to tight constraints on the degree of central condensation and thus on the degree of differentiation that might have occurred, to help in clarifying the past presence or abundance of liquid water in the interior.

Other combinations of observational and theoretical studies of cometary nuclei might aid significantly in addressing the following relevant, although perhaps less central, questions: (1) What is the present size distribution of cometary nuclei and of KBOs and of Centaurs? this information would assist in understanding whether kilometer-sized comets are fragments of larger bodies. (2) What is the true collisional history of KBOs? (3) What is the actual distribution of shapes of cometary nuclei? This information would assist in constraining the strength of nuclei against collapsing to spherical shapes and thus in determining the sizes at which collisional fragments can no longer be recognized. (4) What should be the observable effects of melting the water ice in a cometary nuclei? Should there be strong differentiation leading to abundance differences or gas/dust differences as a function of dynamical age? If observable effects can be predicted reliably, this item could become central to the issue.

SUMMARY

Cometary nuclei are predominantly icy bodies that most likely have never melted on large scales. For most of their 4.6-Gyr lives they have been at temperatures below 100 K, and those in the Oort Cloud have been at temperatures on the order of 10 K. The surface layers have undergone transient heating lasting months to temperatures on the order of 300 K (dependent on heliocentric distance) at previous perihelion passages. It is extremely unlikely that life could exist on comets, but only in a few cases can the possibility be totally ruled out, such as in the outer layers of Oort Cloud comets entering the solar system for the first time. The least likely place for life to exist in a comet is in the interior of a very large nucleus or in a smaller nucleus that was produced by fragmentation of a very large nucleus sometime after any liquid water had solidified. Even this possibility is remote. The task group concluded that cometary nuclei are unlikely to contain organisms capable of self-replication.

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6

Cosmic Dust

Cosmic dust particles (generically referred to as interplanetary dust particles, or IDPs) are derived from a variety of sources, including interstellar grains and the debris from comets, asteroids, and the planets and possibly their satellites. The dominant sources of IDPs on Earth are asteroids and comets, with a small, but still not negligible, amount of dust coming from all other sources combined. The comets certainly are a major contributor at a level ranging from 10 percent to 50 percent; the remainder of the IDPs come primarily from the asteroids. The dust from comets was lifted from the surface of the nucleus by outflowing gas and, except for having been exposed to the solar wind, is essentially unprocessed because it was an integral part of the cometary nucleus. The dust from other sources, however, is processed, most of it having been created in collisions. In the case of asteroidal dust, an impact of a small body onto a typical small asteroid is sufficient to eject considerable debris from the gravitational field of the asteroid. It is thought that particles with diameters greater than 50 µm are derived mainly from asteroids, whereas those with diameters less than 30 µm come from comets (Love and Brownlee, 1991).

Larger collisions are required to give dust enough energy to escape from planets or satellites. Such dust grains have experienced significant spike heating in the impact event that ejected them from the parent body. A possible exception is the dust around Jupiter generated from micrometeorite impact ejecta from some of its satellites, including Europa. However, the amount of this jovian satellite-derived dust is estimated to be small in comparison to captured interplanetary dust (Colwell et al., 1998).

The residence times of IDPs in the solar system depend on several factors (see Nishiizumi et al., 1991). Poynting-Robertson drag forces IDPs into Earth-crossing, inwardly spiraling circular orbits around the Sun. The IDP lifetimes owing to the Poynting-Robertson effect are dependent on particle size; for the IDPs in the range of sizes reaching Earth's surface, lifetimes are estimated to be 10^5 to 10^6 years, although chaotic orbits may decrease this value significantly. Another factor influencing particle lifetimes is the degree to which they are subject to high-velocity disruptive collisions. This factor depends on particle velocity, which decreases with increasing distance from the Sun. How the Poynting-Robertson drag and the disruptive collisional effects influence average IDP lifetimes is difficult to evaluate, but it is likely that in combination these effects act to shorten IDP residence times in the solar system. Measurements of galactic and solar cosmic-ray-generated radionuclides have enabled direct estimates of IDP solar system residence times of 10^5 to 10^7 years, somewhat longer than those projected on the basis of theoretical considerations (Nishiizumi et al., 1991). An exception would be the shorter residence time of dust recently ejected from a cometary nucleus, which might infall to Earth as the comet's coma or tail intersects Earth's orbit, as discussed in Chapter 5.

During their residence in the solar system, cosmic dust particles are exposed to radiation from solar flares and galactic cosmic rays. The dose from these sources is estimated to exceed most organisms' tolerance to radiation when exposed on time scales of 10^5 years (see Clark et al., 1998). Thus, IDPs with residence times in the solar system of 10^5 to 10^7 years would have been radiation sterilized. As is discussed in Chapter 5, a possible exception would be IDPs derived from dust that intersects the orbit of Earth from a cometary coma or tail and for which lifetimes, and thus exposure to lethal radiation, could be as short as days or months.

Samples of cosmic dust for analysis of composition have been obtained from meteoroids collected in the stratosphere by aircraft and Long Duration Exposure Facility (LDEF) satellite and from micrometeorites obtained by the melting and filtration of large quantities of polar ice (Bradley and Brownlee, 1991; Maurette et al., 1991; Maurette, 1998).

Antarctic micrometeorites ranging in size from 100 to 400 mm, as well as smaller particles collected by aircraft and the LDEF satellite, are related primarily to the carbonaceous chondrites, and within this group mostly to the CM chondrites (which account for about 2 percent of meteorite infalls to Earth). Carbonaceous chondrites such as the Murchison meteorite are rich in organic compounds, including many organic compounds, such as amino acids, associated with terrestrial biochemistry (see Cronin et al., 1988). As mentioned above, some IDPs are also derived from comets, which contain abundant simple organic components (see Table 5.1), but whose inventory of complex organic molecules is less well known than is that of the carbonaceous meteorites. Some of the cometary organic compounds such as HCN, aldehydes, and ammonia are involved in the abiotic synthesis of more complex molecules, including amino acids and some of the bases present in DNA and RNA (see, e.g., Miller and Orgel, 1974). Thus, it is not unreasonable to expect that compounds important in biochemistry may also be present in comets, although this conclusion likely is dependent on whether at some time during a comet's history liquid water was present either on its surface or in its interior.

NATURAL INFALL OF DUST TO EARTH

Based on measurements of the impact craters on the LDEF satellite, the rate of accretion of cosmic dust on the present-day Earth is estimated to be $4 \pm 2 \times 10^{10}$ g/yr (Love and Brownlee, 1993). A somewhat higher infall rate of 7 to 25×10^{10} g/yr has recently been estimated from osmium isotopes (Sharma et al., 1997). Direct measurements of the flux of micrometeorites reaching Earth's surface (Maurette et al., 1991; Hammer and Maurette, 1996; Taylor et al., 1996a), and comparison with the IDP preatmospheric flux at 1 AU (Love and Brownlee, 1993), indicate that micrometeorites in the 50- to 500-μm size range deliver to Earth's surface about 2×10^{10} g of extraterrestrial material each year. This annual flux of IDPs is similar in magnitude to that of larger objects (1- to 10-m meteorites and 1- to 10-km asteroids and comets) averaged over longer time scales (Ceplecha, 1992). Most of the IDP mass is in the form of micrometeorites with sizes of approximately 200 mm. The infall rate of IDPs appears to have varied over geologic time (Farley, 1995) and may have been as much as a factor of 10 higher 500 million years ago in comparison to the present-day flux (Schmitz et al., 1997).

It has been predicted that approximately 99 percent of the micrometeorites larger than 100 μm are completely melted upon atmospheric entry and that only small particles of less than 20 μm are not heated to at least 160 °C (Brownlee, 1985; Love and Brownlee, 1991, 1993). These theoretical calculations are critically dependent on the particles' size and on their velocity and angle during entry. Because particles of less than 20 μm make up only about 10^{-3} percent of the IDP or micrometeorite mass, only about 4×10^5 g/yr of the cosmic dust escapes heat sterilization during atmospheric entry. In addition, calculations of helium loss from IDPs in the size range from 5 to 150 μm suggest that only 0.5 percent of the mass of particles (approximately 2×10^8 g/yr) are heated below approximately 600 °C (the temperature at which helium is released) during delivery to Earth's surface (Farley et al., 1997). These predictions thus suggest that only some of the smallest IDPs (particles smaller than 20 μm), which make up only a minor fraction of the original IDP mass flux, escape heating to the temperatures of greater than 160 °C considered necessary for biological sterilization (Microbiology Advisory Committee, 1993) during atmospheric entry. However, this conclusion must be considered somewhat tentative because IDPs are exposed to peak temperatures on time scales of a only few seconds (Love and Brownlee, 1991). Some proteins may be exceptionally resistant to high temperatures and may resist short-term exposure to temperatures in excess of 160 °C (Brown et al., 1990; Taylor et al., 1996b).

Direct examination of micrometeorites collected in the Antarctic has shown that the proportion of unmelted micrometeorites studied was much larger than predicted by models describing frictional heating of micrometeorites upon atmospheric entry (see, e.g., Hunten, 1997; Maurette, 1998). A source of this discrepancy may be that the average density of IDPs is less than the value of 2 g/cm^3 assumed in the theoretical predictions. Recent radar-based observations of comet Hyakutake indicate that particles ejected from its coma consist mainly of "fluffy" grains with densities of less than 1 g/cm^3 (Harmon et al., 1997). Also, recent flyby observations of the C-type asteroid 253 Mathilde indicate that its density (1.3 ± 0.1 g/cm^3) is about half that of CM chondrites (Veverka et al., 1997).

