Perspective

The Future of Science in Space

PETER M. BANKS AND DAVID C. BLACK

IN A RECENT PERSPECTIVE (*1*), JAMES A. VAN ALLEN recounted the outstanding achievements of scientific investigations in space. Citing past successes with unmanned satellites in astronomy, Earth observation, solar-terrestrial physics, and solar system exploration, Van Allen argued that future scientific endeavor in space should use only unmanned facilities and that our future national space science programs can best be accomplished without manned space shuttles or space stations. As one of the pioneers of scientific exploration in space, Van Allen deserves to be heard. Yet, from our perspective his message is seriously flawed. It is our assertion that manned space platforms both improve our ability to conduct traditional space observations and enable us to undertake entirely new and fundamental research programs.

The manned facilities represented by the Soviet Mir space station and the planned U.S.–international space stations can provide many services for scientific research in space. These include on-orbit repair and maintenance of expensive unmanned space science observatories as well as the less glamorous task of caring for smaller systems and research instruments attached to and contained within the space stations. Manned facilities also, for the first time, make possible the pursuit of laboratory-style studies of the effects arising from the microgravity environment of orbiting spacecraft. These various tasks involve complex situations and, at the present time, there is no practical alternative to using humans. Advocates of fully automated repair units or the conduct of laboratory-style space research in remote, unmanned satellites are speaking of technical achievements that, according to a national panel of automation and robotics experts (*2*), are decades away. These experts believe that the year 2010 is the likely date for achieving pervasive, reliable, autonomous robotic and machine-mediated functions in facilities like the space station. To reach this capability, however, the intervening time must be spent in developing the supporting technologies and in gaining practical experience in space. Consequently, from our perspective, space shuttles and space stations with cosmonauts and astronauts are a practical first step that enables us to begin new science and technology in space quickly. As technology in automation, robotics, and other supporting areas advances, the specific tasks assigned to humans will change, perhaps leading to capabilities for completely autonomous operations in certain areas.

The human role in space has been extensively studied (*3*) and, with Apollo, Skylab, Salyut, Mir, and the Space Shuttle, tested. One of the foremost jobs for humans in space is maintaining scientific and other equipment. The increasing complexity and cost of experiments in space, including those carried aboard free-flying satellites, such as the Hubble Space Telescope, and those attached to or contained within the pressurized modules of a space station, lead inevitably to the need for repairs or servicing for experimental equipment. The capability and importance of satellite repairs have been well demonstrated by Soviet rescue activities with Salyut 7 and the Solar Maximum Mission repair from the Space Shuttle. The numerous experiences of astronauts and cosmonauts with a variety of smaller instruments and systems in space shuttles and space stations also demonstrate the importance and value of human services to support space investigations.

Humans are also unique in their ability to conduct laboratory-style investigations. Van Allen's lack of appreciation for humans in space can, perhaps, be traced to his experiences with traditional space science where the methodology is principally that of remote observation. Automated spacecraft, sent far into space, operate relatively autonomously to acquire new, important data not available to us on Earth. Data transmitted to Earth are analyzed at leisure by experts to deduce new information. This type of investigation is the classic style of observational science.

The more general scientific practice of acquiring information about the behavior of the physical world involves interactive experimentation. Hypothesis, experiment, and initial conclusions follow in iterative sequence until new ideas are firmly established. The daily activities of thousands of individuals in terrestrial laboratories involved in physics, chemistry, and biology conform to this methodology and their products give proof of its value. "Space science," with its emphasis on observations of remote objects, omits the rapid interactive aspect of laboratory scientific investigations and thus does not represent the full spectrum of scientific endeavor. From our perspective, space science has been a first phase of space research where relatively simple, automated tools are used to look at the worlds around us. Now, however, we can take advantage of new opportunities provided by humans aboard space shuttles and space stations to pursue a more general exploration of space with a broader range of tools and methodologies.

The most scientifically unique feature of Earth-orbiting space facilities is the microgravity ($10^{-6}g$) environment found near the center of mass. From experiments conducted with aircraft and rocket flights, Skylabs, Salyuts, and a few space shuttle missions, it is known that there are many biological and physical phenomena that are strongly influenced by the acceleration due to gravity. Reduction of ambient accelerations to values of 10^{-5} to $10^{-6}g$ for a substantial period of time has many different consequences, most of which are poorly known at present. This fundamentally different environment, unattainable for any length of time at Earth's surface, offers a new arena for a variety of new scientific investigations and technology development.

At the microscopic level, the absence of gravity removes convection and sedimentation as important mixing processes in gases and liquids. It also removes an important spatial indicator used by developing biological systems (particularly plants) to orient growth. Thus, the elimination or reduction of gravity during space flight produces myriad consequences for complex biological and physical systems. Systematic exploration of the consequences of this environment is a scientific challenge that will be a major thrust of space research in the next decade and one that, by its nature, requires the presence of humans, both to conduct the research and, in the life sciences, for the part humans will play as integral elements in the research studies.

