UTRECHT STUDIES IN AIR AND SPACE LAW

Heaven and Earth: Civilian Uses of Near-Earth Space

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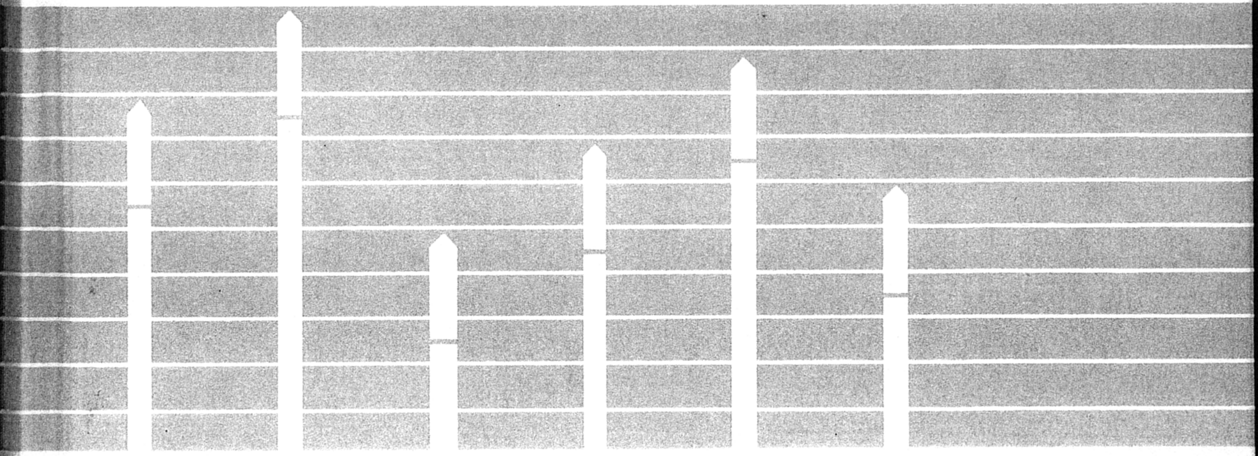
(Editors)



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CHAPTER 6

Exploration of the Universe: Science and Technology

GEORGE FIELD AND JONATHAN MCDOWELL

1. THE IMPACT OF SPACE FLIGHT ON SCIENCE

Our entry into space has changed science in basic ways. Prior to the launch of Sputnik in 1957, all scientific activities – including the study of phenomena in space – were confined to the Earth's surface, oceans, or atmosphere. By providing the opportunity to conduct experiments in space, artificial satellites have radically transformed many branches of science and led to a phenomenal increase in the pace of new discoveries. Since the dawn of the space age, the uniquely human quest to understand the Universe has expanded vigorously to encompass the study of every aspect of living things, the fundamental nature of matter, and the structure of the cosmos – from our planetary neighbors to the most distant galaxies. Consider the impact of space research on several important branches of science:

Astronomy

Before 1957, measurements of faint radiations from objects deep in space could be made only with optical telescopes, radio telescopes, or particle detectors on the ground. The available evidence indicated that the Universe is expanding, that stars form from interstellar clouds and subsequently evolve, and that they become super-dense white dwarfs or neutron stars when they die. There was no way of telling whether the Universe would continue to expand forever, how stars form, and whether theoretical predictions of black holes were correct.

After 1957, the whole electromagnetic spectrum – including the gamma-ray, x-ray, ultraviolet, and infrared bands in which radiation is absorbed by Earth's atmosphere – was opened up for study by orbiting space telescopes. Particle detectors in orbit vastly improved our knowledge of energetic particles arriving at the Earth from great distances. As a result, we now know that

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unless the Universe is dominated by invisible material of a kind unknown to physics, the Universe will expand forever. The composition of interstellar clouds has been identified by orbiting ultraviolet telescopes, newly-formed stars have been observed by infrared telescopes in space, neutron stars, and likely black holes have been observed by orbiting x-ray telescopes, and intense bursts of energy from unknown sources have been recorded by gamma-ray detectors.

Lunar and Planetary Science

Before 1957, all of our knowledge of the planets was obtained with ground-based telescopes or from meteorites which chanced to fall upon the Earth. Relatively crude values were obtained for the physical and chemical properties of the planets and it was inferred that the Earth and the meteorites had formed 4.5 billion years ago.

After 1957, it became possible to make in situ measurements near and on planets and satellites, vastly improving the data base on which to found a science of the solar system. Human exploration of the Moon and the return of lunar samples confirmed that its age is the same as that of the Earth, and revealed a complex geological history that still challenges theoretical interpretation. Robot spacecraft reconnoitering all the planets but Neptune and Pluto yielded accurate data on the masses, atmospheric composition, surface features, temperatures, magnetic fields, and other properties of the planets and their satellites. Detailed studies of Mars and Venus revealed surprises: Mars, although now extremely dry, was once awash with a liquid, presumably water, while Venus has a deep atmosphere that traps solar energy so effectively that its temperature is that of molten lead. Spacecraft have even flown through comet tails, sampling what is thought to be primordial material left over from the formation of the Sun and planets. A start has been made at reconstructing the history of the solar system, including the events that resulted in an Earth completely different from the other planets.

Solar and Space Physics

Before 1957, ground-based optical and radio telescopes revealed a wide range of solar activity, including sunspots, solar flares, and solar prominences. An inspired theorist suggested that there must be a 'solar wind' of hot gases constantly blowing into space in order to account for certain features of comet tails. Others suggested that in order to explain magnetic disturbances on the Earth following solar flares, energetic particles must also propagate to the Earth.

After 1957, the first American satellite, Explorer I, discovered the Van Allen radiation belts around the Earth, in which particles energized by solar activity are trapped; this explained the magnetic events detected earlier. The

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predicted solar wind was verified by direct measurements in space, and its intensity and speed were determined. Solar ultraviolet, x-ray, and gamma-ray telescopes in Earth orbit advanced our understanding of solar activity, showing that it is due to conversion of magnetic energy at the surface of the Sun. Optical telescopes in orbit above the disturbing influences of the atmosphere proved for the first time that the total energy coming from the Sun varies with time, with significant implications for the study of the Earth's climate. Finally, interactions of the solar wind with the magnetic fields of the Earth and other planets were measured and explained in terms of the same principles of plasma physics being used to design the controlled fusion power machines of the future.

Earth Sciences

Before 1957, geological, meteorological, and oceanographic studies were conducted by ground-based instruments such as seismometers, gravimeters, and magnetometers, as well as by instruments flown into the atmosphere and lowered into the sea. Over the years, a quantitative understanding of the lower atmosphere sufficient to permit short-range weather forecasting developed. Properties of the upper atmosphere were inferred by crude telescopic measurements. Geological sciences were well developed, but continental drift remained a speculation. The structure of the interior of the Earth had been deduced from seismology, but the distribution of mass within it was only crudely known.

After 1957, instruments were flown on orbiting spacecraft, and used for remote sensing of the solid, its oceans, and its atmosphere. The vastly increased number of measurements of atmospheric properties opened up the scientific study of the upper atmosphere, and permitted detailed numerical modeling of the lower atmosphere, and hence, improved weather prediction. The long-term effects of continental drift were verified by ground-based measurements, and the rate of drift was measured with the aid of space techniques. The gravitational field of the Earth was measured precisely from its effects on spacecraft orbits, and distribution of mass was inferred. Ocean currents on a large scale were mapped for the first time via remote sensing of the sea from space.

Life Sciences

Before 1957, the scientific community was divided concerning humans' ability to adapt to weightlessness and survive space flight. There was considerable speculation on the question of life elsewhere in the Universe.

After 1957, experiments on animals and humans in orbit demonstrated that astronauts can live and work in space for weeks or months, but that major effects of weightlessness must be better understood before longer duration spaceflights could be attempted. Probes landing on the Moon, Venus, and Mars showed that life is absent at the landing sites. Space exploration stimulated the initiation of the radio search for intelligent life beyond the solar system, with no detections as yet. Remote sensing enabled broad assessments of biota on the Earth, as well as changes in the atmosphere which are important to life.

Fundamental Physics and Chemistry

Before 1957, most fields except the study of general relativity were pursued almost entirely in laboratories on the ground. The three classical tests of general relativity suggested by Einstein were carried out using astronomical observations, and all were positive at the crude level of accuracy available.

