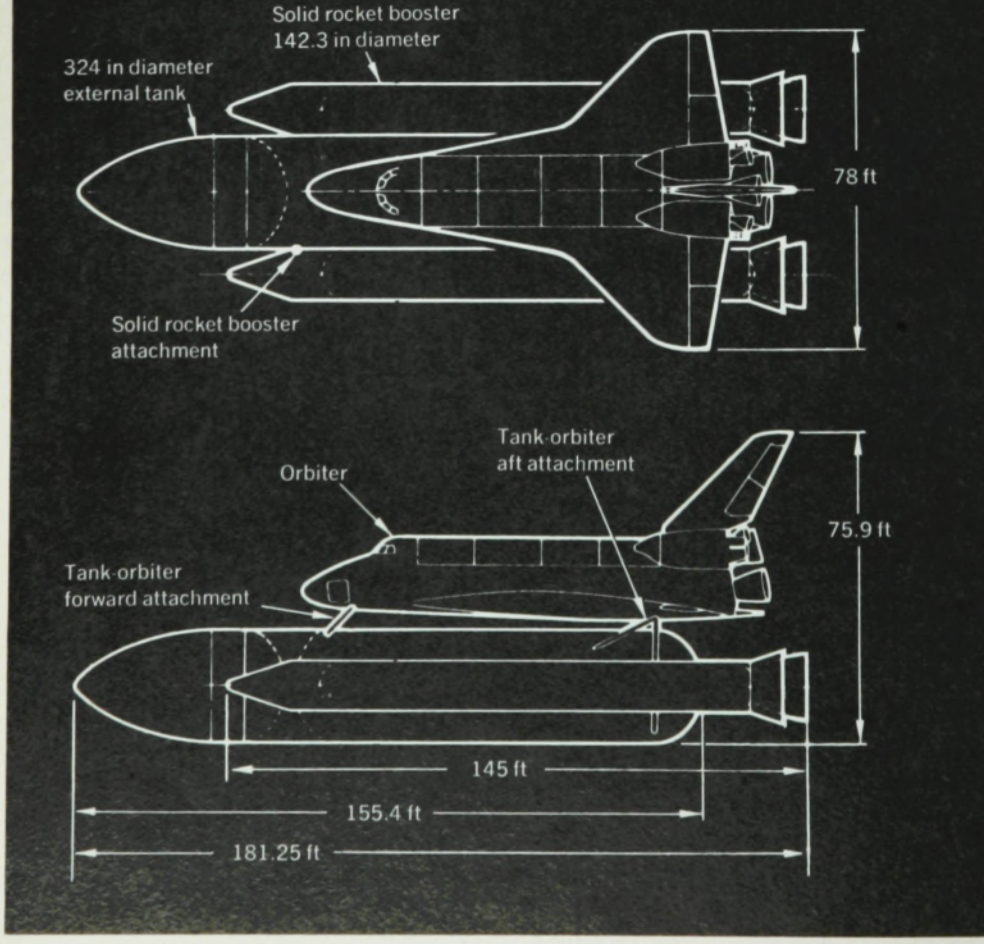
Research with the space shuttle

A laboratory the size of a boxcar will be placed in earth orbit by the Space Shuttle system within the next decade, thus beginning a new era of science in space.

John E. Naugle



Space Shuttle vehicle. The key to the Space Shuttle system is the Shuttle orbiter, which is a delta-wing rocket plane capable of changing orbits and leaving orbit to land on an airstrip. The orbiter rides piggy-back upon a large liquid-hydrogen, liquid-oxygen tank that supplies fuel to the plane's engines during the launch. Further lift is provided two reuseable solid-propellant rockets mounted on either side of the main tank. Figure 1

The new space transportation system based on a reusable space shuttle, currently under development, will substantially change our traditional methods of space research that have been based on a ballistic-missile technology and its reliance on expensive expendable components. The shuttle will not become operational until 1979, but the time is ripe now for planning the space-exploration and space-science programs for the period 1978–85.

Already groups such as the NASA Shuttle Payload Planning Steering Group and the European Space Research Organization (ESRO) have considered possible use of the space shuttle for experiments in astronomy, high-energy astrophysics, atmospheric physics, plasma physics and other fields of physical and biological science. The NASA Astronomy Working Group has recommended the Large Space Telescope (LST) to be the cornerstone of the astronomy program for the 1980's; the objectives of the Atmospheric and Space Sciences Working Group will be to investigate the detailed mechanisms that control the near-space environment of the earth, perform plasma-physics investigations not feasible in ground-based laboratories and conduct investigations important in understanding planetary and cometary phenomena. The Working Group in High-Energy Astrophysics has considered various types of instrumentation that can be taken into space by the Shuttle to map the sky in the x-ray and gamma ray regions of the electromagnetic spectrum, as well as in regions of the cosmic-ray spectrum. NASA has just published a ten-volume set of the final reports of the payload-planning working groups, including the three already mentioned and whose work we shall consider in this article. The other working groups are: Life Science, Solar Physics, Communications and Navigation, Earth Observations, Earth and Ocean Physics, Materials Processing and Space Manufacture, and Space Technology.

The ICBM's and Apollo were developed over the past two decades to satisfy limited objectives, and there was therefore a limited opportunity to influence their basic design to incorporate scientific objectives. This is not the case with the Shuttle, for it is being designed to meet the needs of all groups who will be using space in the 1980's and beyond. This requires that scientists think about the direction of space science and its requirements two decades hence and that they anticipate the scientific discoveries of the next five or ten years; a difficult task, because the real research program of the 1980's is only now beginning to ferment in the minds of today's college and graduate students.

