21 December 1984, Volume 226, Number 4681 SCIENCE

Space Research in the Era of the Space Station

Kenneth J. Frost and Frank B. McDonald

As the first 25 years of the space age come to an end, we can reflect on a series of remarkable advancements and achievements in space science. In the planetary disciplines, there have been detailed analyses of the Apollo moon-rock samples, the Viking landings on Mars, the Pioneer entry and orbiter probes for Venus, the Mariner 10 close-up look at Mercury, and the Voyager measurements of the magnetospheres, atmospheres, rings, and satellite systems of Jupiter and Saturn. Observations of the earth, its atmosphere, land surface, and oceans have provided us with a global view of our own planet. These observations have advanced the scientific basis for weather forecasting and helped characterize the surface of the planet, from the correlation of phytoplankton concentrations with ocean circulation patterns, to the existence of ancient, now subsurface land forms in the Egyptian desert. These pioneering efforts also established the basis for the current operational satellites that daily provide data for geologists, agricultural scientists, meteorologists, and others.

Summary. With the continuing flights and increasing capabilities of the space shuttle, and with the design and development of a space station, there will be a significant increase in our space research capabilities during the 1990's. Ways in which the nation's space science program may evolve in response to these developments are described.

In the solar-terrestrial sciences, studies of the solar wind, the corona, and the release of energy through solar flares have extended our knowledge of our own star and its surrounding heliosphere. The sun interacts in a complex way with the earth's magnetosphere and a large number of plasma processes have been identified and investigated by in situ measurements.

Probes such as Pioneer 10 are providing the first information on the distant regions of the outer heliosphere as they extend the distance space vehicles have traveled. The complete electromagnetic spectrum from radio waves to gamma rays can now be observed, and telescopes sensitive in the near and far ultraviolet regions of light have changed our concepts of the interstellar medium by revealing great expanses of clumped, hot plasmas that are produced by long-lived shocks from supernova explosions. X-ray astronomy provides an unexpected window on astrophysical phenomena, ranging from neutron stars, white dwarfs, and black holes to the hot gaseous medium in superclusters of galaxies. Investigations now concentrate on quasars and other active galactic nuclei, which release great amounts of energy via processes that are only dimly understood at best. The first steps in gamma-ray astronomy offer a new way to study the structure of our galaxy, and infrared astronomy has illuminated the "cool universe," from the birth of solar systems to celestial cirrus clouds of thin dust that may pervade the galaxy. Comparable progress has been made in many other fields ranging from the physics of the upper atmosphere to the nature of cosmic rays.

Many factors contributed to the rapid evolution of these scientific disciplines in space. A necessary condition was the continued development of rocket technology that began in the early part of this century with the pioneering work of Tsiolkovsky, Goddard, and Oberth and underwent a rapid development during World War II and the postwar era (*1*). In the late 1940's and early 1950's, sounding rockets and large skyhook balloons became valuable tools for studying the upper atmosphere, ionosphere, and cosmic rays and opened the field of ultraviolet astronomy. In order to take full advantage of these tools scientists learned how to conduct experiments on remote platforms and, aided by new silicon devices such as solar cells and transistors, how to design light-weight, low-power experiments. It was the coming together of these and other technological developments, as well as the maturity of individual scientific disciplines, that provided the foundation for rapid advances in space research.

This year President Reagan announced that the design and development of a space station will proceed. The program includes a manned facility with co-orbiting platforms, an orbital maneuvering system, and a polar platform (Fig. 1). This space station embodies many national goals, of which science is one.

The station should become operational in the early 1990's. The initial cost estimate is $8 billion (in 1984 dollars). This is on the same order as the development cost of the shuttle and less than 20 percent of the development cost of the Apollo program when compared in 1984 dollars. The space station is not as formidable an engineering challenge as either of those programs. The program is seen as an international venture, and discus-

Kenneth J. Frost is a senior scientist at the Goddard Space Flight Center, Greenbelt, Maryland 20771. For the past year he has served as science adviser to the space station task team at NASA Headquarters. Frank B. McDonald is NASA's chief scientist, NASA Headquarters, Washington, D.C. 20546.