After 1957, tracking of spacecraft by telemetry has resulted in an increase in precision of the classical tests, as well as a fourth independent test which was also positive. A fifth test, of 'magnetic' effects in gravity, is being prepared for flight aboard the Gravity Probe mission. Precise tracking of spacecraft is yielding upper limits on the intensity of gravitational radiation, which is also predicted by general relativity. Initial experiments suggest that many physical processes, such as crystal growth, occur significantly differently in the microgravity environment of Earth orbit.

2. AN EMERGING SCIENTIFIC SYNTHESIS: THE EVOLUTION OF THE UNIVERSE

Leonardo da Vinci and other scholar-scientists of the Renaissance could hope to master every branch of science, from human anatomy to aerodynamics. The explosion of scientific knowledge in succeeding centuries has transcended the limited powers of any human being, and modern scientists work at countless specialties, respecting the work of colleagues in remote fields, but being conversant only with work close to their own. As the 21st century draws near, this picture is changing, largely due to the new perspectives on nature provided by space science.

2.1 The Evolution of Life on Earth

Scientists who are today working on various aspects of space science report unmistakable synergies between long-separated sciences. For example, evolutionary biology has long pursued the hypothesis that living species have emerged very gradually, as subtle changes in the environment gave imperceptible but decisive advantages to those organisms affected by random genetic mutations. The recent discovery that the death of dinosaurs (and many other species as well) appears to have coincided with the impact of a large meteorite from outer space 65 million years ago, together with the observation of the impact of comet Shoemaker-Levy–9 on Jupiter in 1994, led to new interest in the concept of punctuated equilibrium, in which a drastic change in environment (in this case, the pall cast upon the Earth by the giant cloud of dust that resulted from the meteoric impact) can destroy some branches of the tree of life in a short span of time, and thereby open up new opportunities for genetic variants that were previously not very competitive. The story of the evolution of life on Earth – once the province of paleontology and evolutionary biology – now appears to depend on astronomical studies of small bodies in the solar system, the physics of high velocity impact, and our understanding of dust transport in the Earth's atmosphere.

2.2 Changing Conditions and the Survival of Homo Sapiens

Atmospheric scientists are finding that even on the short time scale of decades to centuries, the character of life on Earth may depend strongly on influences originating in the interior of the planet (such as volcanic dust), chemical changes in the oceans and the atmosphere (such as the increase in CO_2 due to human agricultural and industrial activity), and radiations reaching us from the Sun (such as the ultraviolet rays from solar active regions, which affect the chemical composition of the atmosphere). Through mechanisms still not understood, changes in the Earth's climate and the complicated interrelationships between living species also play major roles in the evolution of life. It has become apparent that life on Earth survives in a complex and delicate balance not only with its own diverse elements, but with the Earth itself, the Sun, and perhaps even the Moon. Climatology, geology, ecology, and solar physics are becoming connected in ways never before perceived or anticipated.

2.3 Planets and Life Beyond the Solar System

Are we alone in the Universe? This question has recurred with increasing frequency ever since Giordano Bruno was burned at the stake in 1600 for answering 'no' to this question. Astronomy teaches that our Galaxy is the home of countless stars like the Sun, and that virtually all of them are composed of the same chemical elements as are the Sun, the Earth, and other planets. There seems to be no reason why planetary systems resembling our own should not be scattered everywhere throughout space; our theoretical understanding of the process by which the solar system formed gives no special place to the Sun, but instead suggests that all Sun-like stars are likely locales for planets. Until recently we had only one example of a planetary system, but the Infrared Astronomical Satellite launched by NASA, the Netherlands, and the United Kingdom in 1983 unexpectedly discovered clouds of particles surrounding dozens of stars, much like the clouds predicted by theorists to be one stage in the formation of planets. Subsequent astronomical studies have confirmed and extended these findings, and it is becoming clear that planetary science and astronomy have much to teach each other. And if the theory for the origin of life based on the evolution of large molecules in the oceans of newly formed planets is correct, the planets scattered throughout the Galaxy will be inhabited by living species, some of which may possess something akin to what we call intelligence. Plans are being made to use telescopes in space to detect planets around distant stars and perhaps even to determine the presence of chemical compounds on their surfaces that would point to the existence of life, with important implications for biology. If that life has evolved to intelligence, it should be possible using large radio telescopes to detect radio signals it emits. Such a detection, if it ever occurs, would have profound implications not only for biological science, but also for anthropology, political science, and even philosophy and religion.

2.4 Beginnings: the Big Bang

The 1922 demonstration that Einstein's equations of general relativity imply that the Universe should be expanding from its origin in an explosion – a 'Big Bang' – anticipated the actual discovery of the expansion by seven years. Theory also led observation when scientists in 1948 predicted that the Universe should now be bathed with radio waves emitted during the Big Bang. It is strange that this prediction was not followed up immediately by experimentalists; the epoch-making discovery of the cosmic microwave background radiation was not made until 1965, and even then it was discovered quite by accident.

Recently theorists have made another prediction about the Universe. Based on the so-called 'grand unified theories' of particle physics, it appears that the matter content of the Universe is precisely that required by a unique and special cosmological model – that which will continue to expand forever but with ever-decreasing speed, reaching infinite size just when the expansion speed falls to zero. This remarkable prediction has already stimulated considerable discussion and activity among observational astronomers. The amount of matter required is 100 times that actually observed in the inner parts of galaxies, and ten times more than has been determined to be present in the normal form of protons, electrons, and neutrons, both inside and outside of galaxies. If the grand unified theories are correct, therefore, astronomers so far have missed most of the mass of the Universe; they are currently scrambling to carry out experiments aimed at finding the 'missing mass.' In this search, physicists are playing a leading role by searching for black holes (which are themselves invisible, but which carry mass), by studying the images created by gravitational lenses in space (which could be galaxies made of strange, invisible matter), and by initiating new techniques in particle physics to test the relevant theory.

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2.5 Galaxies and the Universe

When we look into space with big telescopes, we see millions of galaxies; their distribution suggests that there must be 100 billion or more galaxies in the entire observable Universe. Galaxies seem to be more or less the same wherever we look, and it seems justifiable to regard them as the building blocks of the Universe. But why are galaxies billions of light-years apart so similar, and why are there the numbers of them that we observe? Such questions relate to the evolution of the Universe as a whole. We know that there was a Big Bang at the origin of the Universe some 10 to 20 billion years ago, and that before the Universe was 100,000 years old, it was too hot for the matter to condense into galaxies. From study of the microwave background radiation, we know that at that time, the matter in the Universe was distributed remarkably smoothly, with about one part in 100,000 deviation from perfect smoothness. Yet the galaxies around us today represent million-fold localized variations in the amount of matter. How are we to account for this?

According to current versions of grand unified theory, when the Universe fell to a temperature of 10^{28} degrees some 10^{-35} seconds after the Big Bang, the matter present underwent a transition from one type to another, something like the melting of ice to form water. The strange new matter caused the expansion of the Universe to change its character. During a very short period, in which its age increased only tenfold, the Universe inflated in size by a factor of 100 billion billion. As a consequence, all the matter observed today by astronomers out to the utmost limits of their instruments was once in a region much smaller than an elementary particle. This enabled all parts of the Universe to interact readily with one another, providing an explanation of how the cosmos today appears to be so similar in all its parts, even through they cannot any longer interact because they are so far apart. It is as if all the people on Earth had for a brief period been students in the same one-room schoolhouse, so that their shared childhood experiences would have led to a more homogeneous society.

This so-called 'inflationary' cosmology may hold the answer to the 'missing mass' problem discussed in the previous section. As much as 90% of the matter in the Universe may be in the form of strange particles like 'axions' or 'photinos' left over from the inflation. Quantum-mechanical effects would give rise to small variations in the amount of strange matter such that thousands of years later it would collapse under its own gravitation to form 'shadow galaxies' – objects somewhat more massive than the galaxies we see, but totally invisible. Then, the theory goes, the ordinary matter – a mere 10% of the total – would fall into these objects, forming the stars we observe in normal galaxies today.

2.6 Formation of the Chemical Elements

While the course of events during the first second of the Universe's existence is still not well-established, astrophysicists are fairly clear about what happened subsequently. The very first generation of stars to form included some massive stars that used up their hydrogen fuel rather quickly, and successively burned in nuclear fires the helium ashes thus produced to form carbon, oxygen, magnesium, silicon, iron, and other heavier elements. An instability at the end of this process caused a giant explosion (of the type we see in other galaxies, called a supernova), spewing the freshly-formed nuclei of heavy elements into space, where they were incorporated into interstellar clouds from which new stars later formed.