Most of Earth's annual infall of micrometeorites and IDPs lands in the oceans, where their soluble components would dissolve and accumulate if they were not consumed by organisms or destroyed by geochemical processes. Recent analyses of Antarctic micrometeorites have shown that the current global flux of exogenous amino acids from micrometeorites is roughly 3×10^5 g/yr (Brinton et al., 1998). The maximum period of accumulation in the oceans would be 10^7 years, the length of time it takes for the total oceans to pass through hydrothermal vents where all dissolved organic components would be destroyed (Bada et al., 1995). Thus the concentration in the present oceans of extraterrestrial amino acids generated by the infall of cosmic dust would be on the order of 0.1 parts per billion. This interpretation is consistent with analyses of filtered seawater (K.L.F. Brinton and J.L. Bada, Scripps Institution of Oceanography, unpublished results) indicating that the concentration of extraterrestrial amino acids in the modern oceans is below the limit of detection—of less than a few parts per billion—of the analytical method used. These results suggest that although cosmic dust has been constantly accreted by Earth during modern times, organic compounds associated with this extraterrestrial debris do not apparently accumulate to measurable concentrations.

POTENTIAL FOR A LIVING ENTITY TO BE IN OR ON RETURNED SAMPLES OFCOSMIC DUST

Because interplanetary dust particles are derived from a variety of sources, including interstellar grains and debris from comets, asteroids, and possibly planetary satellites, IDPs cannot be viewed as a distinct target body. As a result, the assessment approach used in this study does not lend itself readily to evaluation of the biological potential of IDPs. Instead, the task group considered the potential source(s) of the IDPs being sampled. For the purposes of this study, IDPs are viewed as originating from either a single identifiable parent body or multiple sources. Particles collected near a particular solar system body are viewed as originating from that body, possibly including grains recently released from that body. Thus, the potential for a living entity to be present in returned samples, and the associated containment requirements, are regarding as being the same as those for the parent body. On the other hand, IDPs collected in the interplanetary medium may represent a mixture of dust originating from many parent bodies. Because IDPs in the interplanetary medium are exposed to sterilizing doses of radiation, no special containment requirements are warranted.

An additional consideration is whether the process of collecting IDPs in returned samples results in spiked heating of the sample to the temperatures considered necessary for biological sterilization. If so, then no special containment is required, regardless of the source of the IDP.

SCIENTIFIC INVESTIGATIONS TO REDUCE THE UNCERTAINTY IN THE ASSESSMENTOF COSMIC DUST

An important issue with regard to the collection of IDP and micrometeorite material in space is the temperature to which the material is heated during collection. In the STARDUST mission, aerogel will be used to capture solid particles from comets and asteroids and from the interplanetary medium, as well as charged particles from the solar wind. The estimated capture velocities are in the range of 6 km/s for the cometary particles and within a factor of two of that for most other interplanetary particles. It is possible (albeit unlikely) that an incidental interplanetary dust particle may be collected that is not represented in the vast quantity of particles that rain down on Earth every day, for example, one derived from a planetary satellite. It is assumed that during capture by a spacecraft, temperatures in the range of 400 to 500 °C would be attained (although this would be as a result of pulse heating lasting less than 1 second or so). Thus any organisms, as well as organic compounds, present would likely be destroyed. However, the effect of short-pulse heating on organisms and organic compounds is not well understood. Recent experiments involving the exposure of amino acids to temperatures as high as 1,000 °C for a few seconds have found, surprisingly, that some amino acids survive exposure to high-temperature pulsed heating (D.P. Glavin and J.L. Bada, Scripps Institution of Oceanography, unpublished results). Clearly, research should be carried out with a number of organic compounds and heat-tolerant organisms to further evaluate the effect of pulsed heating at temperatures greater than the assumed sterilization temperature of 160 °C.

SUMMARY

Cosmic dust represents a valuable source of material for evaluation of the composition and characteristics of objects throughout the solar system. Because IDPs cannot be assessed in a fashion similar to the planetary satellites and small solar system bodies examined in this study, the source of IDPs is important. IDPs sampled near a parent body are treated as samples collected from that body. Alternatively, IDPs collected from the interplanetary medium are subject to sterilizing doses of radiation, and therefore no special containment is required. If the IDP is exposed to spiked heating resulting in extreme temperatures during sample collection, then no special containment is required regardless of the source of the IDP.

Cosmic dust particles have collected on Earth throughout its history. The accumulation of the various components of IDPs and micrometeorites has apparently had no known adverse effects on Earth's biota. Thus it would seem unlikely that a returned sample of this type of extraterrestrial material would pose any kind of threat to Earth's biota or biogeochemical cycles. However, the possibility cannot be ruled out that future sample recovery missions will sample objects that are not represented in the present-day IDP and micrometeorite flux to Earth.

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7

Considering the Potential Risks from Returned Samples

The potential for adverse environmental or human health effects arising from extraterrestrial materials returned to Earth would depend on a number of factors such as the likelihood of actually finding a living entity on a particular small solar system body targeted for exploration, including such an entity in a returned sample, and returning an entity that could in fact cause significant harmful pathological effects or large-scale ecological impacts if it were inadvertently released on Earth. Concerns about potential risks from returned extraterrestrial materials are not new, having been raised initially more than three decades ago with the return of lunar samples during the Apollo program. In 1997, the National Research Council revisited these issues, focusing on sample return from Mars. Its updated recommendations for handling returned samples and avoiding planetary cross-contamination (NRC, 1997) are summarized in Box 7.1.

Although Mars was the focus, the 1997 report's recommendations were regarded as generally applicable to any mission that could return from an extraterrestrial object to Earth a sample with a similar potential for harboring life. Indeed, based on the systematic approach developed for use in its own study, the Task Group on Sample Return from Small Solar System Bodies found that the 1997 Mars report's recommendations concerning containment and handling of returned samples constituted a suitably strong framework for guiding its deliberations about the need for containment of samples returned from planetary satellites and small solar system bodies.

In recognition of the diverse types and environmental conditions of small solar system bodies considered in this study, the task group adopted a conservative, case-by-case approach (see "Scope and Approach of This Study" in Chapter 1), taking into account information about the different bodies themselves, the natural influx to Earth of different materials, the possible nature of putative extraterrestrial life, and the range of potential adverse effects that might be caused by incoming sample materials. When applied to the solar system bodies addressed in this study—planetary satellites, asteroids and meteorites, comets, and cosmic dust—the six questions formulated by the task group, taken in the general context of the task group's approach, yield only two possible answers, with no intermediate or compromise outcomes identified: either (1) strict containment and handling as outlined in the Mars report (NRC, 1997), or (2) no special containment beyond what is needed for scientific purposes. In certain cases (e.g., P- and D-type asteroids) the limitations of the available data led the task group to be less confident, and therefore more conservative, in its assessment of the need for containment. In other words, if a body is judged, based on available knowledge about its environmental conditions and history, to have a negligible or very low potential to harbor a living entity, it would be appropriate to allow the return of samples from that body without special containment or handling beyond what is needed for scientific purposes. If, on the other hand, a body is judged to have a potential to harbor a living entity or there is reasonable uncertainty in the assessment about a particular body, then containment and special handling similar to the procedures recommended for samples returned from Mars (NRC, 1997) would be warranted.

BOX 7.1 SUMMARY OF RECOMMENDATIONS FROM THE 1997 REPORT *MARS SAMPLE RETURN: ISSUES AND RECOMMENDATIONS*

Mars Sample Return: Issues and Recommendations (NRC, 1997) concluded that the possibility of including a living organism, either active or dormant, in a sample returned from Mars cannot be ruled out altogether, although the potential for such an occurrence was judged to be low. Moreover, the report recommended that unless and until sufficient knowledge of Mars and its environment was available, due caution and care should be exercised in handling returned materials that might contain hypothetical martian microorganisms capable of inadvertently contaminating Earth and causing a risk of pathogenesis, environmental disruption, or other harmful effects.

Specifically, the report recommended that samples returned from Mars be contained and treated as though they were potentially hazardous until proven otherwise. Strict containment of all pristine sample material was urged, and special handling procedures were outlined for samples en route to and on Earth. In particular, no uncontained martian materials, including spacecraft surfaces exposed to the martian environment, should be returned to Earth unless sterilized. If sample containment cannot be verified en route to Earth, the sample, and any spacecraft components that may have been exposed to the sample, should either be sterilized or not returned to Earth. The integrity of containment should be maintained through reentry of the spacecraft and transfer of the sample to an appropriate receiving facility.

Furthermore, the distribution of unsterilized materials returned from Mars should be controlled and should occur only if rigorous analyses determine that the materials do not contain a biological hazard. Finally, the planetary protection measures adopted for the first Mars sample return missions should not be relaxed for subsequent missions without thorough scientific review and concurrence by an appropriate independent body.

LIKELIHOOD OF FINDING AND INCLUDING A LIVING ORGANISM IN SAMPLESFROM DIFFERENT SOLAR SYSTEM BODIES

In the absence of direct evidence of extraterrestrial life forms, consideration needs to be given to the nature of putative life forms based on analysis of terrestrial analogs and biochemical possibilities. Based on current knowledge of the geophysical and geochemical properties of various solar system bodies and contemporary views on the range of conditions under which life can originate, the conditions required for the preservation of metabolically active organisms in terrestrial environments, and the somewhat different conditions needed to preserve living organisms in a dormant form (see discussion in Chapter 1), it is possible to infer the likely metabolic groups of microorganisms that might be found on small bodies. They are most likely to be anaerobic organisms similar to those found in analogous Earth environments, including hydrothermal systems, sea ice, oligotrophic aquatic environments, deep basaltic rock, and soils.