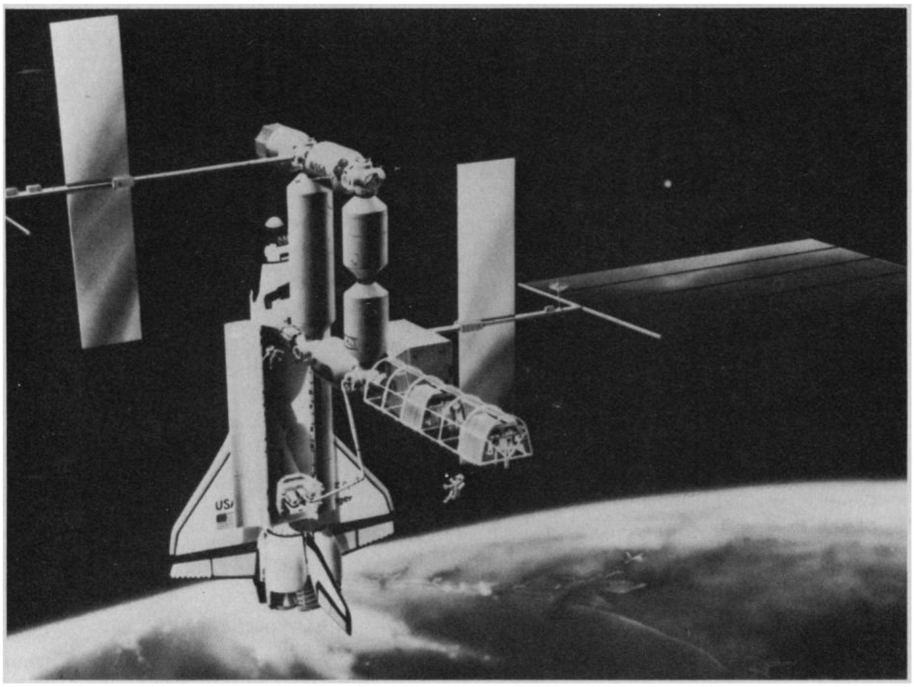

Fig. 1. Artist's concept of space station design showing modular construction. The actual architecture of the system.is still in the preliminary planning stage.

sions about it are already underway with Canada, Japan, and the countries of Western Europe.

The combination of a shuttle and space station along with continued technological advances in such areas as data transmission and microprocessors plus the maturity of space-related science disciplines offer significant increases in our research capabilities during the 1990's. The transition to the era of the space station will be complex and challenging. It will require bringing closer together NASA's manned and unmanned programs, which had been only loosely coupled until the advent of the shuttle.

In this article, we will illustrate how these new capabilities could be used. Since we are in the design phase of the space station project, it is crucial that scientists in different disciplines consider how they might best use the planned research facilities. To put this future in perspective, we will begin with a survey of the current U.S. program for space science.

The Current Program

Voyager II will explore Uranus and Neptune. The Galileo mission will send probes into the Jovian atmosphere, which will provide long-term synoptic observations of the Jovian cloud system, its moons, and its extended magnetosphere. The Venus Radar Mapper, with its synthetic aperture radar, will look through the thick clouds of Venus and map the topology of that planet, and the Mars Geochemistry and Climatology Orbiter will survey the global distribution of the elements on the Martian surface and record the climatic changes over a Martian year. Subsequent planetary exploration will focus on extended detailed studies of cometary nuclei and representative asteroids, and further study of the Saturian system, including Titan, is also under consideration.

In earth science, research satellites such as Nimbus 7, the Solar Mesosphere Explorer, and the International Sun Earth Explorers will continue to provide data along with meteorological and land satellites. The Upper Atmosphere Research Satellite will provide data on the stratosphere to determine how the chemical, dynamic, and radiative processes of this region determine the structure of the ozone layer. The Ocean Topography experiment together with a new research scatterometer will provide observations of the large-scale circulation of the oceans and their response to the atmospheric winds.

Our understanding of solar and terrestrial physics will be advanced by the three dimensional exploration of the heliosphere by the International Solar Polar mission, a joint effort with the European Space Agency. In the planning phase is an International Solar Terrestrial Physics program to better understand the sun and its coupling to the earth's magnetosphere and upper atmosphere.