Succeeding generations of stars thus contained small amounts of elements heavier than helium. These 'metals' were crucial to the formation of Earth-like planets (which consist largely of iron, magnesium, oxygen, and silicon). Even closer to home, carbon, nitrogen, and oxygen (along with the primordial element hydrogen) are the dominant constituents of life. It seems, therefore, that formation of life on Earth required explosions early in the life of our Galaxy. Astronomers are building space instruments that can detect supernova explosions at such great distances that the galaxies in which they are taking place are still relatively young (because of the large light-travel times involved), thereby observing this step in the evolution of cosmic matter.

2.7 Cosmic Evolution – a Grand Synthesis

It is becoming clear that the entire Universe has evolved in an understandable way to the point we see it today, with billions of galaxies and countless stars and perhaps countless planets. There seems to be no evidence that the path of evolution from elementary particles to galaxies to stars to heavy elements to planets and life differs significantly anywhere in the Universe and the physical reality with which we are confronted is in essence beautifully simple.

From this perspective, each of the sciences has its contribution to make to the study of the evolution of the Universe. Particle physicists study the fundamental nature of matter created in the Big Bang. Astrophysicists track the behavior of these particles as they form galaxies, and seek young galaxies and exploding stars at great distances from us. Nuclear physicists study the reactions that led to the creation of heavy elements in stars. Condensed-matter physicists tell us how these heavy elements formed small particles in space – the precursors of planets to be formed around second-generation stars. Planetary scientists infer how planets formed and evolved from studies of their present composition and structure, while geologists, atmospheric scientists, and oceanographers chart the complex interactions by which plate tectonics and volcanic emission of gases on Earth led to our present oceans and atmosphere. Chemists study how complex organic molecules formed in the newly-formed oceans, and molecular biologists study how the DNA 'double helix' makes it possible for living matter to use the energy from the Sun to maintain and develop the complex chemical systems we call life. Even social scientists become involved by studying how certain species developed intelligence, and how intelligent individual organisms cooperated to establish social structures.

As the Universe has become able, through consecutive evolutionary steps, to contemplate itself, we humans stand in awe at the majesty of creation and evolution. Can there be a grander perspective than the development of life from the fires of the Big Bang? Can there be a greater challenge than to use our ability to fly in space to fulfill our dream of understanding the Universe and our role in it? This is the goal of the space science program.

3. A Program for the Future

Studies by the National Academy of Sciences attempt to identify the pressing, fundamental questions facing scientists at this point in history – those questions, that, if answered, would lead to dramatic advances in our comprehension of the world around us. The consensus of several recent studies has been that the time is ripe for an aggressive space science program aimed at understanding the evolutionary processes in the Universe that led to the emergence – and survival – of life. Herewith is a list of questions distilled from Academy reports grouped so as to make evident the interactions of various fields that will be required to address the problems:

- What are the fundamental laws of physics that govern the Universe, particularly the early Universe, the formation of galaxies, the formation of neutron stars and black holes, and the large-scale processes that cannot be studied on Earth?
- How do stars and planets form? How did the Sun, planets, satellites, and small bodies of the solar system form, and how have they evolved?
- How does energy flow from the interior of the Sun through its outer layers and into interplanetary space? How does it interact with the planets? Does the solar output vary enough to influence Earth's climate? If so, what mechanisms are important?
- What are the composition, structure, and dynamics of the interior and crust of the Earth, and how did they form and evolve?
- What are the structure, dynamics, and chemistry of the oceans, atmosphere, and cryosphere, and how do they interact with the solid Earth?
- What is the origin, evolution, and distribution of life in the Universe? What interactions with its environment sustain life on Earth?
- What effects does life – including human activities – have on the composition, dynamics, and evolution of the oceans, atmosphere, and crust of the Earth?

- How do different levels of gravity affect physical, chemical, and biological processes?

Given the remarkable progress science has made since the launching of the first artificial satellite, the utter simplicity of many of these questions may be surprising. But it is for this very reason that the potential rewards of continued space science research are so great. Below we describe some of the current and projected programs which will try and address the basic questions just described. There are many other worthwhile missions underway or under consideration, which we omit for reasons of space.

3.1 A Research Mission to Planet Earth

For the first time in history it is possible to study the entire Earth, from its core to its outer atmosphere, both as it is now and as it has been over the eons, because of advances in the technology of observing systems and computers. Moreover, such a study is conceptually feasible because of advances in theoretical understanding. NASA's Mission To Planet Earth is being undertaken to study the Earth as a system, just as missions to other planets have revealed their key properties.

It is essential that studies of the Earth be carried out with the greatest possible interaction with studies of other planets, for the formation of all the planets from the same common reservoir of gas and dust orbiting the Sun means that insights into the origin of any planet throws light on the origin of all. Moreover, processes now observed on other planets could well have happened on Earth long ago.

The Mission to Planet Earth is based on a strategy of observations, data handling and research markedly different from that prevailing in the past, owing to the necessity of an integrated approach to the whole problem.

Many but not all measurements are best done using satellites orbiting the Earth. Global and simultaneous coverage are essential to many of the observations, and the observing system must produce continuous and consistent records over long periods of time. The cornerstone of the Mission To Planet Earth is the EOS (Earth Observing System) project, a series of satellites to be launched beginning in the late 1990s into polar orbit. These medium-sized satellites will be supplemented by smaller satellites in the Earth Probe series carrying single instruments. In addition, meteorological satellites in geostationary orbit will provide continuous, global observation of basic atmospheric parameters.

Early launches providing data for Mission To Planet Earth include the Upper Atmosphere Research Satellite, which since 1991 has studied the 'middle atmosphere,' comprised of the stratosphere, the mesosphere and the lower thermosphere. UARS will be succeeded by EOS satellites in sun-synchronous orbits. These satellites will orbit in pairs, each at a fixed angle to the dawn/dusk terminator. These satellites will define the different responses to solar-terrestrial events in the northern and southern hemispheres, carrying out remote sensing of winds, temperature and composition.

The International Space Station will provide excellent opportunities for probing the upper atmosphere, and the Tethered Satellite System deployed from the Space Shuttle would allow measurements as low as 120 kilometers, a region only intermittently probed by sounding rockets.

The study of the environment near the Earth requires not only major missions of the type described above, but also smaller scale activities that provide rapid access to space by small groups of investigators, including students. This includes Small Explorer and Earth Probe class missions dedicated to solar and space physics, Spartan-class experiments deployed and retrieved by the Space Shuttle, and balloons and sounding rockets.

Ground-based in situ instruments will be required to measure effects that cannot be detected by remote sensing from space, to provide high spatial resolution over limited areas, and to calibrate and verify observations from space. The number of sites involved ranges from a few hundred to tens of thousands, depending on the nature of the problem under study.

The extremely high volume of data will require data processing of the highest capacity, as well as a significant degree of automation and adaptability of decision making as to which data are important and which data are discarded. Theoretical modeling using the most advanced computers will be essential, as will be the increased degree of interaction between modeling and observational activities made possible by improved communications. The goal is to enable an earth scientist to follow a phenomenon through its entire evolution and reproduce it in a model. This is essential if we are to achieve understanding and, in key instances, the ability to predict the consequences of a perturbation in the system such as an earthquake, volcanic eruption, or hurricane. The Mission To Planet Earth will form part of a larger, international effort to study the planet from space; for instance a TOMS (Total Ozone Mapping Spectrometer) payload flew as a piggyback experiment aboard a Russian Meteor satellite in 1991–1994. NASA's NSCAT scatterometer will fly aboard a Japanese earth observing satellite, ADEOS 1, planned for launch in 1996.

3.2 Life sciences in Earth orbit

The Mission to Planet Earth is geared primarily toward providing a better physical understanding of our planet, but it will include many measurements of interest to life science as well. A vigorous and systematic study of the structure, dynamics and evolution of the biosphere (i.e. living organisms and their interaction with the solid Earth, oceans, atmosphere and cryosphere) from Earth satellites and the Space Station will be an important scientific innovation of the next century. There is particular interest in quantities that are changing rapidly because of human activity, for example the concentrations of ozone and carbon dioxide in the atmosphere.

Of critical importance to the question of early evolution of life on Earth is the continued search for and analysis of microfossils from the earliest possible epoch. This work should be backed up by continued laboratory studies of the synthesis of key biological molecules under conditions approximating the primitive Earth, as well as by chemical analysis of meteorites and in situ study of chemical processes on planets, asteroids, comets, and satellites. In view of the evidence that collisions with asteroids and/or comets had severe effects on the biosphere, astronomical studies of such objects, and continued geological studies of their effects are crucial.