The contemporary views of the nature of different solar system bodies are supported by a considerable body of scientific evidence that has been collected either remotely or from direct analyses of materials delivered to Earth by the natural influx of IDPs, asteroids, and meteorites. Presumably, this natural influx of extraterrestrial materials arriving over time on Earth, albeit with varying transit times in space, has exposed Earth and its biota to risks the same as or similar to those potentially posed by samples deliberately returned from these bodies. Based on the accumulated information and current thinking about the origin, persistence, and preservation of life as we know it, the possibility of including a living organism, either active or dormant, in a sample returned from bodies such as asteroids, comets, planetary satellites, or IDPs is judged by the task group to be very low overall. This judgment is further supported by the complete absence of evidence of the existence of even fossilized extraterrestrial life forms or chemical fossils in meteorites from planetary satellites or small solar system bodies. However, the task group recognizes that its assessment of the potential for such an occurrence is dependent on a number of environmental and historical factors for each solar system body type, especially the presumed exposure to sterilizing doses of extreme radiation or sterilizing temperature.

Undoubtedly, the knowledge base for the composition and physical-chemical environment of various small solar system bodies will continue to expand as remotely sensed data are received from future exploration missions. Likewise, understanding will increase about the resilience of life in extreme environments, its ability to survive over long periods, and its wide versatility both on Earth and possibly in extraterrestrial environments. In the meantime, because samples are likely to be returned from small solar system bodies before we reach certainty on many important questions, it may not be possible in many cases to predict definitively the presence or absence of living entities on all bodies. Additionally, even if the native composition or current environmental conditions on a specific small body were judged inhospitable to life, the possibility of cross-contamination from impact materials originating from other bodies with more hospitable conditions must be considered. In many cases, concern about cross-contamination is negligible, but in others, it may have real significance.

ANTICIPATING THE PUTATIVE NATURE OF LIFE FROM SMALL SOLAR SYSTEMBODIES

In addition to considering the environment in which a living extraterrestrial entity might be found, it is advisable to consider the nature or type of life that might be found. Based on current understanding of solar system history, two alternative scenarios deserve attention: one involving the possible past exchange of life between Earth and other solar system bodies and the other based on an independent origin of life. In the first scenario, the biochemistry of an extraterrestrial life form might resemble that of a terrestrial organism more or less closely if its ancestor had been transported to the sample site from Earth or if the ancestor of terrestrial life has been transported from the sample site to Earth. If the extraterrestrial organism had evolved independently of terrestrial life, much greater differences would be anticipated, and the extraterrestrial life form might not share a common biochemistry with life as we know it on Earth. In searching for an exotic life form, both possibilities need to be considered, because recent experiments suggest that alternative genetic systems are possible (Egholm et al., 1993; Eschenmoser, 1997). The system studied up to now contain purine and pyrimidine bases, but the possibility of genetic materials that do not contain the standard bases cannot be excluded. In addition to considering the two possibilities discussed above, it will also be important to rule out false positives, that is, organisms or their components that may have been transported from Earth as forward contaminants on launched spacecraft or equipment. Clearly, these considerations have implications for risk assessment and for the design of protocols for systems that will eventually be used for sample handling, life detection studies, and biohazard testing of returned materials.

CONCERNS ABOUT POTENTIAL BIOHAZARDS AND ADVERSE EFFECTS

Samples returned from small solar system bodies could be considered biohazardous or unsafe for two reasons: (1) they could contain living entities that might be pathogenic for Earth organisms or (2) they could be capable of causing ecological disruptions. Although chemical toxicity of returned materials would be of concern for investigators working with the materials, it is not considered further in this context because toxic materials will not replicate and spread, and because appropriate handling and laboratory procedures will be utilized.

As discussed in the Mars sample return report (NRC, 1997), agents of pathogenicity can be divided into two fundamental types: toxic and infectious. In general, biologically induced toxic effects of microorganisms are attributable to cell components or metabolic products that interact incidentally with the nervous or immune systems of other organisms, thereby causing damage. Infectious agents may either have coevolved with their hosts or be opportunistically invasive. They cause adverse effects or damage by multiplying in or on a host: viruses are an example. The risks of pathogenicity from putative life forms on small bodies are considered extremely low, because it is highly unlikely that such extraterrestrial organisms could have evolved pathogenic traits in the absence of host organisms. However, because there are examples of opportunistic pathogens from terrestrial and aquatic environments that have not co-evolved with their hosts, the task group cannot say that the risk is zero.

Ecological disruptions by extraterrestrial microorganisms could, in theory, be caused either by displacement of native life forms or by indirect or direct modification of ecosystems as a result of the activities or presence of organisms from outside the system. Currently, there is very little information on the effects of introduced microorganisms on established microbial communities. In addition, other than documented examples of how environmental perturbations can change species composition, little is known about temporal and spatial variation in natural microbial environments on Earth. Thus, it is the task group's opinion that the probability that an extraterrestrial anaerobic microorganism could contaminate a suitable environment on Earth is very low, but not zero.

As with the case of putative martian organisms, the rationale for the above assessments is based on numerous lines of scientific evidence (e.g., the understanding of basic biogeochemical, ecological, and metabolic processes; microbial metabolic needs; resource availability; environmental conditions; physical constraints; the small amount of material sampled; strict containment and handling protocols; and so on). Clearly, it is not possible to rule out entirely the threat of adverse effects caused by the presence of viable organisms, however rare or hard to detect they may be in returned samples. Therefore, it is prudent to contain and quarantine questionable incoming samples and screen thoroughly for indications of both pathogenicity and ecological disruption, even though it is agreed by the task group that the likelihood of adverse biological effects from returned extraterrestrial samples is very low.

CONTAINMENT AND QUARANTINE FACILITIES

In situations when containment and special handling are warranted for samples returned from particular small solar system bodies, it will be advisable to handle and screen materials in a manner similar to that recommended for Mars samples (NRC, 1997). The requirements for strict containment should apply to all relevant mission activities, starting with collection of materials and separation from the target body, through en route transport of the samples, and ultimately to continued quarantine on Earth at an appropriate receiving facility until comprehensive testing is completed.

The prospect of eventually returning samples from diverse bodies throughout the solar system underscores the need for a specialized sample return facility dedicated to the study and detection of life in extreme environments. Development of relevant methods and technologies for research on returned samples is also needed. In anticipation of the variety of proposed sample return missions (see Table 1.1 in Chapter 1), it will be important to be prepared with a suitably stringent containment and quarantine facility with equipment, protocols, trained personnel, and operating procedures in place well in advance of sample return.

TESTING OF RETURNED SAMPLES

Considering the variety of small bodies and environmental conditions from which samples may be returned in the future, it will be necessary to utilize a comprehensive battery of tests combining life detection studies and biohazard screening for overall evaluation of the returned samples. It is clear that multiple lines of testing will be needed to scan returned samples thoroughly for the presence of biological entities and indications of any potential for harm. The task of developing protocols for screening samples from small solar system bodies will require additional study beyond the scope of this report. The challenges will no doubt be similar to those discussed at a recent workshop at NASA Ames Research Center on developing preliminary protocols for sample return from Mars (DeVincenzi, 1998). An entirely new set of tests and analyses will be needed to reflect major changes in science and technology since the return of lunar samples during the Apollo program. The expectation of working with small quantities of material returned from Mars and other solar system bodies introduces additional requirements that will need attention, such as how to provide capabilities for detection at extremely low levels, how to select representative samples, and how to devise suitable experimental controls for tests done during quarantine.

Although individual analytical methods may have weaknesses, a combination of a variety of methods may suffice to verify with a high level of confidence the presence or absence of self-replicating organisms. To avoid added complications from false positives, it will be critical to ensure that strict controls to prevent forward contamination are used during collection and that stringent laboratory protocols are maintained throughout sample testing.

In general, sample materials should be screened thoroughly for chemical clues or signatures as well as structural and morphological features that could be indicative of the possible existence of living entities (e.g., biogenic compounds, cellular components, and so on). Initial investigations should consider the nature of the organic material present in a sample. Analyses for organic carbon content, amino acids, nucleotides, and the components of terrestrial organisms are very sensitive and could detect very small amounts of compounds associated with microorganisms. More general analytical methods using, for example, mass spectrometry combined with chromatography or pyrolysis would be useful, particularly in establishing the presence of life forms if they are different from those with which we are familiar. An additional set of investigations should address morphology. Examination by optical microscopy and scanning electron microscopy will establish whether or not putative (possibly membrane-enclosed) cellular structures are present. The presence of such structures would be an indication of the possible presence of a living entity. However, it is notoriously difficult to distinguish fossil microorganisms from inorganic artifacts, and so morphological evidence alone may not be conclusive.

Regardless of whether these life-detection tests indicate the possibility of living entities, it will also be important to include a battery of appropriately selected biohazard tests based on culture methods as part of the preliminary sample testing to screen for potential biological activity in the sample. Such tests should focus on indications of pathogenicity and important biogeochemical functions. Considering the advances in science and technology (e.g., advances in molecular biology and biotechnology) in the decades since the original analyses of lunar samples during the Apollo program, it is likely that preliminary life detection and biohazard testing can be done without resorting to the use of whole, multicellular organisms.