With respect to the life sciences, a microgravity laboratory provides the capability of studying the mechanisms of gravity perception and cellular and organismic responses over long periods of time, perhaps even generations. Living systems, both plant and animal, have evolved in a constant $1g$ environment and have developed a variety of mechanisms for dealing with gravity. In many

P. M. Banks is a professor in the Department of Electrical Engineering, Stanford University, Stanford, CA 94305. D. C. Black is chief scientist in the Office of Space Station, National Aeronautics and Space Administration, Washington, DC 20546.

cases, gravity appears to be required for normal growth, particularly in plants and embryonic systems. On Earth, study of gravity environments of less than $1g$ is not possible for significant periods of time. In space, it is not only possible to study the basic mechanisms, but it is necessary to assess and understand the consequences of long-term space flight on plants (to be used for regeneration of food and air on lengthy space flights) and animals (including humans), where preliminary and relatively short-term data indicate serious problems with cardiovascular deconditioning, muscle atrophy, and bone decalcification. With respect to gravitational biology, the gravity-sensing mechanisms of plants and animals are poorly understood at both the cellular and the overall system level, and knowledge of these will substantially increase our knowledge about biological systems in general. There is a need to investigate, in long-term experimentation, the development, maturation, reproduction, and adaptability of plants and animals in a gravity-free environment. Finally, the possibility of developing a controlled ecological life-support system in the microgravity environment is of interest to many scientists.

With respect to the physical sciences, fundamental experiments in fluid dynamics are essential to understand the behavior of more complicated systems of materials. Even simple experiments can yield complex, new results, for example, the fluid thermal convection experiments of Hart *et al.* (*4*) on the Spacelab 3 mission. The processes that are strongly affected by gravity include (i) density gradient-driven convection; (ii) sedimentation or buoyancy phenomena in multiphase materials; (iii) hydrostatic pressure effects such as those influencing the shape of liquids or the onset of critical point phenomena; and (iv) containerless processing, where liquids may be positioned by very low force fields in the absence of solid containers that might yield contaminants or otherwise disturb the observation of physical phenomena. The absence of gravity will also affect the behavior of quantum fluids; subtle effects occurring at lower energy states, which will partly determine the macroscopic properties of films and other structures, will finally be observed.

How can we actually perform experimental microgravity science in space? The first steps, taken with rockets, the Apollo missions, Skylab, the Soviet Salyut and Mir space stations, and the scientific missions of the Space Shuttle before Challenger, have involved a blend of automated and human-directed investigations. Contrary to the early experience of space scientists with remote-sensing missions, the automation of physical measurements and scientific operations in laboratories lies beyond the reach of current technology. Although considerable progress with mechanization of laboratory scientific work is possible, the presence of intelligent scientific observers is essential to support the course of the experiments. Experiments and results must follow in rapid succession with interpretive understanding to maintain the pace of investigation and scientific appreciation. This form of investigation of physical phenomena in space we call "science in space," and it is the logical consequence of the growth of our technical capability to deal with the remoteness and harshness of space. Science in space is an extension of what has been done before with limited resources and capabilities. From this perspective, limiting our investigative space programs to just "space science" would be an enormous mistake, a mistake that is not likely to be duplicated by our international companions and competitors.

Van Allen's statement that the development of space stations is part of a "poorly founded, misty-eyed concept" promoted by the President and Congress is wrong. In fact, the desire for well-equipped space laboratories with a suitable scientific staff is supported by a broad community of competent scientists who have watched both the development of the Soviet Mir space station and NASA's plans for a more ambitious space station involving international partners. These scientists believe that there are important, new scientific roles for humans in space and, at the same time, that there are arguments for their presence there for long periods of time. Facilities (space stations) will therefore be needed that can house technical personnel and specialized equipment in space for an extended duration.

The U.S.–international space station program will serve a far larger scientific clientele than microgravity laboratory scientists. The core station will include a large number of externally attached instruments that will be under the dual control of space- and ground-based investigators. These will support many types of space science, perhaps even permitting the development and flight of small, innovative science experiments that have been largely left by the wayside in recent years as NASA and the various scientific disciplines have invested their principal resources in major observatories. The space station program also includes a collection of co-orbital and polar-orbiting, free-flying satellites. Some of these may be large, such as the Advanced X-Ray Facility or the Earth Observation System platforms. However, the largest scientific innovation may well come from smaller, short-term experiments on retrievable, free-flying satellites that have their home base at the space station. It is with these that Freeman Dyson's dictum, "Quick is beautiful" (*5*), may be realized.

Finally, there is no doubt that every scientist connected with space research is concerned with the costs of scientific activities in space and the consequences of the development of expensive flight hardware. It is the scientific community's responsibility to inform NASA of its concerns and to argue in national forums for an economically responsible program for scientific investigations in space that includes a balanced continuation of the older space science investigations as well as the development of new opportunities under the broader title "science in space." At issue is the extent to which national leaders are sincere in wanting to support space research, both as it applies to understanding fundamental processes and as it relates to important, practical applications.

If we do not accept the challenge of manned space exploration, other nations will not wait for us to do so. The Soviet Mir station, and its successors, and the planned facilities to be developed by the European Space Agency and Japan for independent manned space flight will be used for important scientific and technological pursuits. The United States must decide whether its scientists and other space users are to be spectators or participants in this new phase of space exploration.

REFERENCES

1. J. A. Van Allen, *Science* **232**, 1075 (1986).
2. "Automation and robotics for the national space program," *Report CIS/85-01* (California Space Institute, San Diego, CA, 1985).
3. "The human role in space," *Report MDC H1295* (McDonnell Douglas Astronautics Company, Huntington Beach, CA, 1984).
4. J. E. Hart *et al.*, *Science* **234**, 61 (1986).
5. F. Dyson, *Science 85* **6**, 127 (November 1985).