The study of the biology of organisms in space is vitally important if we are ever to exploit the potential of long-duration space flights with astronauts on board, either in Earth orbit or on missions to other planets. The environment for living things in space differs from that on the ground with respect to the strength of gravity, atmospheric pressure, and radiation fluxes. Our knowledge of the effects of these factors is still primitive. With the large amount of time and laboratory volume available for experiments on the Space Station, we expect major improvements in our understanding. Specifically, it will be possible to vary gravity from 10–5 to greater than 1 Earth gravity using centrifugal force in a rotating system, and pressure can be varied from essentially zero to several atmospheres. Radiation fluxes are harder to control without substantial shielding, and pose potential problems both to the survival of organisms and to the interpretation of data.

Of paramount practical importance is human performance and safety. The Russians have had people in space for up to a year and half at a time, and have demonstrated the ability of humans to live and work in orbit. Flights of up to 90 days on the Space Station, with its wider-ranging instrumentation and measurement collection, will permit understanding of the effects of the space environment on the cardiovascular system, dysbarism, space adaptation syndrome, and life support that is sufficient to allow extended flights with a reasonable margin for safety. The problem of loss of bone substance and muscle mass is more persistent, and it is unlikely that an effective empirical solution will be found soon. Therefore, basic research on this problem should continue, both on the ground and in space.

As opportunities for longer flights become available, it should be possible to undertake them on an incremented basis with careful monitoring and evolution of subjects. This will require more detailed monitoring of the environment than in the past, including radiation exposure, environmental toxicology, nutrition as it affects performance, microbial environment, epidemiology, functioning of the body's defense mechanisms, and dynamics of interpersonal interaction in a closed environment.

Health-care delivery must be developed as well. This will be a major issue as plans are made to send astronauts to the planets; rapid return to Earth concentrations

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will be virtually impossible. As little is known of the dynamics of drugs administered in a space environment, the evaluation of even a small 'space pharmacopoeia' will be a major undertaking; similar remarks apply to surgery under microgravity conditions.

There is a wide array of biological problems that have little direct bearing on human performance or safety, but that will nevertheless be addressed by research in space. The vestibular system – the part of the central nervous system concerned with bodily orientation – evolved over long periods under Earth-gravity conditions. Studying its response in detail to microgravity should yield much more information about the central nervous system. This will require mammals (including primates) and facilities for their long-term care, as well as a centrifuge and, if possible, a sled to produce variable accelerations. Experiments should also be undertaken on the sensitivity to gravity of both plants and animals, some of which may be manifested only over long periods of time. To accomplish the goals of life science in space will require space-station facilities for animal care and husbandry, for chemical and other types of analysis, and for neurobiological research focused initially upon the vestibular function. In view of the constraints imposed by limitations in volume, weight and power, it is important that equipment be utilized for multiple purposes wherever possible. Fortunately, facilities which are essential for health-care delivery can be adapted for basic research as well.

3.3 Physics and Chemistry in Earth Orbit

The Space Station will open up opportunities to do a variety of fundamental experiments which are impossible in Earth gravity. For example, a Nobel Prize-winning theory predicts the properties of substances as they pass through their critical points, or cooperative phase transitions. In one such experiment, the heat capacity of liquid helium is measured as it makes a transition to the superfluid state. Although apparatus has been developed to hold a sample at a steady temperature within one part in 10 billion, the variation of pressure through the sample due to gravity is so large that the experiment yields far less accurate results than it could. Reducing gravity by a factor of 10^5, as is possible in the Space Station, will provide a high-quality test of the theory.

In another example, research is proceeding on 'fractal aggregates,' structures which have the remarkable property that their mean density literally approaches zero the larger they become. Such structures are neither solid nor liquid, but represent an entirely new state of matter. So far experiments on such structures are limited by the fact that they tend to collapse under their own weight as soon as they reach 0.01 millimeters in size. In a microgravity environment, they can reach 10^5 times larger, or 1 meter. Such sizes are essential if measurements of physical properties of fractal structures are to become possible.

Research on many other processes, including fractal gels, dendritic crystallization (the process which produces snowflakes), and combustion of clouds of particles will profit substantially from the microgravity environment of the Space Station. It is not unlikely that novel applications will develop from basic research in these areas; one should keep in mind the transistor, which grew out of basic research on the behavior of electrons in solids. It will be important in developing such research to provide flexible and rapid access to a microgravity facility for researchers who in the main will continue to devote the bulk of their effort to ground-based research in normal gravity.

An especially promising avenue of research in space is the pursuit of new tests of Einstein's theory of general relativity. It has long been recognized that because deviations from the Newtonian theory of gravitation within the solar system are minute, extremely sensitive apparatus are required to detect them. Many experiments require the quiet conditions of space. Because Einstein's theory is fundamental to our understanding of the Universe – in particular, to the physics of black holes and the expanding Universe – it is important that it be experimentally verified with the highest possible accuracy.

The curvature of spacetime is manifested by a small time delay of radio signals as they propagate in the solar system. Using the Viking Mars landers, the time delay has been tested to one percent. The Mercury Orbiter proposed for planetary research would improve upon the accuracy of measurement of changes in Newton's gravitational constant achieved with the Viking landers (less than one part in 100 billion per year).

The gravitational redshift has been tested by a very accurate clock on a suborbital flight (Gravity Probe A) to one part in 10,000. Theory predicts that the rotation of the Earth will distort spacetime in its vicinity in somewhat the same way as a magnet acts on electrical currents. This prediction will be tested by Gravity Probe B, which measures the precession of a gyroscope in Earth orbit with extreme precision. A systems test on the shuttle should be followed by a free flyer capable of measuring the effect with 1% accuracy.

Einstein's theory also predicts a unique phenomenon called gravitational radiation, which has not yet been detected. It is produced by masses in motion – for example, by two stars orbiting one another – and by matter collapsing into black holes. Two neutron stars orbiting one another have been shown to be spiraling inward just as predicted if they are losing energy to gravitational radiation.

There is great interest in detecting such radiation, not only because it would test Einstein's theory in a fundamental way, but because it could open a new window through which to study phenomena in the Universe, particularly black holes. Predicted amplitudes of gravitational radiation range from 10^{-18} to 10^{-15} depending upon the period of the wave. Many detectors are in operation or are being built on the ground, but are sensitive only to wave periods less than 0.1 seconds because of seismic noise from the Earth. The radiation predicted from astronomical objects includes longer periods from

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orbiting double stars and black holes with masses above 10^4 suns such as are believed to exist in the nuclei of galaxies. Such radiation can be detected by ranging precisely to spacecraft orbiting the sun. A powerful approach would use a large baseline detector based upon optical laser ranging between these spacecraft in orbit about the sun to detect the minute changes in their separations which would result from gravitational waves.

Finally, instruments deployed for more general purposes can make very worthwhile measurements. For example, a 10-meter optical interferometer in Earth orbit designed for extremely accurate determination of stellar positions could measure the relativistic bending of light by the sun with unprecedented precision. And Star Probe, a mission which plunges close to the sun to study plasma in its vicinity, would measure the gravitational redshift of the sun to high precision. In summary, a variety of experiments on the shuttle and Space Station, in free flyers, and in orbit around the sun and other planets have the capacity to test general relativity to high accuracy. The same theory predicts gravitational radiation from astronomical sources which must be detected in space. When that happens, astronomers will have a new tool with which to study the Universe.

3.4 Astronomy and Astrophysics

The astronomical method is to collect the faint electromagnetic signals from objects in the Universe (as well as cosmic-ray particles from space) using sensitive telescopes at wavelengths appropriate for the object or process under study. To answer the fundamental questions posed earlier requires the study of objects ranging from interstellar dust clouds (for which radio and infrared techniques are most appropriate) to black holes in quasars (for which x-ray and gamma-ray telescopes are required).

To observe celestial, infrared, ultraviolet, x-ray, and gamma-ray radiation, instruments must be launched into space; the Earth's atmosphere is opaque at these wavelengths. Optical and radio astronomy also stand to gain much from space observations – optical astronomy by eliminating atmospheric blurring of the image that plagues ground-based observations, and radio astronomy by providing extremely long baselines for ultra-high resolution interferometers. Astronomical instruments in space can be located in low Earth orbit (LEO), highly elliptical Earth orbit (HEO), geosynchronous orbit (GEO), solar orbit (SO), or even on the surface of the Moon. With a few notable exceptions, most have so far been in LEO, but HEO and SO missions have gained greater consideration in recent years and seem likely to become common, as the operational observing advantages seem to outweigh the advantages of expensive refurbishment by the Shuttle and Space Station.