Only a handful of scientists in the early 1950's recognized the research potential inherent in a ballistic-missile system. Today, many scientists are aware of the potential in space research, but the high cost of this research limits their participation. There are reasons for this high cost. One is reliability; everything has to work the first time. To permit some failures, a certain amount of redundancy can be built in. A new way of building equipment has been developed that uses extensive documentation, quality assurance and almost unending testing prior to launch. Another factor is the weight constraints; we tend to try to pack as much equipment into a spacecraft as possible. We also try to use the latest development, whether it be the scientific equipment, the telemetry system or control system. As a result, our spacecraft come out looking more like an expensive Swiss watch than a piece of research hardware. We will be able to do more research with the resources available if we do not have to spend so much time and effort on reliability and miniaturization. The Space Shuttle will offer us this opportunity.

The Space Shuttle System

The key to the Space Shuttle System is the Shuttle Orbiter shown in figure 1. This 126-foot long delta-wing plane has the maneuvering capability to change orbits and to de-orbit; it has the necessary protection to survive entry into the atmosphere and the ability to land on an airstrip. Basically, this rocket plane carries a crew of four in the cockpit—a pilot, co-pilot, and two payload crew members. Behind the cockpit is a very large cargo bay, 15 feet in diameter and 60 feet long. Behind the cargo bay are the high performance liquid-hydrogen, liquid-oxygen engines that are used for maneuvering in orbit and during landing. This orbiter can carry payloads of 65 000 pounds due east into a 150-nautical-mile orbit; it can carry about one third as large a payload into a 600-nautical-mile orbit. The difference in weight between the nominal payload and the reduced payload is used to carry additional fuels for orbit changes.

The orbiter rides piggy-back on a large liquid-hydrogen, liquid-oxygen tank that supplies the fuel to the plane's engines during launch. Further lift is provided by two reusable solid-propellant rockets mounted on either side of the main tank.

A typical mission profile is shown in figure 2. At launch, both the main engines of the rocket plane and the solid rockets are fired. After about 109 seconds at an altitude of 133 000 feet, the solid-propellant rockets have burned out; they are then dropped and retrieved for subsequent reuse. The Orbiter with its main fuel tank continues to ascend to 500 000 feet. At that point the main fuel tank is dropped at a safe place so that it reenters into a remote ocean area. Fuel contained within the Shuttle Orbiter itself is then burned to make the orbit circular.

The Shuttle is designed to stay in earth orbit for a time as short as one orbit or as long as seven days. With additional expendables for life support, the orbit "stay-time" can be extended to 30 days. After the operation in orbit is completed, the plane uses its engines to de-orbit; it then re-enters the atmosphere, is slowed down, and lands on a runway.

The large cargo bay makes the Shuttle adaptable to a variety of missions because any number of different payloads can be designed to fit into the 15 × 60-foot space. For instance, the bay can carry a spacecraft plus an upper stage to inject a payload into higher orbit or it can carry a large spacecraft into orbit. A manned laboratory can be carried to orbit and used while the Shuttle is in orbit for investigations from a week to a month. The Shuttle can also be used to carry remotely operated experiments into orbit for periods of 7 to 30 days and then return them to earth. The nominal turnaround time between successive flights is two weeks. This time is required to refurbish the orbiter, fit it out with a new expendable hydrogen-oxygen tank, and add new solid boosters.

A reusable tug will be developed to boost spacecraft to a geosynchronous orbit and return them to the Shuttle orbit. This same tug can also give a planetary spacecraft its required velocity.

NASA programs supported in the past, with the exception of Apollo and Skylab, can all be accommodated on the Space Shuttle. In many cases we will use the Shuttle purely as a first-stage booster. For instance, a planetary spacecraft, together with the tug or an additional propulsion stage, can be inserted into earth orbit by the Shuttle; the upper stage, when ignited, will then send the planetary spacecraft on its way to the planet.

The Shuttle as a research tool

Planetary missions are only one example of satellites that require upper stages. Synchronous-orbit missions and highly elliptical orbits require similar capability. A small satellite such as an Interplanetary Monitoring Platform (IMP), by using its own injection stage, could be launched more cheaply with the Shuttle than with traditional