In the astrophysics area truly dramatic advances are expected. The combination of missions now planned includes the Space Telescope, the Cosmic Background Explorer, the Extreme Ultraviolet Explorer, and the Gamma Ray Observatory, along with the development of a new generation of observing instruments on shuttle Spacelab flights and major new observatories such as the Advanced X-Ray Facility and the Space Infrared Telescope Facility. These missions should provide an unprecedented increase in astrophysical knowledge.

In the near term, however, the most valuable elements of the current NASA program are the 17 active scientific satellites returning data to investigators. These missions are the sources of the results presented at meetings and published in the journals, and they maintain the vitality and productivity of our space science program.

On the one hand the U.S. space science program is in a well-balanced state with a level of financial support well above that of Western Europe, Japan, or the U.S.S.R. However, there has been a long-term change toward sustained observations from larger, more complex, longer-lived observatories and planetary orbiters. This evolution has occurred as the exploratory phase of space research has been completed. These programmatic changes, as well as a drop in the level of financial support (Fig. 2), have led to a dramatic decrease in the number of launches of science missions from an average of six per year in the late 1960's to 1.5 per year in the 1980's. The changes in funding for space science are complex with the large peaks from 1964 to 1966 and from 1972 to 1975 caused primarily by transient increases in the planetary program. Decreases in flight programs and funding since 1965 have forced dramatic reductions in many space research groups.

The space shuttle was expected to provide the means for quick, low-cost experiments, which would maintain the vitality of the experimental groups. With the shuttle having just reached operational status, its promise for science has not yet been realized. The fulfillment of the shuttle's capability is a major concern of the space science community. There are several promising developments, such as the Hitchhiker, Get-Away Special, and Spartan concepts, which would allow the use of the shuttle's cargo bay for moderate-size experiments on an as-available basis. Spacelab offers great capabilities, and with increasing use it is becoming a more flexible and cost-effective tool. It is of utmost importance that both the scientific community and the manned space program learn how to use the space shuttle to greater advantage for science. For it is with the shuttle that the systematic merging of the unmanned science program and the manned program will begin. This experience will provide the foundation for the era of the space station.

As viewed from our present experience, the scientific use of the space station can be divided into three broad categories: (i) for in-orbit assembly, refurbishment, and repair of spacecraft and experiments; (ii) as a laboratory for conducting experiments; and (iii) as a base for missions to and from synchronous orbit, the moon, planets, and other distant locations.

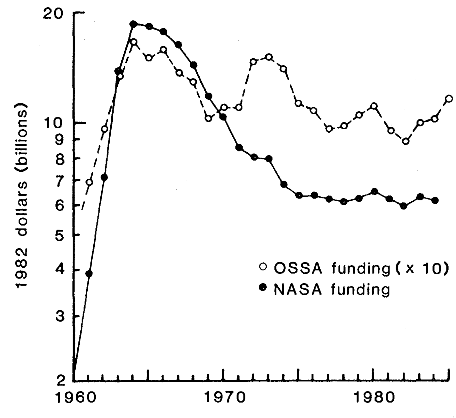

Fig. 2. Funding for NASA and its Office of Space Science and Applications (OSSA) from 1960 to 1985 (estimated) expressed in 1982 dollars. The OSSA share of the total NASA funding has doubled from approximately 9 percent in the peak years (1964–1966) to approximately 18 percent in 1985.

In-Orbit Assembly, Refurbishment, and Repair

Repair and refurbishment are key elements in current NASA planning. The repair of the Solar Maximum mission spacecraft in April 1984 by the crew of the space shuttle mission 41C was impressive. The initial effort by the mission specialist to capture the satellite using an untethered manned-maneuvering unit was not successful due to unexpected material that was mounted adjacent to the spacecraft's trunion pin. However, engineers from the Goddard Space Flight Center were able to stabilize the satellite, and the shuttle crew was able to capture it using the remote manipulator system (RMS). The RMS was then used to bring the satellite into the cargo bay where it was secured to a service table and electrically connected to the Orbiter via umbilical cables.

First, the attitude control system was replaced. The satellite, which was the first multimission, modular spacecraft, was designed to promote the use of common spacecraft subsystems. With slight modification of the modular design, the satellite could also be made repairable in orbit using the space shuttle. The attitude control system was removed by undoing two large jackscrew-type bolts. The control system package was then pulled back, which automatically disconnected the electrical circuits. The replacement system was then brought up and positioned, and the two jackscrew-type bolts were torqued down, pulling the module into place and mating the electrical connectors.