Attempts need to be made to culture putative microorganisms. The culture media should be chosen taking into account the nature of the sample and the environment from which it was obtained. Given that many terrestrial microorganisms are not easily cultured, the chances of culturing nonterrestrial organisms may be small. Nonetheless, it will be important to include this analytical approach in whatever preliminary screening of samples is selected. The utility and importance of biohazard tests should not be minimized, despite their shortcomings. In the end, biohazard tests utilizing conventional culture methods may be more helpful for what they do *not* show; in other words, the absence of growth in test cultures may be sufficient to declare a sample nonhazardous if such results are also accompanied by negative findings in all life detection tests.

Clearly, any indications of biochemicals in combination with morphological evidence of biological structure and/or biological activity in biohazard tests would warrant verification and review by a suitably constituted scientific panel. Moreover, if evidence of viable exogenous biological entities were discovered in samples returned from small bodies, prudence would dictate that they remain segregated from Earth's biosphere in strict quarantine or be made nonviable through sterilization before any distribution outside of quarantine. In the event that fossilized life forms are found and verified, it should be possible to allow distribution under less stringent conditions providing that no other tests indicate signs of living entities in the sample.

SUMMARY

For samples returned from planetary satellites and small solar system bodies that warrant containment, the concerns about biohazards or large-scale adverse effects on Earth are similar to those identified earlier for Mars (NRC, 1997). The task group found that the risks of pathogenicity from putative life forms are considered extremely low, because it is highly unlikely that extraterrestrial organisms could have evolved pathogenic traits in the absence of host organisms. However, because there are examples of opportunistic pathogens from terrestrial and aquatic environments that have not co-evolved with their mammalian hosts, the risk cannot be described as zero. The task group likewise found that the risks of ecological disruption from putative life forms are extremely low. The recommendations on containment and handling in the 1997 Mars report represent a strong basic framework for guiding deliberations on the potential risks associated with returned samples warranting containment. Based on current knowledge of the geophysical and geochemical properties of various solar system bodies and of life on Earth, it is unlikely that extraterrestrial organisms could cause harm or thrive in the oxygen-rich environment on Earth as they are likely to be strict anaerobes (see discussion in Chapter 1). Accordingly, the task group concluded that the probability of an extraterrestrial anaerobic microorganism being able to contaminate a suitable environment on Earth is very low, but not zero.

For overall evaluation of returned samples warranting containment, it will be necessary to apply a comprehensive battery of tests combining both life-detection studies and biohazard screening. The task group concluded that detailed protocols and nondestructive methods still have to be developed to analyze samples, which are anticipated to be small in size but in great demand within the scientific community.

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8

Conclusions and Recommendations

This chapter summarizes all the findings of the task group and presents its conclusions and recommendations organized to respond specifically to the tasks assigned to it. As pointed out in Chapter 1, the task group considered only two possible containment and handling requirements: either (1) strict containment and handling of returned samples as outlined in the Mars report (NRC, 1997) or (2) no special containment beyond what is needed for scientific purposes. The task group ruled out intermediate or compromise procedures involving partial containment. In certain cases (e.g., P- and D-type asteroids) the limitations of the available data led the task group to be less certain, and therefore more conservative, in its assessment of the need for containment.

ASSESSMENT OF POTENTIAL FOR A LIVING ENTITY TO BE PRESENT IN OR ONSAMPLES RETURNED FROM SMALL SOLAR SYSTEM BODIES

Planetary Satellites

Satellites are natural consequences of planetary formation processes. They can form around planets through condensation and agglomeration of material from circumplanetary gas and dust disks. Natural satellites can also develop from shorter-lived disks produced by large impacts on a growing planet; such a process may have produced Earth's Moon. Some satellites may be captured objects, that is, objects that formed elsewhere in the solar system but were drawn into orbit around a planet by aerodynamic drag forces generated by passage through an extended early planetary atmosphere. The task group considered the possibility of sample return from the major satellites of the innermost five planets. These include the satellite of Earth (the Moon), satellites of Mars (Phobos and Deimos), and selected satellites of Jupiter (Io, Europa, Ganymede, and Callisto). The selection was based on scientific interest and the likelihood of possible sample return missions in the near future.

Moon

The Moon is a large rocky body with a history dominated by volcanism and by impacts of interplanetary debris. Many samples of lunar rocks and soils were returned to Earth by the U.S. Apollo and Soviet Luna programs. None has been found to contain any evidence of past or present lunar biological activity. Because of this direct evidence, and because there is no indirect evidence for recent or past liquid water on the Moon (although small amounts of polar ice have recently been discovered), the potential for a living entity to be present in returned samples is negligible.

Phobos and Deimos

The two natural satellites of Mars are small, irregularly shaped rocky objects. With maximum dimensions of 27 km (Phobos) and 15 km (Deimos), they are similar in size and shape to typical asteroids. The origin of Phobos and Deimos is unclear. Both lie in orbits that are low in inclination and nearly circular. Overall, the limited spectral data and poorly determined densities of Phobos and Deimos are broadly consistent with their being similar to C- or P-type asteroids. It is possible that Phobos and Deimos may have experienced liquid water early in their history, but their primitive chemical composition would have led to potentially sterilizing levels of radiation since then. It is unlikely that ice-filled voids, which might have attenuated that radiation, are present today within the upper reaches of Phobos and Deimos that are accessible to sample return missions, because typical subsurface temperatures are far too high for ice to exist in equilibrium. On the other hand, biological materials, if any, could conceivably have been protected in ice pockets at depth for considerable periods of time, transported more recently to near-surface environments by catastrophic collisional disruption, and subsequently reassembled in Mars orbit and by near-surface processes of regolith turnover. Although sampling of any resulting, potentially hazardous material is very unlikely, it cannot be categorically ruled out.

Although it is clear that some small fraction of ejecta from impacts on Mars will be transferred to the planet's satellites, such material would be present only in a random (rather than targeted) sampling from the surface of Mars (which is known to be hostile to biological materials) and would be similar to SNC meteorites already striking Earth (which have been found not to be hazardous). Thus, the potential for a living entity to be present in returned samples is extremely low, but the task group could not conclude that it is necessarily zero.

Io

Io is the innermost of the galilean satellites, with a radius of more than 1,800 km, making it slightly larger than the Moon. Its composition is dominated by rock and possibly metal. Io is the most volcanically active known body in the solar system. Although abundant biologically useful energy is present, there is no evidence for the present or past existence of solid or liquid water at or beneath the surface. Because essentially all of the material at the surface of Io is volcanic, a good case can be made that all accessible material on the satellite has been heated at some point in time to temperatures higher than the maximum tolerated by any organic material. Io is also exposed to Jupiter's powerful magnetosphere; charged particles trapped in the magnetosphere continually bombard Io's surface at high flux levels and with high energy. This radiation would serve as a powerful inhibitor of biological activity at the surface of Io. Because of the lack of water in any form and the additional sterilizing influence of jovian magnetospheric bombardment on near-surface materials, the potential for a living entity to be present in returned samples is negligible.

Europa

Europa is one of the solar system bodies that appears to have a potential for past or present life. Europa has a radius of about 1,600 km, slightly less than the Moon's, and it is probably mostly silicate and metal by mass. It has an upper layer, on the order of 100 km deep, composed of liquid and/or solid water. There is evidence of liquid water beneath the icy crust, first surmised from Voyager data and reinforced by Galileo data. Accordingly, the task group found that there is a potential for a living entity to be present in samples returned from Europa.

Ganymede

Ganymede is the largest satellite in the solar system. With a radius of some 2,600 km, it is larger than the planet Mercury. Ganymede's density is probably roughly 50 percent water by mass. Although there is no evidence of the current presence of liquid water beneath the icy crust, the past presence of liquid water, even if only at a great depth, cannot be ruled out. Hydrothermal activity near the silicate/ice boundary could have occurred through at least some of the satellite's history, and through-going convection in the ice layer could have transported frozen hydrothermal fluids to near-surface regions. It is doubtful, but still possible, that subsurface material was extruded to the surface during the formation of the grooved terrain. Such extrusion, which may have occurred in geologically recent times (e.g., only hundreds of millions of years ago) is certainly a possibility. Accordingly, the task group found that there is a potential for a living entity to be present in samples returned from Ganymede.

Callisto

Callisto is similar to Ganymede in size (with a radius of approximately 2,400 km) but, unlike its neighboring satellite, exhibits negligible evidence of resurfacing or tectonism. Instead, its history has been dominated by impacts. There is no evidence that liquid water ever existed on Callisto, but the possibility cannot be ruled out. Callisto's moment of inertia is consistent with only modest internal differentiation, a significant finding from a biological perspective because it implies that silicates, rather than being concentrated near the satellite's center as they are in Ganymede, are distributed more nearly uniformly. Without a substantial rocky or rocky-metallic interior, silicate magmatism and hydrothermal activity are unlikely to have taken place within Callisto. Thus, no biologically useful source of energy is likely to have existed, even if liquid water was present at some place or time during the satellite's history. Because Callisto lacks an adequate source of energy to melt ice, and there is no direct evidence for past or present liquid water, the potential for a living entity to be present in returned samples is small. Callisto could be subject to cross-contamination by ejecta from another body in the Jupiter system that has some biological potential (e.g., Europa). However, such material would constitute such a trivial volume of Callisto's surface material that the odds of sampling it would be negligible.

Asteroids

Asteroids are the remnants of planetesimals—small primordial bodies from which the planets accumulated. Generally, asteroids are relic planetesimals formed in and beyond the asteroid belt (which is located between 2.2 and 3.2 AU from the Sun), as far away from the Sun as the Trojans, which orbit at Jupiter's distance. Those formed in more distant locations are usually considered to be comets. Common asteroid types include undifferentiated, primitive types (C-, B-, and G-types); undifferentiated metamorphosed types (Q- and S-types [ordinary chondrites]); and differentiated types (M-, V-, J-, A-, S- [stony irons], and E-types). Other types of asteroids have been defined, including the common P- and D-types in the outer parts of the asteroid belt, but little is known about their composition and origin. Others are subdivisions of the types listed above, whereas still others are rare, new types, generally seen only among the population of very small asteroids.