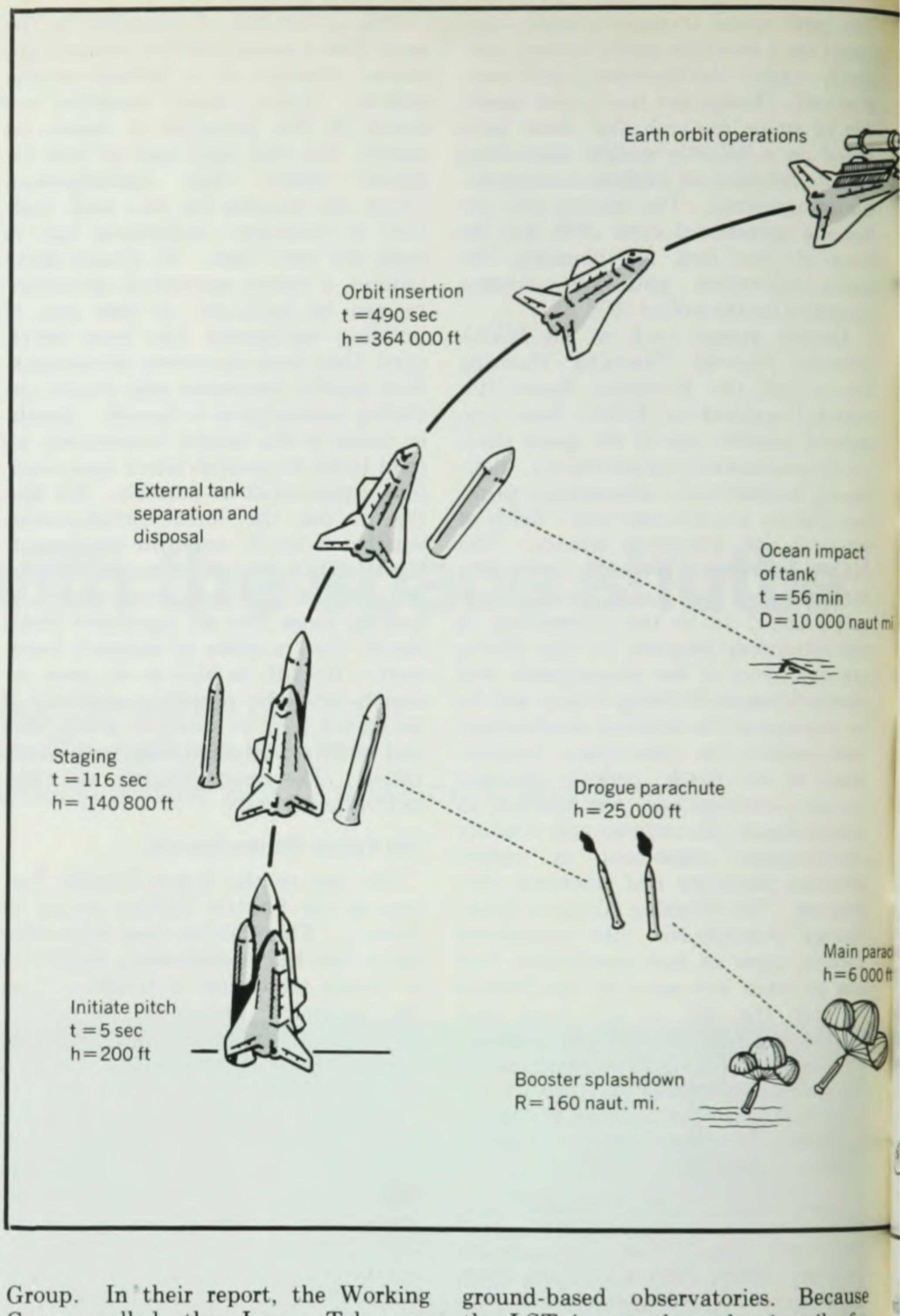
The author is Associate Administrator for Space Science at NASA and chairman of the Shuttle Payload Planning Steering Group.

boosters if such a launch could be combined with other spacecraft on the same mission.

An entirely different situation exists with satellites that stay in an orbit compatible with the Shuttle. In these cases, the Shuttle can rendezvous with a satellite during a subsequent mission to repair, update and replenish expendables; if necessary, the satellite could be placed in the cargo bay and returned to earth. We believe that this mode of operation will make possible the establishment of permanent experimental and observational facilities in space.

In addition to using the Shuttle as a first-stage booster and to launch and maintain large observatories in low earth orbit, we plan to use the Shuttle in the so-called "sortie" or "research" mode. In this mode, we take advantage of the Shuttle's ability to carry men and instruments into space, keep them there for one to as many as 30 days, and then return them to earth.

The European nations are planning to build a space laboratory for use in this mode. The space laboratory will consist of two elements; a manned laboratory and a pallet to carry instruments. A sortie mission may consist of a manned laboratory where the full capability of the Shuttle is used to carry the laboratory; or it may consist of a "pallet-only" mission in which the full capability of the Shuttle is used to carry instruments in the cargo bay of the Shuttle, with these instruments being operated remotely either by someone in the flight deck of the Shuttle or on the ground; or alternatively an orbital mission of the Shuttle may consist of a laboratory and a pallet. Figure 3 shows conceptually how the Shuttle might be used in this mode; here a medium-sized telescope is carried on a mission that is primarily undertaken to launch a satellite.



In the remainder of this article, I shall discuss some of the specific proposals that have been made for utilization of the Shuttle for research in space. These proposals were made by the NASA Shuttle Payload Planning Working Groups. They all appear in a ten-volume set of reports published this year by NASA. I will consider here only some of the recommendations made by the Working Groups in Astronomy and its subpanel on Relativity, Atmospheric and Space physics, which also includes plasma physics, and High Energy Astrophysics, which is concerned with x-ray, gamma-ray and cosmic-ray astronomy.