The second repair involved one of the scientific instruments in the payload—the coronagraph/polarimeter. Here it was necessary to replace an electronics box located inside the instrument module. Contrary to the current design philosophy for spacecraft, none of the satellite's scientific instruments had been designed with repair in mind. In an operation that required demating 12 small electrical connectors, the astronauts removed the electronics box and inserted a replacement box. After a complete check-out, the Solar Maximum mission satellite was found to be fully operational and was returned to free flight by the RMS. The repairs took less than half of the time estimated for them.

The RMS, which played such a crucial role in all phases of the repair activity, is a sophisticated and powerful device. Although not a robotics system in the rigorous sense, it is a stepping stone to the partnership between man and robotics that is planned for the space station. The system was supplied by the Canadian government and was designed and built by Canadian industry. When manipulating the Solar Maximum Observatory, it extended to a length of almost 12 meters and guided the 2200-kilogram spacecraft into and out of the cargo bay with impressive precision. Yet on the ground, the RMS cannot support its own weight in an extended position.

The repair of the Solar Maximum mission satellite is an example of the maintenance and refurbishment that will maintain semipermanent observatories in space, such as the space telescope and the Advanced X-ray Facility. The space station can greatly enhance this capability and enable more complex repair and refurbishment operations and delicate procedures such as the optical alignment of experiments.

Permanent Observatories in Space

In the future, remote-sensing satellites will observe the universe, the planets, the activity of our sun, and the global functioning of the earth. For astrophysics, there will be a family of observatories that will concentrate on various portions of the electromagnetic spectrum. There is a close analogy with large ground-based observatories, such as the Mount Palomar Telescope. When this telescope was first put into operation in the late 1940's, its huge area for collecting light (a 200-inch primary mirror) allowed us to peer deeper into space than ever before. Today its capability to do fundamental astrophysical research has not been exhausted. Progress in the technology used to view the images formed by this telescope and to analyze the data from them allows this telescope to be used in ways not envisaged by its designers.

There is an enormous advantage to placing a large optical telescope and other astrophysical observatories in space. The atmosphere allows only a small portion of the electromagnetic spectrum to reach the surface of the earth. The optical character of our atmosphere and its turbulence and temperature variation along the direction of observation permanently blurs our vision and limits how well, how far, and what we can see. The space telescope, in principle, will provide benefits similar to those that would accrue if the Mount Palomar Telescope were moved into space (Fig. 3).

The capability of the Space Transportation System to maintain the space telescope, once it is in orbit, is integral to ensuring the telescope's success. Along with being serviced, the observing instruments could also be upgraded to keep pace with advances in science and detector technology.

The space telescope is the prototype for long-lived observatories in all fields of remote sensing. For astrophysics, this concept will be extended to other spectral regions by the Gamma-Ray Observatory along with the proposed Advanced X-ray Astronomy Facility and the Space Infrared Telescope Facility.

For earth sciences, the first adaptation of this idea will be the Earth Observing System (EOS) that is under consideration for the space station's polar platforms. To understand the dynamic physical, chemical, and biogeochemical processes that comprise the global earth system, simultaneous observations are required from the full set of remote-sensing instruments in the EOS. To understand the changes at work in our

Table 1. Major space observatories planned for astronomy and the earth sciences.

Observatory	Mass (kilograms)	Length (meters)	Diameter (meters)	Objectives
Hubble Space Telescope	9500	13	4.3	High resolution (0.01 second); for visible and ultraviolet regions
Advanced X-ray Astrophysics Facility	~9000	~13	~4.5	High resolution (0.1 second); for imaging in the x-ray region, 0.1 to 8 kiloelectron volts
Advanced Solar Observatory	~11,000	~8*	~4*	Space platform with high-resolution cluster (0.1 second); for visible through x-ray regions
Large deployable reflector	20,000 to 40,000	20 to 30	10 to 20	High resolution (1 second); for submillimeter region
COSMIC optical interferometer	10,000 to 15,000	15 to 30	4.5	Very high resolution (0.001 second); for imaging in the visible and ultraviolet regions

*For the high-resolution cluster only.

environment, such as the seasonal cycles and the influence of man on the environment, sustained observations are required for a decade or longer. The ability to accommodate and service an integrated set of instruments is the key to accomplishing both tasks.