Virtually the whole electromagnetic spectrum has already been explored using relatively modest space instruments. NASA has now orbited two major facilities (the Gamma-Ray observatory, GRO, for gamma-ray observations, and the Hubble Space Telescope, HST, for visible-light and ultraviolet observations) which will have long lives in orbit, and which will require manned maintenance and refurbishment from the Shuttle and, later, the Space Station. Two additional long-lived facilities, the Advanced X-Ray Astronomy Facility, AXAF, and the Space Infrared Telescope Facility, SIRTF, complete a series of four Great Observatories that will permit the study of faint and/or distant objects at wavelengths across the entire spectrum. AXAF is scheduled for launch in 1998 and SIRTF may fly early next century.

The Great Observatories will address virtually all the major questions now challenging astronomers and astrophysicists. It is impossible to list here the many projects that will be carried out with these powerful orbiting facilities. What follows is a brief list of representative programs included merely to illustrate the capabilities of HST, GRO, AXAF, and SIRTF.

Within the solar system, HST has imaged the outer planets with resolution comparable to that attained by the Voyager flybys. SIRTF will discern the composition of asteroids, comets, and planetary atmospheres. Stars in the process of formation also will be targets for SIRTF, and young, magnetically active stars will be studied by both HST and AXAF. HST, GRO, and AXAF are all well suited to discover and study the end products of stellar evolution in our Galaxy – the white dwarfs, neutron stars, and black holes that are the collapsed remnants of such stars. Both AXAF and GRO will study the emission by superheated gases which are about to be swallowed by stellar black holes. Very distant galaxies and quasars will be targets for all four orbiting telescopes. The most distant objects, which we observe as they were very early in the evolution of the Universe (due to the finite speed of light and the great distances involved), will be sought by every possible means.

The size of the Great Observatories reflects the limitations on weight, size, and power of facilities that can be launched into Earth orbit by the Shuttle. The Shuttle and the Space Station will provide the capability to repair and refurbish the low orbit HST on a regular basis, enabling it to operate over a decade or more.

Further into the future, the permanently occupied Space Station will furnish a vitally important new capability to astronomical research – that of assembling facilities in space that are too large to be accommodated in a single Shuttle launch. Radio telescopes 25 meters in diameter are commonly used on the ground, and optical/infrared telescopes up to 10 meters in diameter are under construction on the ground; neither could be launched by the Shuttle. There are two goals of such large facilities – to increase sensitivity by increasing the area over which radiation is collected, and to increase angular resolution using the principle of interferometry, in which the sharpness of the image is proportional to the largest physical dimension of the observing system. Though one or the other goal will usually drive the design of any particular instrument, it is usually possible to make improvements in both areas simultaneously.

When it becomes possible to construct large facilities in space, both objectives can be achieved over the whole electromagnetic spectrum. Although there are some advantages to constructing such facilities on the Moon (rigid base, freedom from contaminants, longer nights, shielding from Earth light and radio interference), the additional cost involved is substantial with the present space infrastructure. We therefore focus the remaining discussion upon facilities in Earth orbit.

A Large Space Telescope Array composed of eight 8-meter optical-infrared telescopes mounted on a rigid structure would operate in the ultraviolet, visible, and infrared. The combination of increased size of each telescope with the large number of telescopes would make this instrument 100 times more sensitive than HST. Because the image would be three times sharper, the limiting faintness for long exposures would be even more than 100 times that of HST. Such an instrument would enable detailed studies of the most distant galaxies, and studies of planets with exquisite angular and spectral resolution. A smaller array of telescopes mounted on a rigid structure and using a null interferometer technique could be used as an effective tool to directly image extra-solar planets in the infrared. This mission concept might require the array to be placed in the outer solar system, beyond the infrared emission associated with interplanetary dust.

A set of 100-meter radio telescopes could be constructed in Earth orbit by astronauts as part of a very long baseline array to observe radio sources, with the radio signals transmitted to a ground station. Such radio telescopes in space could greatly extend the power of the ground-based Very Long Baseline Array now under development. The angular resolution of the latter, 0.3 milliarcseconds (the size of a dime in Washington as seen from Tokyo) could be improved 300-fold by putting some telescopes in orbits ranging out as far as 1 million kilometers. The resulting microarcsecond resolution would enable us to image activity in the center of our Galaxy – which is believed to be due to a black hole – down to a few Schwarzchild radii of the hole. It would also provide images of more massive black holes at distances as large as 10 million parsecs within which there are several exploding galaxies.

A long-baseline optical space interferometer composed of two or more 8-meter telescopes separated by 100 kilometers would also provide microarcsecond resolution, although not fully synthesized images. This resolution would permit us to detect the motion of a nearby star due to the pull of a planet no larger than the Earth, and to measure the gravitational deflection of light by the Sun as a high-precision test of general relativity.

Planned x-ray telescopes (such as AXAF) have limited apertures and, hence, limited sensitivity. A Very High Throughput X-Ray Facility could be assembled in orbit having about 100 times the collecting area of AXAF. This would permit detection of very faint objects, such as supernova explosions in distant galaxies, and high spectral resolution on brighter objects, permitting a study of x-ray lines which are diagnostic of the composition, temperature, and motion of the emitting gases. For example, the theory that most of the heavy elements are produced in supernovae could be tested by study of the gaseous ejecta in supernova remnants.

A Hard X-Ray Imaging Facility with a large (30 m^2) aperture is needed to study x-rays from 10 KeV to 2 MeV. Sources of such radiation are known, but are too faint for smaller-aperture instruments to analyze in detail. It is important to discover the cause of a faint background radiation at these energies which is apparently coming from very distant objects. Do these objects belong to some already-identified class, such as quasars, or are they of an entirely new type, such as gas clouds heated by supernova explosions accompanying galaxy formation?

The future development of gamma-ray astronomy, based on the results of GRO, show that larger collecting areas and higher spectral and angular resolution will be needed to sort out sources and carry out detailed spectroscopy. Cosmic-ray studies will require a superconducting magnet in space with 30 m^2 of detectors, to determine the trajectories of individual particles, and hence their energy and charge. GRO has also renewed interest in identifying their source and nature.

If the funding climate permits, major facilities to follow the Great Observatories in the next century will push technology to its limits, including the capability of assembling large structures in orbit (or on the Moon), the design of structures that are extremely rigid and that can be tracked and moved with great precision, and the development of facilities on the Space Station for repairing astronomical devices in orbit. Because of the huge information rates anticipated with such facilities, great advances in computing will be required, especially massive data storage (up to 10^{14} bits) accessible at high rates. It is expected that on-board processors with carry out preliminary analysis of the data in orbit, transmitting only the most important data to the ground.

3.5 Study of the Solar System

The solar system is of great interest not only because it is our home, but also because it represents a so-far unique phenomenon in which small solid bodies – the planets, satellites, comets, and asteroids – are found in orbit around a central star which interacts vigorously with them. In pursuing the question of the origin and evolution of the Sun and planets, we hope one day to discover other such systems, and by comparative studies, learn more about both. In this section we shall consider the study of planets, satellites, and small bodies. The study of the Sun itself and its interaction with the planets follows in the next section.

Because we live within the solar system, we get a close-up view of what is going on. In particular, our parent star is 300,000 times closer than the next nearest star, and we can thus obtain a detailed knowledge of it which is unique. When and if planets are discovered outside the solar system, we shall always be able to find out more about the planets of our own system for the same reason.

With the advent of the space program, it became possible to make in situ measurements throughout the solar system using spacecraft which are automated and operable from Earth, as well as, in the case of the Moon, human expeditions. The Space Science Board of the National Academy of Sciences has developed a systematic strategy for this activity which has served as the scientific basis for the program. In general terms, it advocates a balanced program of reconnaissance of the different types of objects in the solar system by telescopic observation and flyby missions. This is followed up by more detailed exploration, for example by orbiters and even landers. Finally, intensive studies are undertaken as appropriate. This might involve return of a sample to Earth for analysis, or even exploration by astronauts.

The overarching goal of planetary exploration, enunciated by the Space Science Board, is to determine the origin, evolution, and present state of the solar system. Two additional goals are to better understand the Earth through comparative studies with the other planets, and to understand the relationship between the chemical and physical evolution of the solar system on the one hand, and the origin and evolution of life on the other.

The 1990s have seen a number of major planetary exploration missions. The Galileo project for the study of Jupiter grew out of plans for a Pioneer Jupiter Orbiter in the late 1970s. Galileo begins its exploration of the Jovian system in December 1995. The Magellan probe mapped the Venusian surface with radar in a highly successful mission from 1989 to 1993. The Cassini probe to Saturn and Titan is planned for launch in 1997. In the early 1990s two new series of missions were developed, the Discovery and Mars Surveyor projects.