The Shuttle and astronomy

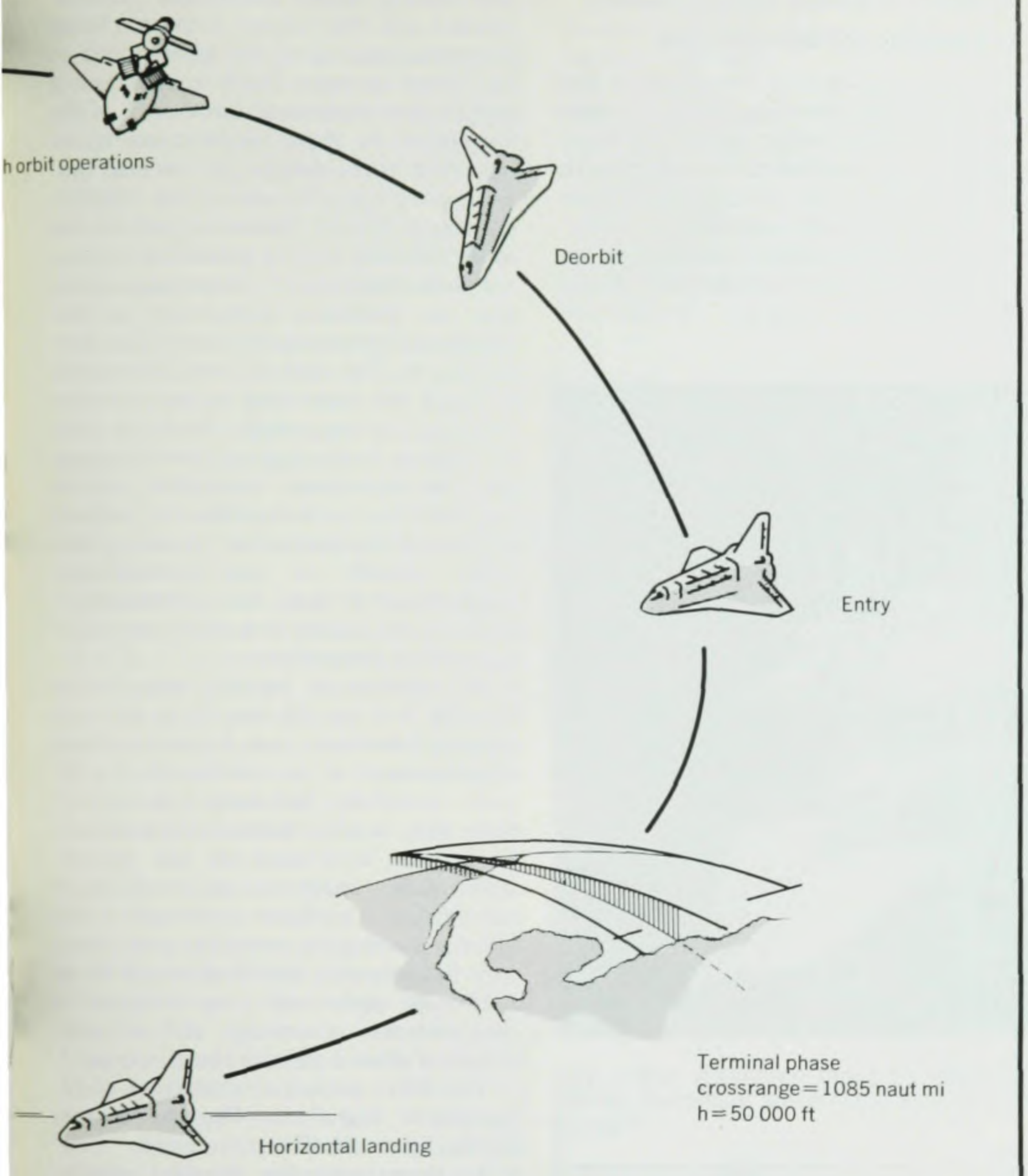
Nancy Roman of NASA headquarters and David Leckrone of the Goddard Space Flight Center are co-chairmen of the NASA Astronomy Working Group. In their report, the Working Group called the Large Telescope (LST) the "cornerstone" of their recommendations for the astronomy program of the 1980's. It is a diffraction-limited telescope with a three-meter aperture. The telescope will optimally function in the ultraviolet and the visible regions of the spectrum but it will also be usable in the infrared region. The instrument will be operated as an automated satellite and will be periodically serviced by the Shuttle (see figure 5). The LST will extend significantly the distance to which we are able to probe the universe. The cosmological problem, whose solution has not been possible from the ground, might be solved using the LST.

A balanced program requires that this major instrument be supplemented by other more specialized instruments such as are also required in ground-based observatories. Because the LST is not planned primarily for the infrared, early emphasis in the Shuttle Sortie program is placed on this special region. Two infrared telescopes are proposed:

- A 1.5-meter aperture telescope, cryogenically cooled to about 20 K, specifically for the 10–50-micron wavelength region.
- A very large uncooled telescope for the far-infrared and microwave region, and for planetary studies and narrow-band spectroscopy over the whole infrared range.

Although both telescopes could operate as automated free-flyers based on the same spacecraft Support System Module developed for the LST, both would gain by operation on the Shuttle. For the uncooled telescope the Shuttle allows the accommodation of larger optics than would be possible

Space Shuttle mission profile. The Space Shuttle transportation system will change our traditional methods of space research that have been based on a ballistic-missile technology and its reliance on expensive expendable components. Figure 2



with the Titan-compatible Support System Module, as well as the possibility of interchanging instruments at the focal plane during flight. The cryogenic system for the cooled telescope would be much simpler and less expensive on the Shuttle. These telescopes will be powerful tools in the exploration of such diverse phenomena as the immense infrared energy output of galactic nuclei, the conditions in the interstellar medium leading to star formation, and the physical properties and composition of planetary atmospheres and surfaces.

In the ultraviolet, there is a definite need for:

▸ A wide-angle telescope to provide an ultraviolet survey in one broad wavelength band if the LST is to be used for many years to maximum effect. (Subsequent use for studies at different wavelengths of for an ultraviolet spectral survey would be valuable but less urgent.)

▸ A one-meter diffraction-limited telescope for the ultraviolet and visible to provide high angular-resolution imaging over relatively wide fields of view (0.5°).

The major advantage of the Shuttle for both these instruments is that it will allow use of photographic and electronographic detectors with their very large information-storage capability. The 1-meter telescope will also provide an important test bed for auxiliary instrumentation for LST, allow specialized observations of a "one-of-a-kind" nature and relieve LST of observations of relatively bright sources.

Several other instruments considered briefly are typical of those that the Shuttle program should include. Examples are a very-wide-angle ultraviolet camera for the study of large-scale, low-surface-brightness nebulae and star clouds, a grazing-incidence telescope for the extreme ultraviolet between the normal x-ray region and the Lyman limit of hydrogen, Explorer-class free flyers (to measure the cosmic microwave background for example), and rocket-class instruments that can fly frequently on a variety of missions.

The five major telescopes mentioned above constitute a balanced ensemble of instruments for achieving many of the objectives of ultraviolet, optical and infrared astronomy in the 1980's. To some degree the functions of these instruments overlap. However, each one possesses unique capabilities that make it the best telescope of the five for particular programs of research.