Long-lived observatories, made possible by the ability to repair and update both the satellites and the experiments they carry, would introduce fundamental changes in the manner in which the U.S. space science program is conducted. For example, there would be fewer new missions. A long-term commitment from NASA and from the scientific community will be required to ensure that the scientific vitality of these observatories will be maintained, but in return, however, there would be a continuous flow of data and opportunities for new experiments. The ability to replace experiments should stimulate the development of detector technology and information processing.

For planetary exploration, the space station can play a vital role as a staging point for the assembly, fueling, and inspection of large outbound spacecraft. In addition, it could act as a receiving laboratory or quarantine facility for samples from the surfaces of planets, comets, or asteroids. Missions to bring back such samples from Mars and from a comet could take advantage of the new space station, leading to simpler and less costly implementation than might have been possible otherwise. NASA is in the process of establishing a program of missions to explore the solar system based on technology developed during the last decade. With the space station acting as a receiving laboratory, the program could include the goal of systematically acquiring samples from throughout the solar system.

Finally, the space station will serve as a microgravity laboratory. The ability to manually conduct extended experiments in this environment will make possible a broad range of fundamental experiments in the life sciences, material sciences, physics, and chemistry.

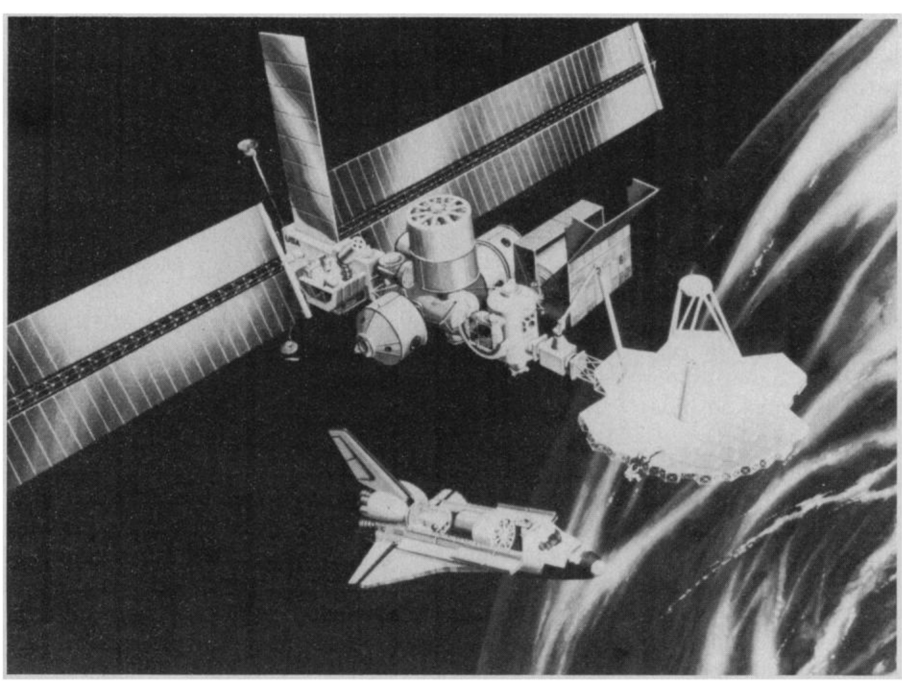

Fig. 3. Artist's concept of the construction in space of a large (diameter, approximately 20 meters) reflector array for astronomical studies in the far-infrared region.

Requirements for a Space Station

The space station will allow us to go beyond how we presently do science in space. To meet this challenge, however, we must learn to effectively combine our technologies, our structures, data systems, detectors, and so forth, into permanent observatories in space. A number of such observatories are in the early stages of planning and we should reexamine them. In the present program, the space telescope, the Advanced X-Ray Facility and the Space Infrared Telescope Facility each will completely fill the shuttle payload bay at launch. The larger observatories of the future must be assembled in orbit and will require special facilities at the space station.

