

Chapter VII

Beyond “The Gate of Heaven”: Marshall Diversifies

“Open the gate of heaven.” With these words, recalled Ernst Stuhlinger, Wernher von Braun defined the Center’s mission during the early Saturn years. Marshall would develop rockets for scientists and astronauts to use.¹ But cuts in NASA’s funding in the late 1960s led the Center to redefine its role. As Saturn development wound down in the mid-1960s, however, Marshall had a head start in dealing with hard times. Consequently Von Braun reorganized his Center to compete with other NASA Centers for scarce resources. In 1968 von Braun designated Dr. William Lucas as “his vice president for new business” and head of the new Program Development office.² Diversification continued under the leadership of Eberhard Rees and Rocco Petrone, reaching fruition after Lucas became director in 1974.

By the mid-seventies Petrone’s wish that Marshall become “a scientific bounty hunter” had come true.³ The Center made major contributions to *Skylab*, scientific instruments, satellites, applied engineering, and a wide range of space sciences. Diversification would culminate when Marshall became Lead Center for NASA’s two major scientific projects for the 1980s, Spacelab and the Hubble Space Telescope.⁴ Such a variety of projects involving piloted and scientific spacecraft, and both engineering and scientific research were unmatched by other NASA Centers. Praising Lucas for making Marshall “a very diversified Center,” Andrew J. Stofan, director of NASA’s Lewis Research Center from 1982 to 1986, said, “Bill diversified that Center beautifully. That’s one thing he really did well.”⁵

When Marshall diversified, Center personnel confronted new technical and managerial challenges. Their solutions changed Marshall’s culture and relationships with other organizations. Internally Marshall enhanced its scientific sophistication by adding researchers with doctoral degrees and expanding cooperation between engineers and scientists. Externally the Center extended

circles of cooperation with academic scientists, other NASA Centers, commercial interests, and other government agencies. Such growth, not surprisingly, was accompanied by struggles to control new territory. Marshall's success in many struggles propelled the Center beyond the "gate of heaven."

From Specialty to Diversity

Throughout most of the 1960s, Marshall personnel worked primarily on one very big engineering project—the Saturn launch system. The technical and managerial challenges of developing the mammoth boosters and supporting the lunar landing mission necessarily led to specialization in engineering rather than scientific research. Center strengths were in areas related to propulsion technology such as metallurgy and fluid dynamics. German and American engineers avoided intimacy with science and scientists unrelated to rocketry, making the popular term "rocket scientist" a misnomer. A kind of polarization developed between scientists and engineers; Stuhlinger recalled that engineers often argued that "we will build a spacecraft, and when it is all said and done and we have the lock-and-key job completed, then the scientists may come in and hang their pictures on the wall."⁶

In part this narrowness was a legacy of Army practices. At White Sands, V-2 rockets had launched the instruments of American scientists.⁷ But the real task of the Army Ballistic Missile Agency had been to develop launch vehicles. ABMA rockets nonetheless continued to offer opportunities for scientific research in the upper atmosphere.

Accordingly the German and American rocket engineers worked with outside scientists in a relatively clear division of labor. The Army provided launch vehicles and the scientists provided instrument packages. In 1958 on Explorer I, the first American satellite, the Jet Propulsion Laboratory and James Van Allen of the State University of Iowa developed instruments; ABMA supplied the Jupiter C booster and integrated the instruments into an ABMA satellite. The teamwork paid off when Explorer I discovered radiation belts in the Earth's magnetosphere. Even after ABMA's group became the Marshall Space Flight Center in 1960, outside scientists and the rocket engineers continued this relationship in the Explorer and Pioneer programs. Relying on scientists from universities and research institutes, of course, was nothing new for NASA, but Marshall never had hundreds of experimenters like the Goddard Space Flight Center (GSFC) or Jet Propulsion Laboratory (JPL).⁸

Marshall’s few scientists primarily supported engineers. Personnel with science training worked in all of the Center’s laboratories. Scientists in the Aero-Astrodynamics Lab studied wind loads during launch and others in the Test Lab investigated the acoustic-seismic effects of engine tests. Most scientists, however, worked in the Research Projects Lab headed by Stuhlinger. Research Projects had the fewest permanent personnel of any of the Center’s eight labs; it had only 87 permanent onboard slots while five other labs had over 600 each.⁹