The first Discovery mission to fly will be the Near Earth Asteroid Rendezvous (NEAR) spacecraft, which will be launched in February 1996 and rendezvous with minor planet (433) Eros in 1999. This will be followed by the Mars Pathfinder spacecraft, which will deliver a small lander and the Sojourner micro-rover to the surface of the Red Planet in 1997, and by the Lunar Prospector mission which will study the Moon from lunar orbit later that year, following up the earlier survey by the Clementine probe launched by the U.S. Department of Defense.

Following the loss of the Mars Observer probe, it was decided that a more robust approach to Martian exploration would be to launch a larger number of less capable robot explorers. NASA now plans to send two probes to Mars at each biannual launch window as part of the Mars Surveyor project. The first launch in the series is the Mars Global Surveyor, which will be launched in 1996 together with Mars Pathfinder. Mars Global Surveyor carries a camera and a spectrometer.

Another major goal of the planetary exploration program involves the return of physical samples from selected bodies for the study of solar system history and to inventory the natural resources of the solar system. With the exception of the samples returned from the Moon by the Soviet robot Luna spacecraft and the American Apollo astronauts, and meteoritic materials which have fallen naturally on Earth from , it is believed, the asteroids, the Moon, and Mars, we have no samples of materials from bodies elsewhere in the solar system that can be studied in Earth-based laboratories. Decades of study of meteoritic materials and lunar samples have demonstrated that vast amounts of information can be learned about the origin, evolution, and nature of the bodies from which samples are derived, because laboratory techniques for analyzing the chemical and physical characteristics of materials have progressed to the point that precise conclusions can be drawn from an analysis of even a microscopic sample.

The laboratory apparatus involved is heavy, complex, and in need of intimate involvement of people; thus, it does not appear to be feasible to operate it effectively under radio control on the bodies of greatest interest. There appears to be no escape from the conclusion that by far the best method is to acquire and return samples to Earth, as was done by Apollo. It is believed that robot vehicles will be the most cost-effective approach to sample acquisition and return in the foreseeable future.

The advantages of being able to analyze samples on Earth are obvious. Equally important is that, unlike meteoritic materials, the samples will be obtained from known sites, whose location in an area which has been studied by remote sensing makes it possible to generalize the results to the body as a whole. Because of the variations among different provinces, samples are required from several different sites in order to develop an adequate understanding.

One of the primary goals of sample return activity is to aid in the construction of a uniform time scale for dating events in the solar system. Much can be accomplished in this direction by counting craters on a surface if one assumes that the rate of meteoritic impact is constant over certain periods. But in fact, the rates are known to have varied by orders of magnitude, and in any case, this method gives relative, not absolute time intervals. The latter is achieved by the use of radioactive dating, which requires analysis of samples.

3.6 Inventory and Exploitation of Resources in Space

It is desirable to construct an infrastructure to enable a wide variety of activities in space. Such an infrastructure will require materials such as hydrogen and/or hydrocarbons for chemical propulsion, oxygen for propulsion and respiration, carbon and other elements for growing food, crushed rock for radiation shielding, silicon for solar cells, aluminum, titanium, and iron for fabrication, and many other materials for assorted purposes.

Because of the deep gravitational well of the Earth, it is energetically expensive to bring materials into space from its surface. Hence it may be advantageous to procure them from bodies of lower gravity: the Moon and Earth-crossing asteroids. Before this can be done, additional research must be carried out on the physical and chemical composition of the surfaces of such bodies.

Apollo exploration and sample return demonstrated that the lunar surface is composed largely of finely crushed rock whose mineralogy is not unlike that of rocks on the Earth. Because it is already crushed, material for shielding and for making ceramic materials is readily available there. However, there is no evidence that metals have been concentrated into ores anywhere on the Moon, so processes quite unlike those familiar on Earth would be required to recover the titanium (0.4– 6%), aluminum (6–14%), iron (4–14%), manganese (0.05–0.2%), magnesium (4–6%), chromium (0.07–0.3%), and oxygen (41%– 45%) in the ordinary surface rocks. Traces of carbon, hydrogen, and nitrogen have been implanted by the solar wind in the lunar soil in amounts ranging from 0.001 to 0.03 weight percent; it is not clear whether recovery by heating would be worthwhile in view of the low concentrations involved. The only places where high concentrations of hydrogen and/or carbon may occur on the Moon appear to be deep craters at the poles, where the lack of warming by sunlight could in principle have resulted in trapping of volatiles such as water and carbonaceous materials.

The Moon is not the only tempting target for resource development. From the fact that 40 Earth-crossing asteroids are known, it is estimated that some 1000 with diameters exceeding 1 kilometer may exist. Because the energy to get to such a body is about equal to that to get to the Moon, and because a single 1-kilometer asteroid contains 2 billion tons of material, such bodies could also be a useful resource, although recovery of materials in virtually zero gravity could be difficult. Offsetting this potential disadvantage is the fact that meteorites (which are believed to originate in asteroids) contain materials which would be quite useful. Iron meteorites are relatively pure alloys of iron (90%) and nickel (5–10%); a 1-kilometer asteroid of such composition would be worth about $1 trillion if it were located on the Earth. Carbonaceous meteorites, which are rather rare (4% of all fall), contain several percent carbon and several percent water (as water of crystallization).

Another important reason for studying the Earth-crossing asteroids is the danger they pose to Earth itself. The impact of comet Shoemaker-Levy-9 on Jupiter in 1994 brought home the reality of the possibility of a major impact. A network of ground based telescopes could perform a detailed inventory of all asteroids in Earth-crossing orbits down to a size range of less than a kilometer.

The first step in surveying extraterrestrial resources was the Clementine probe, which mapped the surface of the Moon in several wavebands in 1994. It provided a global map, including the poles of the Moon, of surface elemental and mineralogical composition. A Lunar Prospector probe to be launched in 1997 will detect water and other volatiles if they are present. The present program of searching for and characterizing Earth-crossing asteroids should be expanded, as should efforts to match classes of meteorites and asteroids, and to determine surface mineralogy from telescopic observations. Research into methods of material processing on the Moon or an asteroid should be supported.

Finally, a number of current technology programs could be modified somewhat so as to be in a better position to take advantage of resources in space, should they prove economically useful. For example, elements of the Space Station can be designed so that they could also be used as parts of a manned lunar base. An orbital transfer vehicle (OTV) designed for the trip from LEO to GEO and return could be modified so as to make it possible to reach the Moon or to rendezvous with Earth-crossing asteroids. Mass drivers should continue to be investigated as a means of transporting large amounts of material from the Moon or asteroids to Earth orbit. Means of supplying the approximately 1 megawatt needed to extract 300 tons of oxygen per year from lunar soil – which could be used as propellant at LEO – should be developed.

3.7 Solar and Space Physics

There are several important reasons for vigorously pursuing solar and space physics, defined as the study of phenomena that occur in and on the Sun, and in the surrounding region called the heliosphere. First, the Sun is the only star that can be studied with high spatial resolution, owing to its proximity; information about solar physics is useful in the study of all stars. Second, the regions around the Earth and planets known as magnetospheres appear to be the same phenomenon that occurs in many other places in the Universe from pulsars to quasars. Moreover, solar and space physics have important implications for Earth sciences. Variations in solar radiation may affect the Earth's weather and climate, and the precipitation of charged particles in the magnetosphere, whose energy is ultimately due to the solar wind, can disrupt the steady-state circulation pattern of the upper atmosphere, playing a role in the formation of weather systems in high northern latitudes. Finally, understanding the near-Earth space environment is vital to the proper operation of the subsystems of space vehicles, including electronic and power systems which are sensitive to the charged-particle environment. The threat of radiation to people in space outside the protective shield of the magnetosphere makes it mandatory to seek sufficient understanding to permit environmental predictions.

The objective of this field is to understand the physics of the Sun and the heliosphere, and the magnetospheres, ionospheres, and upper atmospheres of the Earth, planets, and other bodies of the solar system. With this in mind, studies of the processes which generate solar energy of all kinds and link it to the Earth should be emphasized, both because the physical mechanisms involved are of basic interest, and because there are potential benefits to life on Earth.