The early environment of C-type asteroids may have been suitable for harboring a dormant living entity in buried ice pockets. There is unequivocal evidence of liquid water having been active within at least some C-type asteroids approximately 4.5 Gyr ago. There is meteoritic evidence that some C-type asteroids have experienced temperatures above 160 °C following aqueous activity, but a substantial fraction have not been so heated. Except for possible localized volumes of water ice in C-types, the interiors of C- and undifferentiated S-type asteroids would have experienced sterilizing doses of radiation from the decay of natural radionuclides during the 4.5 Gyr since cessation of aqueous activity. Meteorites and IDPs have delivered samples of many asteroids to Earth. Whether the C-type material received on Earth is representative of a particular target body remains uncertain, because the sampling of C-type asteroids may be sporadic and nonrepresentative. Meteorites and the precursor fragments from which they are derived may well have been large enough that their interiors have been protected from sterilizing doses of radiation from galactic and solar cosmic rays while in transit to Earth. Furthermore, pockets of volatile compounds within chondritic materials could potentially shield dormant organisms from radiation damage. For these reasons, although the potential for a living entity to be present in returned samples from C-type asteroids is extremely low, the task group could not conclude that it is necessarily zero. To reduce uncertainty when assessing the potential for a living entity to be present on C-type asteroids, it would be helpful to conduct studies to document whether such a body targeted for a sample return mission is similar to nonhazardous meteorites falling naturally on Earth.

Very little is known about P- and D-type asteroids. It is plausible that they are like C- type asteroids and dormant comets derived from the Jupiter zone. But caution is warranted as their nature is truly only a matter of speculation. There is a small, perhaps negligible, natural influx to Earth of meteorites from P- and D-type asteroids. For most P- and D-type asteroids that have been observed, there is no evidence that liquid water was present in the past. Because of the general lack of information about P- and D-type asteroids, the potential for a living entity to be present in samples returned from them cannot be determined and, therefore, is considered conservatively by the task group as possible at this time.

Undifferentiated metamorphosed asteroids and differentiated asteroids are dry and have been heated to very high temperatures. A minor fraction of S-type asteroids may have experienced a transient episode of aqueous activity, but the great majority of S-types have never been exposed to liquid water. Like C-type asteroids, S- and Q-types would have experienced sterilizing doses of radiation from decay of natural radionuclides during the 4.5 Gyr since cessation of any aqueous activity. Thus, for all S-type asteroids, the potential for a living entity to be present in returned samples is negligible. Liquid water can also be ruled out for all differentiated asteroids, and so the potential for living entities to be present in samples returned from these asteroids is similarly negligible. However, there is clear evidence in meteorites that substantial cross-contamination of material from one asteroid to another has occurred. Therefore, for all undifferentiated metamorphosed asteroids as well as for differentiated asteroids, the potential for a living entity to be present in returned samples is extremely low, but the task group could not conclude that it is necessarily zero.

Comets

Comets are believed to have formed in the protoplanetary disk, at distances from the Sun ranging from the distance of proto-Jupiter to far beyond the distance of proto-Neptune. Cometary nuclei are predominantly icy bodies that, most likely, have never melted on large scales. For most of their 4.6-Gyr lives they have been at temperatures below -173 °C (100 K), with those in the Oort Cloud at temperatures on the order of -263 °C (10 K). The surface layers have undergone months-long transient heating to temperatures on the order of 27 °C (300 K) (depending on heliocentric distance) at previous perihelion passages. The generally accepted view is that cometary material is sufficiently porous that the volatile substances escape as vapor rather than remaining trapped as a liquid.

Irradiation by galactic cosmic rays of most cometary bodies outside the heliosphere (Oort Cloud comets but not Kuiper Belt comets) would be sufficient to destroy any preexisting life in the outermost tens of meters, and the temperatures are so low that life could not form. The best estimates of the radiation environment of the deep interior indicate that sterilizing doses of radiation may be achieved in time scales of the same order of magnitude as the age of the solar system. Some cometary nuclei have a large quantity of organic material present in the form of volatile and refractory molecules, but the presence of such molecules can be explained by abiotic formation; such molecules have also been detected in the interstellar medium, where they are certainly produced abiotically.

It is generally agreed that Earth has received samples of comets. Unsterilized cometary dust has been delivered episodically to the surface of Earth, but it is not clear whether this has occurred within the last 500 years. It is unlikely that a living entity could exist on comets, but the possibility cannot be completely ruled out except in a few cases, such as in the outer layers of Oort Cloud comets entering the solar system for the first time. Thus, the potential for a living entity to be present in returned samples from all comets was considered by the task group to be extremely low, but the task group could not conclude that it is necessarily zero.

Cosmic Dust

Cosmic dust, or interplanetary dust particles (IDPs), represents a valuable source of material for the evaluation of the composition and characteristics of objects throughout the solar system. Because interplanetary dust particles are derived from a variety of sources, including interstellar grains and debris from comets, asteroids, and possibly planetary satellites, IDPs cannot be viewed as a distinct target body. As a result, IDPs themselves cannot be readily assessed by the approach used in this study. Instead, the task group considered the potential source(s) of any IDPs that might be returned in samples. For the purposes of this study, IDPs are viewed as originating from either a single identifiable parent body or multiple sources. Particles collected near a particular solar system body are viewed as originating from that body, possibly including grains recently released from that body. Thus, the potential for a living entity to be present in returned samples, and the associated containment requirements, will be the same as those for the parent body. On the other hand, IDPs collected in the interplanetary medium may represent a mixture of dust originating from many parent bodies. Because IDPs in the interstellar medium are exposed to sterilizing doses of radiation, the potential for IDPs to harbor viable organisms or a living entity is negligible.

An additional consideration is whether the method of collection for IDPs in returned samples results in spiked heating of the sample to temperatures extreme enough to cause biological sterilization. If so, then no special containment is required, regardless of the source of the IDP.

Cosmic dust has been introduced to Earth throughout its history. The accumulation of the various components of IDPs and micrometeorites has had no known adverse effects on Earth's ecosystems. Thus, it is unlikely that a returned sample of this type of extraterrestrial material would pose any kind of threat to Earth's biota or biogeochemical cycles.

CONTAINMENT AND HANDLING OF RETURNED SAMPLES

The task group's conclusions and recommendations on containment and handling of samples returned from planetary satellites and small solar system bodies are based on its analysis of the potential for a living entity to exist in or on such samples. Table 8.1 summarizes the results of the task group's assessment. It is important to note that the task group's recommended approach is provided only as a guide and not as an inflexible protocol for determining

TABLE 8.1 Summary of Currently Recommended Approach to Handling Samples Returned from Planetary Satellites and Small Solar System Bodies Assessed by the Task Group on Sample Return from Small Solar System Bodies

I No Special Containment and Handling Warranted Beyond What Is Needed for Scientific Purposes		II Strict Containment and Handling Warranted
I[a] *High Degree of Confidence*	I[b] *Lesser Degree of Confidence*[a]	
The Moon	Phobos	Europa
Io	Deimos	Ganymede
Dynamically new comets[b]	Callisto	P-type asteroids
Interplanetary dust particles[c]	C-type asteroids	D-type asteroids
	Undifferentiated metamorphosed asteroids	Interplanetary dust particles[d]
	Differentiated asteroids	
	All other comets	
	Interplanetary dust particles[e]	

[a] Subcolumn Ib lists those bodies for which confidence in the recommended approach is still high but for which there is insufficient information at present to express it absolutely. This lesser degree of confidence does not mean that containment is warranted for those bodies; rather, it means that continued scrutiny of the issue is warranted for the listed bodies as new data become available. The validity of the task group's conclusion that containment is not warranted for the bodies listed in Ib should be evaluated, on a case-by-case basis, by an appropriately constituted advisory committee in light of the data available at the time that a sample return mission to the body is planned.

[b] Samples from the outer 10 meters of dynamically new comets.

[c] Interplanetary dust particles sampled from the interplanetary medium and from the parent bodies listed in subcolumn Ia.

[d] Interplanetary dust sampled from the parent bodies in column II and collected in a way that would not result in exposure to extreme temperatures.

[e] Interplanetary dust sampled from the parent bodies listed in subcolumn Ib.

whether containment is required. The final decision must be based on the best judgment of the decision makers at the time and, when possible, on experience with samples returned previously from target bodies.

On the basis of available information about the Moon, Io, dynamically new comets (specifically the outer 10 meters), and interplanetary dust particles (sampled from the interplanetary medium, sampled near the Moon or Io, or sampled in a way that would result in exposure to extreme temperatures, e.g., spike heated), the task group concluded with a high degree of confidence that no special containment is warranted for samples returned from those bodies beyond what is needed for scientific purposes.

For samples returned from Phobos and Deimos, Callisto, C-type asteroids, undifferentiated metamorphosed asteroids, differentiated asteroids, and comets other than dynamically new comets, the potential for a living entity in a returned sample is extremely low, but the task group could not conclude that it is zero. Based on the best available data at the time of this study, the task group concluded that containment is not warranted for samples returned from these bodies or from interplanetary dust particles collected near these bodies. However, this conclusion is less firm than it is for the Moon and Io and should be reexamined at the time of mission planning on a case-by-case basis.