ABMA created the Research Projects Lab in 1956 and teams working on the Explorer and Pioneer projects formed its nucleus until 1962. Personnel supported the satellite programs with management and design studies, devising scientific requirements for engineering development. While still part of the Army, the lab designed and built spacecraft for Explorers I, III, IV, and VI, and later in NASA did the same for Explorer VIII and XI. This was a major task since so little was known about the thermal, radiation, and meteoroid environment of space. By 1962 the lab widened and deepened its experimental research. Experts worked on spacecraft thermal control, radiation environment and shielding analysis, meteoroid protection, electric (plasma and ion) propulsion, materials research, and lunar soil and terrain studies.¹⁰

Despite the utility of their research, the team struggled to get respect in an engineering-centered organization. Both German and American engineers expressed patronizing attitudes for payload work, referring to Research Projects as “Stuhlinger’s hobby shop.” Von Braun contributed to this attitude, Stuhlinger remembered, because the Center director preferred providing services for outside scientists to specializing in science. ABMA originally designated Stuhlinger’s group as the Research Projects Office, rather than as a laboratory, signifying their inferiority to the engineering labs.

The scientists also lacked resources for research. Even in the early days in NASA, Research Projects had no budget allotment for scientific equipment. Bill Snoddy, then a young American scientist in the lab, recalled how his colleagues in 1961 and 1962 had to bootleg hardware using procurement lines from other labs. Von Braun, though reluctant to support science at Marshall, was delighted when finally shown the fully equipped scientific laboratory.¹¹ Within its engineering mandate, the Research Projects Lab still did useful science and played the leading role in two science projects, High Water and Pegasus. Project High Water was an experiment in atmospheric physics that emerged partly in response to criticism of the absence of science in stage-by-

stage testing. The Block I Saturn I test flights lacked scientific instruments and had a dummy upper stage filled with tons of ballast sand. To add science to the tests, Marshall developed the simple High Water experiment, which NASA Headquarters publicized as “the first purely scientific large-scale experiment concerned with space environments” and as a “bonus” project that took advantage of Saturn’s wasted lifting capacity.

On the second and third Saturn I flights in 1962, Marshall replaced the ballast sand with 86,000 kilograms of water and used explosive charges to release the water into the upper atmosphere. When exposed to the low pressure of the ionosphere, the water boiled violently, then quickly evaporated and became a frozen mist. Within three seconds an ice crystal cloud expanded to 10 kilometers in diameter and produced electrical discharges much like a thundercloud. Scientists on Earth, in planes and on ships, studied the events using cameras, radar, and radio receivers. From High Water they not only learned about clouds, but also about the effects of fluid and gaseous discharges on telemetry.¹²

A more sophisticated mix of scientific and engineering research came in the three meteorite sensing satellites of Project Pegasus. The idea for Pegasus came in 1961 when the earth-orbital-rendezvous mode was still under discussion and Marshall engineers were worrying about meteoroid impacts on orbiting vessels. To maintain conservative standards and check designs of spacecraft and fuel tanks, they wanted more information about meteoroid size and frequency. Accordingly the Research Projects Lab conceived detection satellites, and Center personnel and the Fairchild Corporation built them.

The Pegasus satellites were mounted on an S-IVB second stage, and each had detection panels with a wingspan of 15 meters, electronic sensors and communicators, and solar power panels. Making use of Saturn’s lifting capacity, they were NASA’s largest satellites to date and were easily seen from Earth, having a surface area 80 times larger than Explorer meteoroid detectors. NASA launched the satellites in the spring and summer of 1965. Although Pegasus I had a flawed communications system, the second and third missions worked perfectly with Marshall’s improvements. Marshall personnel monitored the missions from a Satellite Control Center at Kennedy Space Center and quickly analyzed the data so NASA engineers could use them immediately.¹³

One newspaper columnist criticized the program, writing that Pegasus set “a record for futility even in the annals of the National Aeronautics and Space

Administration." He thought that the program's hidden purpose was to justify the cost of Saturn I, Wernher von Braun's "\$900 million dead-end kid," which, before Pegasus, had launched nothing "more glorious than a few tons of over-priced, 'space-rate' ballasting sand."