Relativity and the Space Shuttle

A subpanel of the Astronomy Working Group made recommendations for use of the shuttle to perform experiments in relativity. In rough order of priority, as judged by their feasibility and importance these were the experiments:

Cosmology experiments
Drag-Free satellite
Geodetic-gyro precession
Blackbody radiation spectrum and isotropy
Eötvös experiments
Second-order gravitational redshift
Lense-Thirring gyro precession
Strong equivalence principle tests (clocks)
Solar oblateness
Solar light deflection
Gravitational-radiation experiments
Measurements of "G"

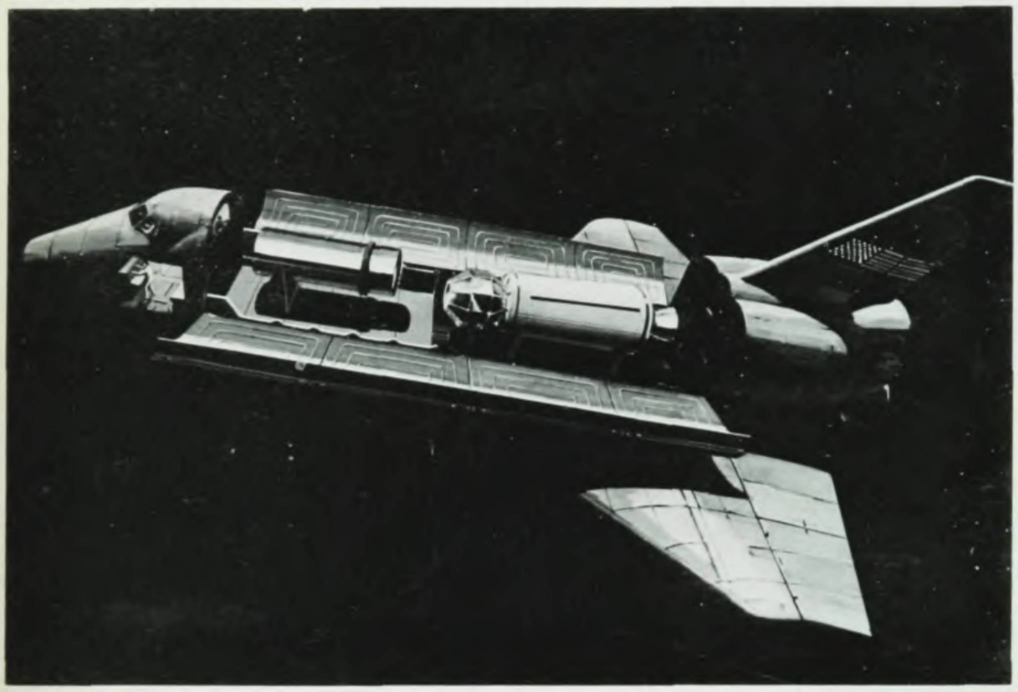
The panel was unanimous in the view that cosmology would be the most exciting and important aspect of research in general relativity in the next decade. Many cosmologically interesting experiments will become possible with telescopes and detectors of the type already being planned for space; the main advantages of these are wider spectral range, higher resolution, and lower sky brightness.

The virtually force-free environment of a drag-free probe offers unique opportunities for experiments to measure new post-Newtonian gravitational effects. An important experiment to measure four-dimensional curvature is the measurement of the precession of the spin angular momentum of a gyroscope as it makes a closed orbit around a gravitational source—the geodetic precession. Another gyro experiment may also demonstrate the gravitational induction field due to moving-mass "magnetic" gravitational fields—the Lense–Thirring effect. The measurement of this effect would be extremely interesting. The magnitude of the Lense–Thirring gyro procession is very small (0.05 arc sec per year for a 500 nautical-mile polar orbit) and will require gyroscopes having extreme stability.

The subpanel also suggested that a major effort should go into precision measurements of the orbital parameters of planets, asteroids, or drag-free artificial satellites of the sun to determine the post-Newtonian corrections to their equations of motion. Measurements of the perihelion rotation of fast-moving objects offer tests of relativistic gravitational theories to second order in ϕ/c^2 (where ϕ is the Newtonian potential and c is the speed of light). Precision measurements of the orbital parameters of objects with different orbital radii or inclination to the rotation axis of the sun may give a better estimate than we now have for the gravitational quadrupole moment of the sun.

Atmospheric and space physics

In their report, the Atmospheric and Space Physics Working Group (headed by Erwin Schmerling of NASA headquarters) stated that the Space Shuttle brings with it the opportunity to perform the research needed to understand the phenomena discovered in the earth's near-space environment during the previous two decades. By the time the Shuttle becomes operational, the Working Group expects that the exploratory and survey phases of research in the earth's near-space environment will have been essentially accomplished and they expect to have a fairly extensive catalog of the phenomena to be found in near-Earth space, and a rather good statistical knowledge of the variations in these phenomena to be expected with changes in season, latitude, solar activity, and so on. Still to be accomplished, however, will be the more difficult task of achieving a genuine understanding of these phenomena, and an intimate knowledge of the cause-and-effect relationships that govern them. The lack of such knowledge is being felt right now in our inability to assess the long-range effects on Man of modern technological developments such as supersonic transports and in our inability to determine the hazards to Man of the particular types of pollutants already in our environment. Such research may have profound effects on the health and even survival of succeeding generations.