This grand objective includes various subgoals: the processes which link the interior of the Sun to its corona; the transport of energy, momentum, plasma, and magnetic field through interplanetary space by means of the solar wind; the acceleration of energetic particles on the Sun and in the heliosphere; the Earth's upper atmosphere as a single dynamic, radiating, and chemically active fluid; the effects of the solar cycle, solar activity, and solar-wind disturbances upon the Earth; the interactions of the solar wind with solar-system bodies other than the Earth; and magnetospheres in general. Without presupposing any specific direct connection, the possible influence of solar-terrestrial connections upon the weather and climate of the Earth should be clarified.

A number of near-term activities will contribute to the advancement of solar and space physics. The joint ESA/NASA Ulysses spacecraft was launched in 1989 and used the gravity of Jupiter to enter a polar solar orbit, flying out of the ecliptic. In 1994–1995 it made measurements of the activity at the poles of the Sun, showing that the solar wind at high latitudes has different properties from the equatorial wind and travels at higher speed. The outer heliosphere is being investigated by Voyager 1 and 2 as well as by the Pioneer 10 spacecraft launched in 1972 and now sixty astronomical units (the earth-sun distance) from the Sun. The twenty-one year long series of scientific investigations with the Pioneer 11 probe recently came to an end as its power levels became inadequate to support the instruments. In the next few years, it is hoped that Pioneer 10 and the Voyagers will detect the heliopause, the transition region where the solar wind flows into the interstellar medium. The location of this region is an outstanding piece of basic information about stellar systems which is currently unknown.

The Global Geospace Science program, with joint American and Japanese participation, is to study the flow of matter and energy, from the solar wind through the Earth's magnetosphere into the upper atmosphere; investigate the origin, entry, transport, storage, energization, and loss of plasma in the Earth's neighborhood; and assess the importance to the terrestrial environment of temporal variations in the rate of deposition of energy in the upper atmosphere. It consists of three spacecraft: Geotail and Wind, which are orbiting the outer magnetosphere of the Earth-Moon system; and Polar, at this writing awaiting launch into a low polar orbit. The four European Cluster satellites will also probe the properties of the solar-terrestrial interface, while the Advanced Composition Explorer will study the isotopic composition of the solar plasma and of cosmic rays.

Interactions of solar plasma with planets, satellites, and comets were investigated by the Soviet, Japanese, and European encounters with Comet Halley in 1986, by the Voyager encounter with Uranus in 1986 and with Neptune in 1989, and by the Pioneer Venus Orbiter in the 1980s. More data will be provided by the forthcoming Galileo encounter with Jupiter in 1995, and the planned Cassini encounter with Saturn and Titan early next century.

Up to the present, information about the Earth's magnetosphere has been based upon measurements made continuously as various spacecraft move through the plasma and magnetosphere field in that region. Consideration is being given to the possibility of obtaining a global image of the entire magnetosphere using ultraviolet emission at 304 ångstroms from ionized helium in the low-temperature plasma located in the magnetosphere. Ten-minute 'snapshots' of the emissions having a resolution of 100 kilometers would be obtained by optical instruments located at a convenient place near the Earth, such as the Moon or one of the Lagrangian points. It may also be possible to form an image of more energetic plasma by observing energetic neutral atoms as they propagate from various regions, having charge-exchanged with plasma ions there.

Innovative experiments will be conducted from the Shuttle to investigate the effects of waves, plasma beams, and neutral gases injected into the Earth's magnetosphere. The dynamics of the thermosphere were investigated by the Dynamics Explorer 2 satellite as well as by ground-based methods, and the middle atmosphere is being studied by the Upper Atmosphere Research Satellite (UARS) launched in 1991.

Up to now, our knowledge of the outer atmosphere of the Sun has been based upon remote sending from distances comparable with the distance of the Earth. In a new concept called Star Probe, a spacecraft would be sent on a trajectory coming to within 4 solar radii of the surface of the Sun, only 1/40th of the Earth's distance. The spacecraft would carry instruments to measure the density, velocity, and composition of the solar-wind plasma, together with its embedded magnetic field, in an attempt to discover where the solar wind is accelerated to the high velocities observed near the Earth. Possible trajectories include a Jupiter swingby or a hypersonic flyby in the upper atmosphere of Venus. Such a mission would yield vital data on the gravitational field of the Sun (used to study its interior), and would test general relativity with higher precision. If a thruster were fired at the closest approach to the Sun, the energy change would be great, and the spacecraft would leave the solar system at great speed, reaching 100 times the distance of the Earth in only nine years. Measurements in this region would address the question of where the solar wind is stopped by the local interstellar medium.

Ulysses initiated observation of phenomena at the poles of the Sun; to acquire high-resolution data over a long period, a Solar Polar Orbiter with the ability to point instruments precisely at targets on the Sun could be flown. One ESA study considered a complementary mission called the Heliosynchronous Orbiter, which would have orbited the sun synchronously with its 25-day rotation period at a distance of 30 solar radii. A network of four spacecraft at the distance of the Earth but positioned every 90 degrees around the Sun would accomplish two objectives: it would provide stereoscopic views of

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solar features which are otherwise difficult to locate in space, and would also monitor solar flare events over the whole Sun. In addition to achieving important science objectives, such a network would give early warning to any astronauts outside the protective shield of the Earth's magnetic field. In another direction, high angular resolution of solar features can be achieved by diffraction-limited optics operating in the far ultraviolet or even the X-ray regime.

Finally, we consider plasmas in space. Plasma is an inherently complex state of matter involving many different modes of interaction among the charged particles present and embedded magnetic fields. Our understanding of the plasma state is based upon theoretical research, numerical simulations, laboratory experiments, and observations of space plasmas. Additional complex phenomena occur if not all the gas is ionized (so that neutral atoms are present) and if dust particles are present (as in planetary ring systems and in comets). It is important to study these phenomena, perhaps by injection of neutral gases and dust particles into space plasmas. Injection of plasma beams and radiation will also advance our understanding of the pure plasma state. The U.S. CRRES mission in 1990–1991 injected ions into the magnetosphere to create artificial plasma tracers, while the Russian Aktivniy and Apeks missions used active plasma beams.

3.8 The Search for Extra-Terrestrial Life

The space age has transformed the search for life in the Universe from the idle musings of a few eccentric natural philosophers to the forefront of modern, high-technology scientific research. Sophisticated radio telescopes are listening for signals from alien civilizations, and robot spacecraft have already examined the soil of another planet for signs of biological activity. When we think of extra-terrestrial life, we usually conjure up images of intelligent, human-like creatures on planets around distant stars. But the search for life beyond Earth begins in our own cosmic back yard – the solar system.

Mars, slightly more than half the size of the Earth, has often been proposed as a possible abode of life. Although its average temperature is much lower (–400° Centigrade) than the Earth's, the presence of polar caps which change with the seasons suggested to some the presence of an atmosphere and conditions which could support life. Speculation that there is life on Mars reached a zenith early in this century, when Percival Lowell announced the 'canali' (channels) reported earlier by the Italian astronomer Schiaparelli must be great engineering works of an advanced civilization. Thus in the public mind the possibility of life in some form became a near certainty of intelligent life.

The detailed images sent back by NASA's Mariner spacecraft from 1965 to 1971 forever laid to rest such fantasies. Mars is a complex and fascinating world, but there are no canals constructed by an advanced civilization. Instead, the surface displays craters like those on the Moon and Mercury, showing that large areas have suffered no major changes since early in the life of the solar system. Mars also has volcanic craters showing that it may have gone through a period of vigorous volcanism which released water vapor and other gases from the interior which on the Earth formed the atmosphere and oceans. Although the Mars Viking landers of 1976 found no evidence of living organisms, or even of molecules of biological significance at the landing sites, that does not necessarily imply that there has never been life anywhere on Mars. For example, studies of images of Mars made by cameras on the Viking orbiters reveal that there is complex layering of carbon-dioxide ice and dust in the polar regions, indicating long-term changes in the climate. And geological formations startlingly like those of terrestrial flood plains strongly point to flows of some liquid – presumably water – in the remote past. Today Mars is cold, and veiled only with a thin atmosphere, but water could still exist there, frozen beneath the surface; conditions could at one time have been favorable enough to support life in some areas. When we return to Mars to obtain samples for analysis back on Earth, we should examine areas where floods have occurred, and excavate to discover whether organisms could have been suddenly buried in such floods.