Such criticism unfairly ignored the achievements of Pegasus and how the satellites had yielded valuable information about meteoroid size and frequency. Before Pegasus, data had been highly uncertain and had indicated that spacecraft would be vulnerable to meteoroid damage. Pegasus data showed that the danger was minimal and that protective standards could be greatly relaxed. NASA engineers used Pegasus to create criteria for spacecraft design and ensure the success of the Apollo Program. Von Braun believed that the "Pegasus data have really become the main criteria . . . for all manned and unmanned spacecraft."¹⁴

Pegasus notwithstanding, in comparison to later years, Marshall personnel in the 1960s worked on science projects that were limited in number and range. Stuhlinger grumbled in a Weekly Note in 1969 that science at NASA remained just "a stepchild," and in 1966 one of his lab's division chiefs lamented that scientists had "the lowest priority in the budget."¹⁵ As Saturn development came to a close in the late 1960s, however, Marshall personnel found opportunities to diversify.

By 1969 the *Skylab* Program and the Program Development Office sponsored multiple, sophisticated scientific projects. *Skylab* was significant not only because it represented the first big project outside of propulsion, but also because it combined manned flight and space science.¹⁶

At the same time Marshall was coping with the new technical challenges of *Skylab*, von Braun and his top assistants worked out a new Center strategy and organization.¹⁷ Faced with declining budgets, manpower limitations, and Headquarters' pressure, Center managers decided in late 1968 that Marshall's survival depended on winning new projects, especially big science projects. Consequently the organizational changes sought to make science more prominent. Von Braun appointed Stuhlinger to the new post of Associate Director for Science. Von Braun created the position reluctantly, Stuhlinger remembered, and only after NASA Administrator James Webb urged him to improve the "image" of Marshall among scientists. Von Braun also created the Program Development Office and chose Dr. Lucas as its head. The broadening of mission

also showed in new organizational names. The Research and Development Operations Directorate, the name for the laboratory side of the Center, became Science and Engineering. In 1969 the Research Projects Lab became the Space Sciences Lab.¹⁸

Following these changes, the Center diversified into new areas. By the mid-seventies, new research and development work included multiple *Skylab* and shuttle projects on solar astronomy, Earth resources, biophysics and materials processing, the HEAO series of satellites for high-energy astronomy, and the Hubble Space Telescope for planetary, stellar, and galactic astronomy.

To attract and support such scientific projects, Marshall began hiring scientists with doctoral degrees. This was necessarily a slow process given NASA's hiring limits and Marshall's personnel gaps. Stuhlinger, when asked in 1991 to describe Marshall's strengths in the space sciences during the late sixties, replied, "Sorry, almost none. There was practically no support for scientific work from Center management, and consequently not much from Headquarters." Although this was an overstatement, it was clear that to build strength, Marshall managers needed the support of Headquarters. In 1971 Center Director Rees complained to Harry Gorman, NASA Deputy Administrator for Management, that Marshall was working on a wider variety of important science projects than any other Center, but with fewer scientists. The Center, Rees said, had "an urgent need to continue to strengthen our in-house capability in space-related sciences."¹⁹

Marshall's Space Sciences Lab did become stronger. Finally protected by Center leaders from the reductions-in-force that decimated the rest of Marshall, the lab maintained about 150 personnel and gradually added Ph.D. scientists. While Center personnel was declining by one-third overall, the number of people holding scientific doctoral degrees increased.²⁰ By 1980 the Center had specialists in atmospheric science, solar physics, magnetospheric physics, high-energy astronomy, X-ray physics, superconductivity, cosmic rays, infrared physics, and microgravity science. Nevertheless Marshall never became a dominant NASA research center. The Center's managers had accepted the role of a development center, but had argued for the latitude to propose science projects. They laid out their position to Headquarters in 1968, just after the peak of the Apollo-Saturn program:

“Roles and missions [for field centers] are desirable only in a way which makes the best possible utilization of the Center’s capability, experience, and motivation. The Centers should be encouraged to maintain a competitive position with other Centers within reasonable bounds. There is a danger in setting irrevocable roles and missions. We need to foster the Headquarters/Center relationship in much the manner that a customer/contractor relationship exists. The Centers should be free to submit competitive bids for projects for which they have the capability and capacity. The competition must not go to the point where the inter-Center relationships and mutual trust are damaged. For example, research Centers probably should not get heavily involved in development. Nor should development Centers get heavily involved in research. It would be equally wrong to legislate against research Centers doing any development or development Centers doing any research.”²¹