For samples returned from Europa and Ganymede, the task group concluded that strict containment and handling requirements are warranted. Because the knowledge base for P- and D-type asteroids is highly speculative, the task group concluded conservatively that strict containment and handling requirements are warranted at this time. Strict containment and handling requirements are also warranted for interplanetary dust particles collected near these bodies unless they are sampled in a way that would result in exposure to extreme temperatures, e.g., spike heated.

For samples that are returned from planetary satellites and small solar system bodies and that warrant containment, the concerns about biohazards or large-scale adverse effects on Earth are similar to those identified earlier for Mars (NRC, 1997). The task group concluded that the risks of pathogenicity from putative life forms are extremely low, because it is highly unlikely that extraterrestrial organisms could have evolved pathogenic traits in the absence of host organisms or could cause ecological harm. However, because there are examples of opportunistic pathogens from terrestrial and aquatic environments that have not co-evolved with their hosts, the risk cannot be described as zero. The recommendations on containment and handling in the Mars report (NRC, 1997) represent a strong basic framework for addressing potential risk associated with returned samples warranting containment.

The microbial species composition of most anaerobic environments on Earth is not known, and consequently it is also not known how the species composition of these anaerobic microbial communities might change over time, what environmental factors might influence these changes, or what the incidence of and successful colonization by new species of microorganisms in these habitats might be. Accordingly, the task group concluded that although there is a low likelihood of a viable anaerobic microorganism surviving transport through space and finding a suitable anaerobic habitat on Earth, growth in a suitable habitat if found might be possible. This conclusion is necessary because of the current lack of information about anaerobic environments on Earth that may be analogous to environments on other solar bodies, and the likelihood that the metabolic properties of such an extraterrestrial anaerobe would resemble an Earth anaerobe from a similar environment.

For overall evaluation of returned samples that warrant containment, it will be necessary to apply a comprehensive battery of tests combining both life-detection studies and biohazard screening.

Recommendation: Samples returned from the Moon, Io, the outer 10 meters of dynamically new comets, and interplanetary dust particles (from the interplanetary medium, near the Moon, Io, or dynamically new comets), or sampled in a way that would result in exposure to extreme temperatures (e.g., spike heated), should not be contained or handled in a special way beyond what is needed for scientific purposes.

Recommendation: For samples returned from Phobos and Deimos, Callisto, C-type asteroids, undifferentiated metamorphosed asteroids, differentiated asteroids, comets other than dynamically new ones, and interplanetary dust particles sampled near these bodies, a conservative, case-by-case approach should be used to assess the containment and handling requirements. NASA should consult with or establish an advisory committee with expertise in the planetary and biological sciences relevant to such an assessment. The goal of such an assessment should be to use any new, relevant data to evaluate whether containment is still not warranted. This assessment should take into account all available information about the target body, the natural influx to Earth of relevant materials, and the likely nature of any putative living entities. Such an advisory committee should include both NASA and non-NASA experts and should be established as early in the mission planning process as possible.

Recommendation: Based on currently available information, samples returned from Europa, Ganymede, P- and D-type asteroids, and interplanetary dust particles sampled near these bodies should be contained and handled similarly to samples returned from Mars (NRC, 1997). Interplanetary dust particles sampled in a way that would result in exposure to extreme temperatures, e.g., spike heated, should not be contained or handled in a special way beyond what is needed for scientific purposes.

Recommendation: Returned samples judged to warrant containment should be quarantined and screened thoroughly for indications of a potential for pathogenicity and ecological disruption, even though the likelihood of adverse biological effects from returned extraterrestrial samples is very low.

Recommendation: NASA should consult with or establish an advisory committee of experts from the scientific community when developing protocols and methods to examine returned samples for indicators of past or present extraterrestrial life forms.

Recommendation: The planetary protection measures adopted for the first sample return mission to a small body whose samples warrant special handling and containment should not be relaxed for subsequent missions without a thorough scientific review and concurrence by an appropriate independent body.

SCIENTIFIC INVESTIGATIONS TO REDUCE UNCERTAINTY

Identified by the task group in Chapters 2 through 6 is scientific research that could help to reduce the uncertainty in its assessment of the potential for a living entity to be contained in or on samples returned from planetary satellites and small solar system bodies. Because most of the suggested research topics are general in scope, they are not repeated here. However, one topic is of sufficient importance that it requires emphasis.

Because organisms subjected to sterilizing conditions for a sufficient time period pose no threat to terrestrial ecosystems, it is important to assemble a database on the survival capacity of a wide range of terrestrial organisms under extreme conditions. Despite the existence of a rich literature on the survival of microorganisms exposed to radiation and high temperatures, the studied taxa represent only a small sampling of the microbial diversity known to exist in the biosphere and, in general, have not been taken from extreme environments. Little is known about the radiation and temperature resistance of microorganisms from environments on Earth that have the chemical and physical characteristics likely to be encountered in or on small solar system bodies.

Recommendation: NASA should sponsor research that will lead to a better understanding of the radiation and temperature resistance of microorganisms from environments on Earth that have the chemical and physical characteristics likely to be encountered in or on small solar system bodies. Information on the survival of organisms subjected to long- or short-term ionizing radiation needs to be collected for both metabolically active and dormant stages of diverse groups of microorganisms, including hyperthermophiles, oligotrophic chemoorganotrophs, and chemolithoautotrophs. Likewise, it is important to establish short- and long-term temperature survival curves for similarly broad groups of metabolically active and dormant organisms. In particular, data are required on survival of diverse microorganisms under flash heating (1- to 10-second exposures) to temperatures between 160 °C and 400 °C.

REFERENCE

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Appendixes

A Biographical Sketches of Task Group Members

Leslie Orgel, *chair*, is a senior fellow and research professor at the Salk Institute for Biological Studies. Since 1964, he has also been an adjunct professor at the University of California, San Diego. Dr. Orgel's research interests include chemical evolution and synthesis of oligonucleotide analogs and bioconjugates. He was a member of NASA's Molecular Analysis Team for the Mars Lander I and II. Dr. Orgel is the recipient of the Harrison Prize, the Evans Award (Ohio State University), and the U.C. Urey Medal (International Society for the Study of the Origin of Life). He was a Guggenheim Fellow and is an elected fellow of the American Academy of Arts and Sciences. Dr. Orgel is a member of the National Academy of Sciences, a fellow of the Royal Society, and a member of Sigma Xi. He received a B.A. degree and a Ph.D. degree in chemistry from Oxford.

Michael A'Hearn is a professor of astronomy at the University of Maryland at College Park. Dr. A'Hearn's research interests emphasize the origin, composition, and role of comets in our solar system. He was recently involved in the organization of the worldwide plan for the comet Hale-Bopp observing opportunity, acting as the observational campaign's co-coordinator. Dr. A'Hearn is a fellow of the American Association for the Advancement of Science and a member of the American Astronomical Society, the Institute of Navigation, and the International Astronomical Union (IAU). He plays a prominent role in the science advisory community, sitting on a number of working groups and review panels and participating currently as chair of the Hubble Space Telescope time allocation committee, as a member of the Keck Review Team and of the Space Station Attached Payloads Peer Review Panel, and as associate editor for the journal *Earth, Moon and Planets*. The asteroid 3192 A'Hearn was named in his honor. He chaired the Task Group on Ballistic Missile Defense Organization/New Technology Orbital Observatory and was a member of the U.S. National Committee for the International Astronomical Union. He is currently president of IAU division III on planetary systems sciences. Dr. A'Hearn received a B.S. degree from Boston College and a Ph.D. degree in astronomy from the University of Wisconsin.

Jeffrey Bada is a professor of marine chemistry and the director of the NASA Specialized Center of Research and Training (NSCORT) in Exobiology program at the Scripps Institution of Oceanography at the University of California, San Diego. His research deals with the cosmogeochemistry of amino acids, the possible sources, the stability, and the composition of the organic material on the primitive Earth and other solar system bodies, and the development of methods for detecting remnants of ancient life on Mars, all areas of investigation central to the task group's deliberations. Dr. Bada is a past recipient of an Alfred P. Sloan Research Fellowship. Dr. Bada is a member of the American Association for the Advancement of Science, the International Society for the Study of the Origin of Life, the Geochemical Society, and the Geochemistry Division of the American Chemical Society. He received a B.S. degree in chemistry from San Diego State University and a Ph.D. degree in chemistry from the University of California, San Diego.

John Baross is a professor in oceanography at the University of Washington. His research speciality is in the ecology, physiology and taxonomy of microorganisms from hydrothermal vent environments, as well as the use of biochemical and molecular methods to detect, quantify, and classify the same. Dr. Baross has particular interests in the microbiology of extreme environments and in the significance of submarine hydrothermal vent environments for the origin and evolution of life. He is a member of the American Society for Microbiology, the American Chemical Society, the Oceanography Society, the American Geophysical Union, the American Society for Limnology and Oceanography, and the Society for Industrial Microbiology (Puget Sound Branch). Dr. Baross is a former member of the National Research Council's Ad Hoc Task Group on Planetary Protection and of the American Academy of Microbiology Committee on the Future of Microbiology; a member of the Ridge InterDisciplinary Global Experiments (RIDGE) Steering Committee and of the RIDGE Observatory Coordinating Committee; and an advisory member for Europa Ocean Studies. Dr. Baross received a B.S. degree from San Francisco State University and a Ph.D. degree in marine microbiology from the University of Washington.