The sortie-laboratory mode of the Space Shuttle with the pallet completely open. Pictured here is a medium-size telescope being carried on a mission that is primarily undertaken to launch a satellite. Figure 3

SHUTTLE PARAMETERS

Volume available	Cylindrical diameter 4.5m, length 18m
Weight available	20 000 kg
Power available	1–5 KW for all experiments on shuttle
Data system	50 K bits/sec for all experimenters on shuttle
Shuttle-orientation stability	1 degree
Modes available	Fixed open pallet Pointable open pallet Pressurized container pallet, not man-rated Pressurized "shirt sleeve" man-rated lab Shuttle-launched "free-flyer," recoverable Shuttle-launched rocket for deep space probes
Flight duration	5 to 30 days sortie 6 months free flyer
Orbital parameters	Altitude 150 km to 250 km
Shuttle availability	Starting in 1980, with pallet space "as available" and free-flyer launch and/or recovery on 6 months intervals approximately
Availability of Man	Part-or full-time within shirt-sleeve lab, or from crew compartment Occasional EVA to pallets

An enormously fruitful area for the Shuttle will be the use of space as a plasma laboratory (see figure 5), where experiments can be performed in a region essentially free from the wall effects that so often bedevil the researcher in the laboratory on the ground. Also, using space as an atmospheric laboratory to perform experiments that have a bearing on cometary and planetary phenomena, the Shuttle will be an extremely useful tool to investigate the mechanisms governing the environments of other bodies in the universe.

The three principal objectives of Atmospheric and Space Physics program for the Space Shuttle are:

- to investigate the detailed mechanisms that control the near-space environment of the earth;
- to perform plasma physics investigations not feasible in ground-based laboratories; and
- to conduct investigations on planetary and cometary phenomena.

The Working Group primarily concerned itself with studying three important characteristics of the sortie mode: a high payload weight and size capability, a 7–21-day duration, and the presence of Man. These features can be used very effectively for all the major research needs foreseeable in the discipline, except for those that may require long-term gathering. Taking these considerations in mind, the Working Group was able to propose various explicit experiments. I shall detail some of them.

Shuttle as source. The Shuttle can "paint" a significant fraction of an entire orbit with chemicals such as barium or helium. Observation of such a trail, with aircraft and ground-based cameras, could provide in one day more information on global circulation than years of sounding-rocket releases. Both neutral and ion winds can be studied, and temperature data can also be obtained.

The use of electron accelerators to generate artificial auroras could provide definitive answers to significant questions concerning acceleration mechanisms and plasma instabilities. Ground-based and aircraft observation stations would be needed, and rocket flights could also provide useful diagnostic data. The same accelerator in the "electron echo" mode can provide data on magnetic and electric fields integrated over long paths. One very important application here will be the use of electron beams, stepped or ramped in energy, and operated in both reflection and transmission modes, in order to determine the electric potential drop along entire magnetic lines of force.

Shuttle as a plasma laboratory. The stimulation of plasma resonances with an on-board transmitter can provide rapid answers to questions concerning the critical power levels, the interaction volumes, and the resonant (Fourier) structure if a maneuverable sub-satellite is used as a probe.

Shuttle as perturbation. The wake behind the Shuttle can be mapped with a maneuverable sub-satellite. Both the real wake (including outgassing) and the wake from a clean test body can be investigated in detail.

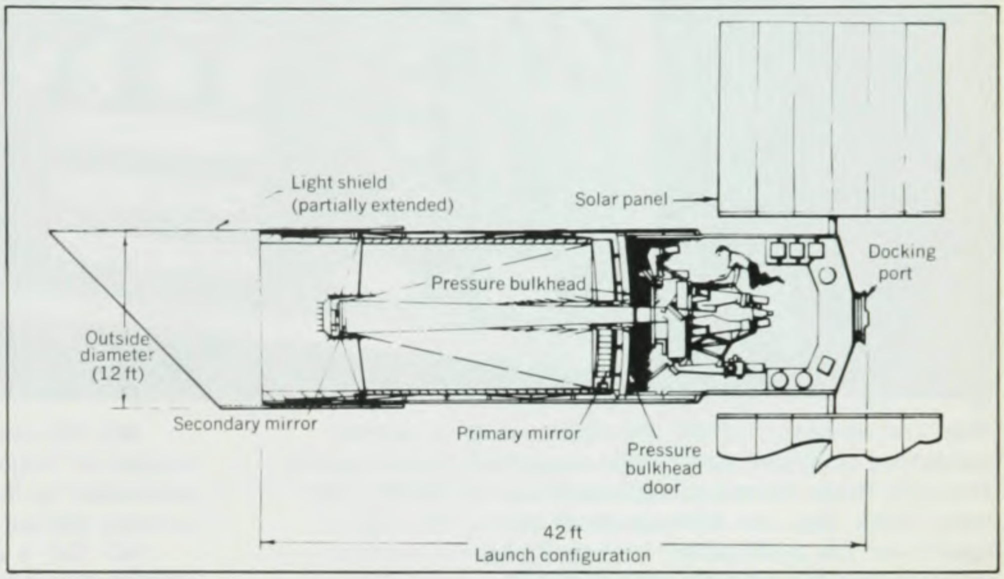
Shuttle as observing platform. The Shuttle provides a versatile platform for investigating a wide range of wave-particle interactions. The waves may be generated on board, to interact with ambient particles; or particle streams may be generated on board to interact with radio waves transmitted from the ground. The interactions that have been suggested range from the weak perturbations that trigger VLF emissions to the strong interactions that could produce significant perturbations in the radiation belts.

Shuttle as a precipitator. It has been pointed out by a number of workers that conditions often exist in the magnetosphere under which the addition of small amounts of cold plasma at appropriate locations will result in rapid growth of wave instabilities and produce subsequent dumping of large amounts of trapped particles into the atmosphere. Several Shuttle experiments are envisioned in which canisters of 20–40 kg of light gases are released just inside or just outside the plasmapause to explore the question of whether tubes of magnetic flux can thus be emptied of their energetic-particle contents for short periods of time. These experiments, if successful, will point the way toward active control of the radiation content in the Van Allen belts.