Marshall’s diversification and enhanced scientific sophistication did not bring a revolutionary change in culture. Dr. Charles R. Chappell, a physicist who came to Marshall in 1974 and later became associate director for science, observed that “S&E,” the Science and Engineering Directorate, was “mostly E.” The Center still had hundreds fewer scientists than Goddard or JPL. Moreover Marshall’s scientists continued to play a role in engineering support as they conducted space science research. They sometimes believed that they lacked the autonomy experienced by their NASA peers and the resources needed to conduct research and maintain expertise.²²

Most resources went to propulsion projects like the Space Shuttle. But in addition to being a propulsion Center, Marshall became an engineering organization for big science projects. As in the Saturn era, the Center’s mission remained providing spacecraft and instruments for science rather than conducting all of the scientific research. Much of the experiment conception and analysis came from external scientists. Stuhlinger, in view of the strong orientation of the Center’s top management toward engineering rather than science—but determined to maintain a high standard for Marshall’s scientific projects—set forth the philosophy in 1966, arguing that Marshall should avoid the Goddard Space Flight Center’s “authoritative way” of in-house science. Marshall should only help define the mission, provide cost and schedule constraints, and select competent project managers. The experimenter should define the goals of research, and NASA should provide assistance in producing a “flyable package that does not compromise the experimenters’ objectives.”²³

By becoming an engineering center for space science Marshall diversified and survived. Essentially, the new strategy evolved out of rocket engineers' alliance with external scientists. Marshall took advantage of its strength in engineering and avoided confinement to particular scientific fields like NASA's research Centers. With this strategy, almost any field was open, and over time the Center's space scientists became known and respected by colleagues at other Centers and universities. The first big step through the "gates of heaven" was *Skylab*.

***Skylab* Science**

For *Skylab*, the first American space station, Marshall was Lead Center, designing and developing the workshop and a substantial portion of its scientific hardware. The Center also led NASA efforts to solicit experiment proposals from external scientists, managed experiment integration, and ensured that scientific hardware mated with the workshop. Moreover, Marshall helped with engineering, operations, and research support for *Skylab* science. Particularly significant were the contributions to the Apollo Telescope Mount (ATM).

For *Skylab* experiments, NASA relied primarily on scientists from universities and research institutes. The complexity and quantity of experiments on board the workshop, however, led Marshall to develop a more formal organization for managing science and coordinating its activities with other Centers and outside scientists. A new Experiment Development and Payload Evaluation Project Office supported NASA's system for selecting experimenters and helped scientists build hardware.

Marshall managed 51 of 94 experiments flown on *Skylab*, including experiments in astronomy and solar science, engineering and technology, materials processing, student experiments, and science demonstrations. Engineering studies gained insights into thermal controls, habitability, crew vehicle disturbances, and spacecraft environment. The processing experiments examined metallurgy, fluid dynamics, and crystal growth (which are discussed later in this chapter).²⁴ NASA initiated the student experiments in 1971 in order to attract interest in *Skylab*. NASA and the National Science Teachers Association held a competition among high school students and Marshall helped select the winners from 3,409 entries. The Center also developed hardware for the 11 studies which ranged from fluid mechanics to spider web formation to earth orbital neutron analysis.²⁵

During the *Skylab* missions the Space Sciences Lab also conceived several demonstration experiments. Astronauts on the first two missions asked for simple experiments to perform during their free time. In addition to their scientific and educational results, the demonstrations gave the third *Skylab* crew a change of pace. Since some experiments had clear objectives but offered limited guidance, the astronauts could choose the best method in orbit. The Space Sciences Lab devised demonstrations involving minimal equipment and studying such microgravity phenomena as the slow diffusion of liquids and the stability of a toy gyroscope.²⁶

The variety and complexity of *Skylab* science forced Center engineers to adjust. Dr. Stuhlinger recalled that working on a project that included such a large program of purely scientific investigations was a new situation for Marshall. In the past, engineers at the Marshall Center had been working with other engineers, with engineering contractors, and with project and program managers from Headquarters. Much of the scientists’ thinking, their way of planning and rationalizing, even their language was unfamiliar to them. During the early phases of the *Skylab* project, *Skylab* engineers and *Skylab* scientists lived in two different worlds. The engineers complained that the scientists “didn’t really know what they wanted,” and that they “changed their minds all the time”; and the scientists complained that the engineers “didn’t even try to understand their viewpoints, and the needs of a scientific experiment.”²⁷