Clark Chapman is a scientist with the Southwest Research Institute in Boulder, Colorado. He is also a consulting scientist for Science Applications International Corporation. His research interests encompass the study of small bodies in the solar system, including the study of the near-Earth asteroid population. Dr. Chapman is a member of the Galileo imaging science team, with his role focused on the data returned from the Galilean satellites. He is a member of the American Astronomical Society, the American Geophysical Union, and the International Astronomical Union (IAU) and is a fellow of the Meteoritical Society. Dr. Chapman was chairman of the Organizing Committee for the 1991 International Conference on Near-Earth Asteroids and a member of a number of advisory groups, including IAU Colloquia on Mercury and the Moon, the NASA Near-Earth Objects Survey Working Group, and the Comet Rendezvous Asteroid Flyby Science Working Group (NASA later canceled the CRAF mission). He served on the Space Studies Board's Committee on Planetary and Lunar Exploration. Dr. Chapman received a B.S. degree from Harvard University and a Ph.D. degree in planetary science from the Massachusetts Institute of Technology.

Michael Drake is a professor of planetary sciences and geosciences at the University of Arizona. He is also head of the Department of Planetary Sciences and director of the Lunar and Planetary Laboratory at the University of Arizona. Dr. Drake's research has focused on investigations involving understanding the petrology and geochemistry of lunar samples and meteorites, the evolution of planetary bodies, and mineral-melt equilibria. He is currently the chair of NASA's Planetary Materials and Geochemistry Management Operations Working Group and has served on numerous other NASA advisory committees or working groups. Dr. Drake served as an associate editor of four peer-reviewed journals, including *the Proceedings of the Lunar and Planetary Science Conference, Journal of Geophysical Research*, and *Geochimica et Cosmochimica Acta*. He is a fellow of the Meteoritical Society and a member of the American Geophysical Union, the American Astronomical Society, the Geochemical Society, and the European Union of Geosciences. Dr. Drake received a B.S. degree from the University of Manchester and a Ph.D. degree in geology from the University of Oregon.

John F. Kerridge is a research cosmochemist in the Department of Chemistry at the University of California, San Diego. His research has focused on the physics and chemistry of the early solar system, particularly the formation and geochemical evolution of small bodies, and the synthesis of organic molecules. Dr. Kerridge has served on a number of advisory and review boards, including the AIBS/NASA Exobiology Advisory Panel, a NASA workshop "Cosmic History of the Biogenic Elements," the Scientific Organizing Committee for the Comet Nucleus Sample Return Workshop, the NASA Exobiology Discipline Working Group, and The Origins of Solar Systems Review Panel (on which he served as chair). Dr. Kerridge is a fellow of the Meteoritical Society, as well as a member of the American Geophysical Union and the International Society for the Study of the Origin of Life. He is also a past member of the Space Studies Board's Committee on Planetary and Lunar Exploration. Dr. Kerridge received a B.S. degree from the University of Birmingham and an M.S. degree and Ph.D. degree in crystallography from the University of London.

Margaret S. Race is an ecologist at the SETI Institute in Mountain View, California. Her current research focuses on planetary protection, environmental impact analysis and risk assessment for extraterrestrial sample return missions. Concurrent with her work at the SETI Institute, Dr. Race is a research affiliate with the Energy and Resources Graduate Group at the University of California, Berkeley, and a Lawrence Hall of Science Fellow, where she works on science education curricula for K-12 schools. She was a member of the Space Studies Board's Task Group on Issues in Sample Return and the Transportation Research Board's Study on Transportation and a Sustainable Environment. Dr. Race received a B.A. degree in biology and an M.S. degree in energy management and policy from the University of Pennsylvania and a Ph.D. degree in ecology from the University of California, Berkeley.

Mitchell Sogin is the director of the Bay Paul Center for Comparative Molecular Biology and Evolution at the Marine Biological Laboratory at Woods Hole, Massachusetts. Dr. Sogin's research interests emphasize molecular phylogeny and the evolution of eukaryotic ribosomal RNAs. He is a member of the American Society for Microbiology, the Society of Protozoologists, the International Society of Evolutionary Protozoologists, the Society for Molecular Biology and Evolution, the American Association for the Advancement of Science, and the American Society for Cell Biology. Dr. Sogin is an associate fellow of the Canadian Institute for Advanced Research, a division lecturer for the American Society for Microbiology, a recipient of the Stoll Stunkard Award from the American Society of Parasitologists, a fellow of the American Academy of Microbiology, a Fellow of the American Association of Arts and Sciences, and a visiting Miller Research Professor at the University of California, Berkele. He also serves on several editorial boards in his specialization. Dr. Sogin received B.S., M.S., and Ph.D. degrees in microbiology and molecular biology from the University of Illinois at Urbana.

Steven Squyres is a professor in the Department of Astronomy at Cornell University. His research includes the study of the geophysics and tectonics of icy satellites and the planet Mars as well as the use of planetary gammaray spectroscopy. He is the recipient of two NASA group achievement medals as well as the American Astronomical Society's Harold C. Urey Prize. Dr. Squyres has experience as a research scientist at NASA Ames Research Center and as a geologist with the U.S. Geological Survey in Flagstaff, Arizona. He is currently a member of the Cassini imaging science team and a co-investigator for the Champollion lander imaging investigation for the European Space Agency-led Rosetta mission to a comet. His experience on advisory boards includes terms on the NEAR mission Design Review Board, the NASA Solar System Exploration advisory subcommittee, the Inter-Agency Consultative Group for Space Science's Panel on Planetary and Primitive Bodies, and the NASA Mission to the Solar System Roadmap Team. He is a member of the Space Studies Board Task Group on Research and Analysis Programs. Dr. Squyres received a B.A. degree and a Ph.D. degree in planetary sciences from Cornell University.

B Letter of Request

National Aeronautics and Space Administration **Headquarters**
Washington, DC 20546-0001

Reply to attn of: SR

May 5 1997

Dr. Claude Canizares
Space Studies Board
National Academy of Sciences
2101 Constitution Avenue, NW Washington, DC 20418

Dear Dr. Canizares:

NASA's planetary protection policy aims to preserve solar system conditions for future biological and organic constituent exploration and to protect the Earth and its biosphere from extraterrestrial sources of contamination. The Space Studies Board (SSB) has been the primary group advising NASA on its efforts in planetary protection and continued advice is needed to ensure that our planetary protection policy remains sound. In particular, we continue to seek the Space Studies Board's advice on issues and concerns about samples returned from planetary bodies.

The recent publication of the SSB report, *Mars Sample Return: Issues and Recommendations* has been timely in assisting us in the consideration of missions which will collect samples for possible return to Earth. The SSB has made valuable recommendations on the justification and procedures for quarantine of samples returned from Mars. Indeed, we expect that similar sample quarantine procedures may be applicable to any returned extraterrestrial material that may be a potential hazard to Earth's biosphere.

Recent data has indicated that the focus of our previous request on Mars sample return should be expanded to include other solar system bodies. For example, natural satellites, asteroids, and comets represent a wide range of bodies from which NASA may someday take and perhaps return a sample, not only during missions such as Rosetta, but also during missions proposed to NASA's Discovery Program and in our possible joint work with the Department of Defense. With the advent of possible sample return missions from multiple planetary bodies, we feel that it would be prudent to initiate a study that would extend current advice on Mars to other small solar system bodies by addressing:

1) The potential for a living entity to be in a sample returned from different planetary bodies, such as satellites, comets and asteroids;

2) Detectable differences among small bodies that would affect the above assessment;

3) Scientific investigations that should be conducted to reduce the uncertainty in the above assessment;

4) The potential risk from samples returned directly to Earth by space flight missions, as compared to the natural influx of material that enters the Earth's atmosphere as interplanetary dust particles, meteorites, and other small impactors.

Your help in addressing the question of planetary protection for missions that may return material from a wide range of small bodies is greatly appreciated. Dr. Meyer will be working with you and the SSB staff to finalize a Statement of Task for this study effort. Please contact him (202-358-0307) if you need further information about this request.

Sincerely,

Wesley T Huntress

Wesley T. Huntress, Jr.
Associate Administrator for Space Science

cc:
SR/Dr. M. Meyer
S/Dr. C. Pilcher
S/Dr. R. Rahe
NRC/Dr. M. Allen

C Additional Perspectives on Contamination from Space

A substantial body of speculative literature on the origins of life was considered by the Task Group on Sample Return from Small Solar System Bodies but was judged to have too little experimental or theoretical justification to warrant evaluation in the body of this report. The task group also noted earlier reports, which have since been discredited, of evidence for living cells in meteorites. This appendix directs the reader to some of this material.

CLAY-BASED LIFE

Graham Cairns-Smith, in a series of papers and books, has argued that the earliest form of life on Earth was inorganic, probably based on a self-replicating clay (Cairns-Smith, 1982). The task group saw no way of evaluating this proposal and no reason to take account of it in formulating its recommendations.

PANSPERMIA

The idea that the first living organisms on Earth came from space has appeared in many guises over a period of more than 100 years. In the 19th century the seeds of life were thought to have arrived driven by the pressure of light from distant stars or encapsulated in meteorites (see, e.g., Oparin, 1957). More recently, deliberate or accidental seeding through the activities of a technologically advanced civilization has also been suggested, although not always seriously (Gold, 1960; Crick and Orgel, 1973). These proposals for the origins of life are in no way irrational, although most students of the subject think it more likely that life originated de novo on the primitive Earth. The possibility of cross-contamination of planetary bodies via meteorites and other small bodies is considered in the appropriate parts of this report. The possibility of the contamination of the planets by microorganisms carried on space probes has been discussed elsewhere.