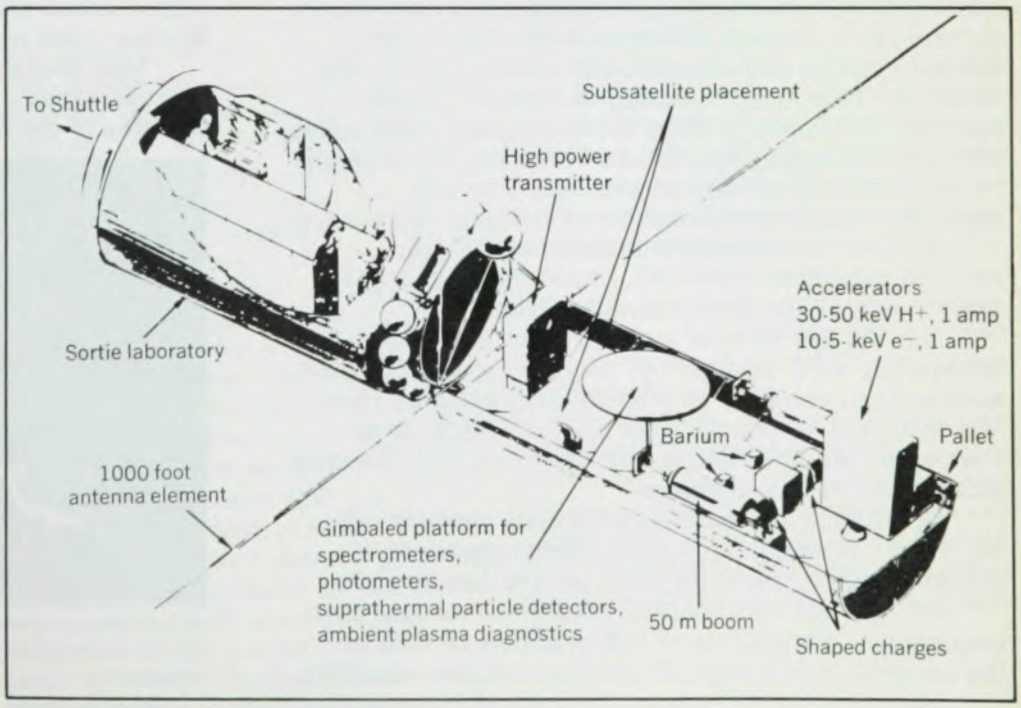
High-energy astrophysics

High-energy astrophysics is an important and critical part of the present explosive growth of our knowledge of the cosmos. It is concerned primarily with the detection of x rays, gamma rays and cosmic rays. Because of their absorption by the earth's atmosphere, these radiations must of necessity be examined from space. The High Energy Astrophysics Working Group headed by Albert Opp of NASA, proposed a program that would be a continuation of the present program, which uses satellites, sounding rockets and balloons. The Shuttle generation of research will not only see instruments of greatly approved sensitivity but also a great expansion in the repertoire of observational techniques. In their report, the Working Group made recommendations separately for each of the three subfields.

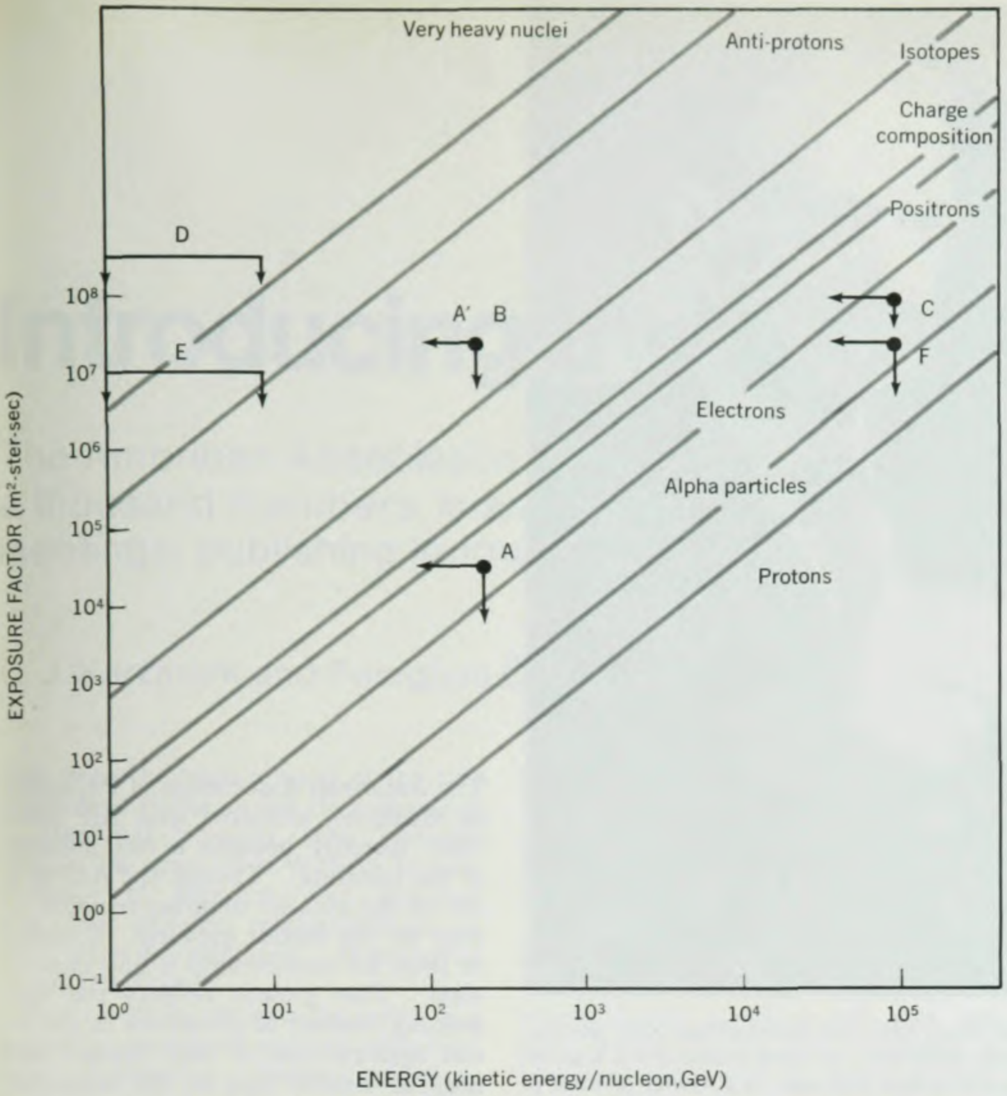
Soft x-ray astronomy. Traditionally, x-ray astronomy lies within the domain of 1–20 keV. Shuttle-era research should continue the work start-