Examples of large space observatories for astronomy and the earth sciences are listed in Table 1. To provide a specific example, it is useful to consider the large deployable reflector (Fig. 3), for which early definition studies have already begun. This instrument will study the far-infrared (30 to 200 micrometers) and submillimeter (200 micrometers to 1 millimeter) radiation from newly forming stars and planetary systems as well as the ancient, red-shifted signals from galaxies and pregalactic gas located at the edge of the universe. A 1–arc-second resolution, sensitive observations of spectral lines, and a large collecting area are necessary to undertake these investigations. As currently envisaged, the reflector is approximately 20 meters in diameter and composed of 60 mirror segments. It is expected that the mirror segments will have to be continuously adjusted in order to maintain acceptable image quality because of the thermal and mechanical disturbances during a given orbit.

This instrument is but a sample of what the 1990's hold for space science. Similar missions are planned for earth observations, communications, and experiments to detect gravity waves and to verify aspects of the general and special theories of relativity. Many anticipated payloads are beyond the launch capability of any available booster, and all press the capability of the shuttle itself. The shuttle would be able to carry into orbit the materials needed to assemble one of these observatories. However, the time, the crew, and the facilities required to both assemble and check these observatories are beyond what the shuttle can handle. The space station, however, will make the assembly and implementation of such observatories feasible.

From the Shuttle to the Space Station

Concurrent with developing the space station architecture, NASA should enhance the level of science done with the space shuttle during the remainder of the 1980's. Such an approach would move space science into the era of the space station with optimal advantage to both the scientific community and the space station itself. Such an approach would also avoid the difficulties that have been associated with the transition to the space shuttle. Contrary to widespread belief, the shuttle program appears to have had little impact on the funding of space science (Fig. 2). However, the decision to eliminate some types of expendable launch vehicles before the shuttle became operational did delay programs such as the Galileo mission to Jupiter and the International Solar Polar mission, which resulted in significantly higher costs for these programs.

The scientific features and capabilities that have been broadly sketched in this article are not necessarily an automatic, predetermined part of a space station program. For example, the Soviet Union has had a very active space station program starting in 1971 and has launched six Salyut space stations into orbit (*2*). With Salyut, the Soyuz spacecraft for ferrying crews, and Progress vehicles for the resupply and refueling operations, the Soviet Union has demonstrated the ability to maintain man in space for periods as long as 6 months. Salyut 7 and COSMOS 1443 were linked together to form an orbital complex capable of housing as many as six crew members. These missions have made important advances in studying the long-term effects of microgravity on human physiology, and the Russian cosmonauts have carried out a number of on-board experiments including material science studies and astronomical and earth science experiments. In fact, the long-term objective could well be toward the colonization of space. Repair, maintenance, and refurbishment of the Salyut station itself appears to have been a major activity. However, the Soviet Union has apparently not attempted to maintain scientific observatories in space nor begun the on-orbit assembly of large structures for scientific experiments.

The Future

The limits we face in putting experiments in space are not fundamental, like those posed by the earth's atmosphere for a ground-based telescope. Our present limits are technological and managerial. The space station is an opportunity to move those limits with creativity and imagination. It should be approached in that manner and not viewed as an alternate opportunity to implement our current program.

The experience, expertise, and creativity that resides in our space research communities are unique resources that must be used to assure that the space station will be a step forward for space research. How to effectively utilize these resources is a crucially important challenge in managing the development of the station.

Under the auspices of its Advisory Council, NASA has established a study group, with Peter Banks of Stanford University as chairman, to define the scientific requirements of the space station. The Space Science Board of the National Academy of Sciences, under the leadership of Thomas M. Donahue of the University of Michigan, is undertaking a 2-year study to define the nation's long-range objectives in space science for the period 1992 to 2015. These studies will be closely linked and will form a crucial part of NASA's long-range planning for effective scientific utilization of the space station.

The space station will be judged on the magnitude of the advance it affords in the utilization of space. Effective utilization is as important as that of engineering the hardware itself. The responsibility for designing and building a scientifically useful space station is a mutual one. It is shared by NASA and the scientific community jointly, and jointly they are responsible to the public for our progress in space.

References

1. H. Newell, *Beyond the Atmosphere* (NASA SP4211, National Aeronautics and Space Administration, Washington, D.C., 1980).
2. Office of Technology Assessment, *Salyut, Soviet Steps Toward Permanent Human Presence in Space* (GPO Stock No. 052-003-00937-4, Government Printing Office, Washington, D.C., 1983).