A somewhat different proposal was put forward by Hoyle and Wickramasinghe (1986), who suggested that bacteria and viruses capable of establishing infections in terrestrial organisms are constantly impinging on Earth and suggested comets as a possible source of viral epidemics. The task group did not think it necessary to take account of these suggestions in formulating its recommendations.

ARTIFACTS IN METEORITES

As stated above, the idea that living organisms arrived on Earth embedded in meteorites was widely discussed in the 19th century (see, e.g., Hahn, 1880). Subsequently, it has been claimed from time to time that organisms have been identified in samples of meteorites collected in the field and/or stored in museums (see, e.g., Claus and Nagy, 1962). Although such claims have attracted considerable attention, subsequent investigations have shown in all cases that the putative microfossils were either terrestrial contaminants or abiotically produced indigenous mineral structures (see, e.g., Rossignol-Strick and Barghoorn, 1971). There is at present no evidence for any organisms of extraterrestrial origin in meteorites from planetary satellites or small solar system bodies.

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D Planetary Protection Policy—NASA and COSPAR

NASA'S POLICY

NASA's efforts in planetary protection seek to preserve planetary conditions for future exploration of biological constituents and to protect Earth and its biosphere from potential extraterrestrial sources of contamination. Both to preserve future scientific opportunities and to comply with existing U.S. treaty obligations, particularly the 1967 Space Treaty, NASA is committed to exploring space while avoiding the biological contamination of other solar system bodies and protecting Earth against potential harm from materials returned from space. Under the provisions of NASA Policy Document (NPD) 8020.7 and the lower-tier document NASA Policy Guidebook (NPG) 8020.12, which places responsibility for implementing planetary protection policy with the associate administrator for space science, NASA maintains a planetary protection program to evaluate objectives. The associate administrator delegates the management of NASA policy to a planetary protection officer (PPO). One other salient feature of the current NASA directives is that NASA is required to seek the advice of internal and external advisory groups in implementing planetary protection policy, most notably from the Space Studies Board of the National Research Council.

For each solar system body that might be explored, NASA's requirements may range from no further action (in the case of missions to bodies not of interest with respect to life or chemical evolution) to a variety of mission constraints, including careful record keeping, a requirement for altering spacecraft trajectories to avoid hitting a planet unintentionally, or even heat or gas treatment of a spacecraft to kill the biological organisms it may carry. For returned spacecraft, depending on the target of exploration there may be no additional constraints or there may be constraints as severe as a requirement to quarantine the returned spacecraft and even sterilize its contents.

Constraints on spacecraft involved in solar system exploration missions depend on the nature of the mission and the identity of the target body (or bodies) to be explored. No strict set of procedures are in place for a given solar system body. Instead, individual missions are placed into different categories depending on the concern for the target of the mission and the type of mission envisioned.

The restrictions and categories given in Table D.1 are shown as they were presented in reports on NASA's planetary protection policy (DeVincenzi and Stabekis, 1984; DeVincenzi et al., 1996), with minor modifications in wording as embodied in NPG 8020.12, and current thinking on the status of Europa (personal communication, John Rummel, May 6, 1998). Categories I through IV apply to missions or targets where "forward contamination" is a concern. Category I applies to all missions to targets thought to be of no biological interest. These missions have no associated planetary protection requirements. Category II applies to all missions to targets in which there is a minimal biological interest, but which may be of intrinsic interest for the study of chemical evolution and for which documentation is required to ensure that planetary protection goals are being met. Categories III and IV apply to targets with significant biological interest, or with a potential to be contaminated. Category III applies to missions intended to make direct contact with these targets. Category IV applies to missions intended to make direct contact.

TABLE D.1 Categories and Associated Restrictions That Apply to Solar System Exploration Missions

	Category I	Category II	Category III	Category IV	Category V
Type of mission	Any but Earth return	Any but Earth return	No direct contact (flyby, orbiters)	Direct contact (landers, probes)	Earth return
Target planet	Sun, Mercury, Pluto	Any except Mars, Sun, Mercury, Pluto	Mars	Mars	To be determined
Degree of concern	None	Documentation only	Passive bioload control	Active bioload control (more stringent for life detection mission)	*Inbound* Restricted Earth return: –No impact on Earth or the Moon –Sterilization of returned hardware –Containment of any sample
Representative range of procedures	None	Documentation only	Documentation (more involved than category II)	Detailed documentation (substantially more involved than category III)	*Outbound* –Per category of target planet/ outbound mission *Inbound* Restricted Earth return: –All category IV –Continual monitoring of project activities –Preproject advanced studies/ research –Possible sample containment Unrestricted Earth return: None

SOURCE: As presented in DeVincenzi et al. (1996), with minor modifications in wording as embodied in NASA document NPG 8020.12.

Category V applies to all missions that make contact with another solar system body and then return to Earth and is given in addition to the category assigned for the outbound phase. Category V missions can be designated either as "unrestricted Earth return," in which case they would warrant no further planetary protection requirements, or as "restricted Earth return," which might involve requirements for extensive constraints on the mission to guarantee the safety of Earth's biosphere.

Cospar Policy

NASA's program in planetary protection is represented on the international stage largely through the mediation of the International Council of Scientific Unions' Committee on Space Research (COSPAR), a nongovernmental organization that consults with the United Nations on planetary protection issues, particularly with respect to the provisions of the 1967 Space Treaty. COSPAR comprises several scientific commissions, and planetary protection is the province of Scientific Commission F, which is concerned with "life sciences as related to space." COSPAR policy is proposed by Scientific Commission F and adopted by the COSPAR Council, which is made up of commission representatives and the representatives of national members and international scientific unions. In the past, U.S. representatives have taken a leading role in the formulation of COSPAR planetary protection policy, and COSPAR policy has roughly mirrored NASA policy. NASA document NPG 8020.12 stipulates that NASA will not participate in international missions unless each international partner agrees to follow COSPAR planetary protection policy.

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E Glossary

Ablation—	the process whereby material is heated, vaporized, and lost from the surface of a projectile penetrating Earth's atmosphere
Allotrope—	one of two or more existing forms of an element
Astronomical unit (AU)—	mean distance of the Earth from the Sun
Back contamination—	biological contamination of Earth as a result of samples returned from solar system bodies
Commensurability—	a location (e.g. in the asteroid belt) where a body orbits with a period that is a simple fraction (e.g., 2/5 or 1/3) of the period of another large body (e.g., Jupiter) where resonant effects can build up
Containment—	physical and biological isolation and handling of returned samples as specified for samples returned from Mars[1]
Crater palimpsests—	circular features of very little relief that are apparently vestiges of large ancient impacts
Endolithic—	living on the surface of rocks, e.g., lichens
Eukaryotic cells—	cells with a defined nucleus that contains most of a cell's DNA and is enclosed by a membrane, e.g., fungi
Extremophiles—	microorganisms capable of growing under extreme physicochemical conditions such as high temperatures and pressures
Forward contamination—	biological contamination of a solar system body from a sample return mission
Gram-negative bacteria—	bacteria that show a red color from Gram's stain procedure
Gram-positive bacteria—	bacteria that show a purple color from Gram's stain procedure
Hydrolase—	any of a class of enzymes that break hydrogen bonds

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[1] National Research Council (NRC). 1997. Mars Sample Return: Issues and Recommendations. Washington D.C.: National Academy Press.

Interplanetary debris complex (IDC)—	the ensemble of dust and larger particles (e.g., boulder size) in interplanetary space, generated by the gradual erosion and disintegration of asteroids, comets, and other bodies; components of the complex are manifested in diverse ways (e.g., zodiacal light, IDPs collected in Earth's stratosphere, and so on) and are generally small enough so that their motions are governed not only by gravitational forces but also by radiation forces (e.g., light pressure or Yarkovsky forces) and forces sensitive to particle charge
Kirkwood gap—	a narrow zone in the asteroid belt (generally surrounding a commensurability) that has been depleted of asteroids
Kuiper Belt—	a torus-shaped volume beyond the orbit of Neptune populated by bodies ranging up to many hundreds of kilometers in size; the source region for most short-period comets
Laplace orbital resonance—	a commensurability in the mean motions that causes repeated alignment of planetary satellites at identical points in their orbits
Nuclease—	an enzyme that degrades nucleic acids
Oort Cloud—	a spherical zone beyond the outer solar system, extending part way to the nearest star, where long-period comets originate
Poynting-Robertson drag—	forces interplanetary dust particles into Earth-crossing, inwardly spiraling circular orbits around the Sun
Prokaryotic cells—	cells without a defined nucleus, e.g., bacteria
Protease—	an enzyme that degrades proteins
Protoplanetary disk—	another term for the solar nebula at the time it was flattened into a disk, or an analogous disk from which a single planet (e.g., Jupiter) and its satellites were formed
Secular resonance—	occurs where the frequency for an asteroidal orbital precession rate matches a main frequency for planetary eccentricities in Brouwer and van Woerkom's secular theory
SNC meteorites—	achondrites that originate from Mars
Sterilization—	the destruction of all living microorganisms including vegetative forms and spores
Stickney—	the largest crater on Phobos
Tektites—	glassy meteorite-like objects formed when the ejecta of large terrestrial craters was lofted above Earth's atmosphere and then reentered
Tidal heating—	heating of a planet or satellite as a result of the work performed on the object's materials by the flexing due to gravitational interactions between bodies
Trojan asteroids—	asteroids located at the 1/1 mean-motion resonance (commensurability) with Jupiter, librating about the L4 and L5 points 60 degrees ahead of, and behind, Jupiter in its orbit
Vibrios—	comma-shaped bacteria that are common to aquatic environments