The Large Space Telescope (LST) will be a versatile international observatory. Through use of the Space Shuttle for repair and maintenance, it will have a long life and will show progressive improvement in the capabilities of its instrument systems. The LST's resolution will exceed the present observations by at least three orders of magnitude. Figure 4



The Plasma Physics and Environmental Perturbation Laboratory (PPEPL), developed with widespread participation of the scientific community, will consist of a pressurized cabin and an unpressurized pallet. Two 50-m retractable booms are mounted at the far end of the pallet. They can be fitted with instruments such as antennae, particle detectors and magnetometers. The pallet will also contain particle accelerators, a transmitter with antennae extendable to 300-m and a gimbled platform for holding instruments. Figure 5



Exposure factor (geometry factor times exposure-time) required to measure cosmic-ray fluxes at a given energy. These curves were drawn assuming that all charged particles have the same power-law energy spectrum and that it is desirable to gather at least 100 events. The range of exposure and energy covered by the various detectors that will be carried by the Shuttle are indicated by arrows. Figure 6

ed by the x-ray satellite Uhuru in mapping the sky for various x-ray sources. In addition, x-ray observations with the Shuttle should have impact on studies of the structure and dynamics of stellar atmospheres and of the interstellar and intergalactic media. Also new classes of objects might possibly be discovered. The Working Group felt that x-ray astronomy has already developed to the point where a large national facility is clearly justified. The basic instrument they proposed is a high-resolution imaging telescope that will reflect and focus x-ray photons up to at least 4 keV. It will have an observational capability comparable to optical telescopes. In addition to imaging, the telescope will have supporting instruments to do spectroscopy and polarimetry. To cover the remaining part of the soft x-ray spectrum a large-area proportional counter array will be used; this is the only means known to obtain a large effective area for x-ray detection in the 3–15-keV region.

The hard x-ray and gamma ray sky appears quite different from the low-energy x-ray sky. An intensive effort during the Shuttle era to determine the origin and spectra of these radiations will set the stage for discoveries that may well parallel the remarkable advances made by Uhuru. The wide range of energies of this region of the spectrum dictates that a variety of observational techniques will be used; basically, hard x-ray observations (10–300 keV) will use detectors that totally absorb the input photons while, in the MeV range, electron–positron pair production must be utilized.

Cosmic-ray astronomy: The same high-energy processes that are responsible for x rays and gamma rays also produce high-energy charged particles, which are then trapped in the galaxy for a lifetime of approximately one million years by magnetic fields. The resulting energy density of cosmic rays (approximately 1 eV/cc) is comparable with that of the containing magnetic fields, with starlight and with the kinetic motion of bulk matter; high-energy cosmic rays therefore are a major element of galactic structure, and the study of them is an important complement to the whole range of astronomical observation from radio waves to gamma rays. The Working Group listed three types of experiments that will have high priority in the early Shuttle missions; they are all within the state-of-the-art of cosmic-ray instrumentation but not of present spacecraft.

The experiments will determine accurately, from *direct* measurements, the energy, mass, and charge spectra of the more abundant cosmic-ray nuclei (from hydrogen to iron) from about 10^{10} eV to the maximum possible energy, and the charge distribution of nuclei heavier than iron; they will determine accurately the energy spectra of cosmic-ray electrons and positrons above 10^{10} eV, and will search for antinuclei in the primary cosmic rays. Figure 6 gives an indication of how the exposure factor and the kinetic energies of the various cosmic-ray particles determine the type of instrumentation that must be used to detect them.

An invitation

The Space Shuttle System will become operational in six years and substantially change our traditional methods of space research, opening up an era of permanent observatories and laboratories in space. Its capabilities as a research tool are summarized in the box on page 34.

Scientists who want to help shape the Shuttle system to their needs should begin to make their needs known. The scientists who will be on the frontiers of space research in the 1980's will be those who have recognized the potential of this new transportation system and planned their research to exploit it.

In addition to two pilots and one mission specialist, the Shuttle will provide facilities for from one to four crew members. It will be essential that these crew members be scientists with professional competence to make value judgments pertaining to the scientific goals of the mission and to have an intimate familiarity with the instrumentation. The Shuttle era will also then be an era of the scientist in space in a quite literal sense.

Scientists who desire to participate in the Shuttle Payload planning activities or who want additional information on this subject can contact the executive secretary of the NASA Shuttle Payload Planning Steering Group, Gerald W. Sharp, Code SG, NASA Headquarters.

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The material in this article is drawn from a talk given by the author at the April, 1973 APS meeting and from the ten-volume set of reports of the NASA Shuttle Payload Planning Working Groups that was published by NASA in May 1973. □