Mars has also taught us something of practical value. From time to time, dust storms are initiated on its surface, which quickly envelop the whole surface, greatly reducing the amount of sunlight reaching its surface. If the same thing were to happen on the Earth, surface temperatures would drop to the point that life would be threatened. It is believed that the mass extinctions, including that of the dinosaurs which occurred 65 million years ago, were caused by the impact of a large meteorite which put so much dust into the atmosphere of the Earth that sunlight was cut off and plants died, affecting the whole food chain. If this is correct, it has significant implications for the evolution of life on Earth. Studying the inner planets, we conclude that their atmospheres, oceans (or lack thereof), and surface temperatures are the result of a complex interplay between plate tectonics, solar radiation, and meteoritic infall – if not other factors not yet recognized. This in itself is an important new scientific perspective; furthermore, there may be important implications for the future of life on Earth.

The hostile conditions on Mercury and Venus and on all but a few of the planetary satellites make it very unlikely that a search for life on any of these bodies would yield positive results. However, the atmospheres of Jupiter and Saturn contain molecules of interest to the origin of life, such as ammonia, methane, and somewhat more complex molecules as well. Titan, the largest moon of Saturn, is the only satellite in the solar system known to have an atmosphere. Largely nitrogen, like the atmosphere of the Earth, it also contains methane and even traces of hydrogen cyanide – believed to be one of the building blocks of biological molecules. But the oxygen atoms needed for other biological molecules are missing – locked forever in the form of ice on Titan's surface as a consequence of its dismally low temperatures (1800°

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Centigrade below freezing). Still, there will be surprises as space chemists of the future examine worlds like Mars, Jupiter, Saturn, and Titan in far greater detail.

We return now to the question of planetary systems around other stars. Planetary scientist and astronomers alike are excited about the possibility of detecting such systems and it appears that we are on the threshold of success. Recently, NASA has made the search for planets – and life – an explicit priority of the agency.

The discovery by IRAS of dusty disks around stars was confirmed by optical followup observations. The Hubble Space Telescope has identified 'proplyds' (proto-planetary disks) around young stars in the Orion Nebula. Observations with HST and the forthcoming Infrared Space Observatory will continue these investigations; the disks could be a precursor to or even an indicator of planets.

Another technique for searching for extra-solar planets is to track very carefully the position of a target star over a number of years. Although planets are much lighter than stars, they nevertheless exert a significant gravitational force on them, swinging them about in a tight orbit which is the reflection of the planetary orbit. A star like the Sun at 30 light years distance would be swung about through an angular displacement of 0.001 arc seconds (or 1 milliarcsecond). Even now, stellar positions are routinely determined with an accuracy of 10 milliarcseconds, so improvements in technique should enable this method to succeed. Ground-based work has produced several candidate planetary systems, and future advances in adaptive optics are likely to provide definitive results. The first planetary sized objects discovered outside the solar system were found in a related but unexpected way. Rapidly spinning magnetic neutron stars, or pulsars, provide a very stable and accurate clock. Studies of variations in the arrival times of the pulses from one such pulsar indicate that there are at least two planets orbiting the pulsar; by analysing the pulses we can measure the tug of the two planets on the pulsar, and even see the effects of the pull of the two planets upon each other, an important self-consistency check. However, it is not clear if these planetary mass objects are really planets as we would understand them, orbiting the remnant of a supernova explosion. They may be a new kind of object associated with the destruction of the pulsar's parent star.

Of course inferring the existence of a planet by its gravitational pull on its parent star is a very different thing from imaging the planet itself. This is best done in the infrared, where the contrast between the planet and the glare of its parent star is less marked. While Jupiter's might be detectable with a single large infrared telescope in the vicinity of the Earth, to detect Earth's it appears necessary to use an interferometer. Interferometry combines the outputs of two telescopes at some distance apart in such a way as to yield very high angular resolution. It should be possible to detect planets – if they exist – around at least the nearest stars like the Sun. The interferometer may need to be placed beyond the asteroid belt since the light from the target planet would be hard to see against the emission from interplanetary dust in our inner solar system. It may even be possible, by searching the spectrum of light reflected by the planet, to find features of gases, such as oxygen, which could betray the existence of at least plant life on any planets which are discovered.

Beyond such studies is the search for extraterrestrial intelligence, or SETI. For several decades it has been technologically possible to detect radio signals (if any) directed at the Earth by alien civilizations on planets orbiting nearby stars. Because technology in this area has advanced rapidly, it is now possible to detect such signals from anywhere in our Galaxy, opening up the study to over 100 billion candidate stars. It is true that at this time we do not know of a single Earthlike planet outside our solar system, but the studies described earlier should give us some idea of whether planets are the rule or the exception. Certainly finding that planets are common would lend more weight to SETI, although with present technology, if intelligent life does exist beyond the solar system, it is far easier to detect messages from such life than it is to detect the planet on which such life exists.

There is a vast literature debating how likely it is that intelligent life exists beyond the solar system. No firm conclusions can be drawn; we must regard it as an experimental question, which in principle might be resolved by a systematic long-term program of direct observations. No one doubts the impact that messages from extraterrestrial civilizations could have upon our own. Concurrently with experimental programs in this area, serious thought should be given as to how humanity can best approach the information in such messages so as to minimize any harm to our own values as human beings.

4. Conclusion

The stage is set for several decades of extraordinary accomplishments in space science. Using advanced technology, it will be possible to address the fundamental question of the origin of the Universe, the evolutionary steps which led to galaxies, stars, planets, and life on Earth, and whether there is life elsewhere in the Universe. To bring about these accomplishments would require the dedicated effort of the world scientific community, the constant support of universities, industries, and government, and leadership at every level. The result would be a prize worthy of the ages – one which integrates the findings of many diverse disciplines of science into a comprehensive world-view which makes available to all humanity an understanding of the place of the human race in the Universe.

The single overarching goal of science in space is to understand the origin and evolution of the Universe as a whole, and of our Galaxy, our Sun, and our Planet Earth within it to the point that life flourished here. The future will see a coordinated research program with synergy among the various scientific disciplines involved (astronomy, planetary and lunar science, solar and space physics, Earth science, life sciences, and fundamental physics and chemistry). A significant change in space science occurring over this decade is the use of new computer and networking technologies to store the massive quantities of data being obtained and to make it available immediately and easily to scientists across the world so that such data can confront as quickly as possible the theoretical models being developed to understand it.

We have come to recognize the importance of dynamic phenomena over a wide range of time scales on the Sun, Earth, and planets; we will study them intensively so as to provide the maximum warning time for events which may adversely affect living things. We have the opportunity to confront key predictions of theoretical physics relating to gravitation, plasma physics, particle physics, and condensed-matter physics by using astronomical observations of selected objects and physical experiments in the space environment. We are carrying out an intensive program of fundamental research upon the response of animal and human organisms to the space environment, including various levels of gravity, radiation, and degrees of confinement, with the hope of establishing the viability and useful function of humans over prolonged periods in space.

A comprehensive study of the Earth from space, the American component of which is called Mission to Planet Earth, is mobilizing both space-based and ground-based instrumentation for a long-term global study of the interior, oceans, atmosphere, cryosphere, and biosphere of the Earth, directed at a fundamental understanding of the evolution of the Earth, the dynamical interactions among its subcomponents, and the effects of human activities on the terrestrial environment. Information gained from comparative studies of other planets will be important in understanding our own system.

In the future we expect that permanent astronomical facilities will be established in low and high Earth orbit, in near-Earth solar orbit, and possibly on the Moon and in the outer solar system. These facilities will have sufficient throughput and angular resolution in all parts of the electromagnetic spectrum to study phenomena at the limits of the observable Universe and to search for planets beyond the solar system.

We will continue the reconnaissance of all planets, satellites, and types of small bodies in the solar system, and carry out exploration of specific targets as recommended by the Solar System Exploration Committee with the goal of understanding the evolution of the solar system and, through comparative studies, a better understanding of planet Earth. An important long-term goal is the return of samples by robot spacecraft from Mars and from comets and minor planets. We should initiate appropriate studies of mineral and other resources on the Moon and on Earth-crossing asteroids which may be useful to support human activities in space. Special emphasis should be placed upon the search for water and for other sources of hydrogen, including hydrocarbons.

Key goals of solar and space physics are to continue the comprehensive study of the flow of energy from the interior of the Sun through its outer layers and into the solar system, as well as its interaction with the magnetospheres and atmospheres of the planets, especially the Earth. This will require studies of the Sun by instruments in or near the orbit of the Earth and in situ measurements by interplanetary probes. Study of the solar-terrestrial interactions which could contribute to changes in climate should be continued. A proposed Star Probe should be initiated which, by a close approach to the Sun, appropriate firing of thrusters, and subsequent escape from the solar system at high speed, would provide fundamental data to various branches of space science, including gravitational physics, the structure of the interior of the Sun, the generation of the solar wind, and the interaction of the solar wind with the interstellar medium.