The Space Sciences Laboratory tried to bridge the gap between engineers and scientists. A team of Center engineers and scientists serviced each scientific specialty. An engineer worked full time on one or two experiments, helping in design, development, and qualification. Integration engineers worked on a group of experiments to maintain compatibility with *Skylab* systems. “What was new” for engineers, observed Rein Ise, project manager of the Apollo Telescope Mount, “was the appreciation of the science itself, that is the understanding of what the scientists were trying to achieve and the system [that] could best support them.” Experiment scientists from the Space Sciences Lab acted as “representatives” for the principal investigators and helped engineers resolve development problems, thereby winning new prestige with their engineer colleagues and also with outside scientists.

Not until *Skylab*, when Marshall engineers became dependent on in-house scientists, Snoddy recalled, did they stop making references to the Space Sciences

Lab as a “hobby shop.” “All of a sudden they had all these experiments from throughout the world that were flying on that thing . . . and suddenly they found it kind of handy to have some people here at the Center who understood this stuff and could interface with the scientists.” Stuhlinger said “improvements came slowly [but] during the later phases of Project *Skylab*, cooperation between engineers and scientists worked well; MSFC had learned a few good and very useful lessons.”²⁸

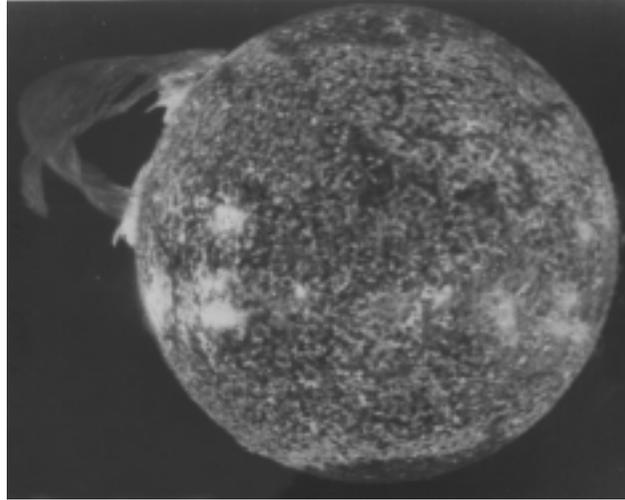
Achieving cooperation between scientists interested in particular experiments and engineers involved with the whole workshop was not always easy. The ATM system, Marshall’s first experience in developing and managing a science payload for a manned mission, was especially troublesome. The Center had to coordinate ATM operations with other experiments and resolve conflicts with the earth resources or medical experiments. The problems in planning operations were compounded by the lack of a chief project scientist at Marshall and at NASA Headquarters. One ATM investigator, Dr. Richard Tousey of the Naval Research Laboratory, complained to Stuhlinger in 1968 that “most of the problems which have plagued us in the ATM project are caused by the lack of a science-oriented person within the ATM project structure.” Acting as liaison for the scientists, Stuhlinger warned Frank Williams, director of the Center’s Advanced Systems Office, that “workshop planning” and “astronomy planning” were not “on a converging course” and that “if we lose the astronomers as customers. . . it will be most difficult to maintain a workshop development program.”²⁹

Conflicts over mission planning culminated in meetings in late 1970 and early 1971. The ATM principal investigators rejected the operations plan of Martin Marietta, Marshall’s experiment integration contractor. Without informing NASA, the scientists developed their own plan. After the shock of this rebellion subsided, NASA accepted most of the scientists’ program.³⁰

Marshall’s Space Sciences Lab managed the scientists’ joint observing program. Lab personnel and the principal investigators established a team of scientists and technicians for each ATM instrument. Before *Skylab*’s launch, the teams developed plans for maximizing research, making routine observations, and tracking dynamic solar events. Also before the mission, they practiced coordination with mission controllers and ground-based observatories. Cooperation with ground-based researchers around the world allowed for

synergistic study of solar events and took advantage of ATM’s ability to make simultaneous photographs in multiple wavelengths.

During the 13 months of *Skylab* missions, the Space Sciences Lab’s assistant director and over 20 specialists moved to Houston and helped run the joint observation program. The NASA teams met daily with the investigators to plan observations and coordinate work with ground-based observatories and 300 solar



The dynamic Sun, photo from Skylab’s ATM.

scientists around the world. While operating, an “ATM czar” from Marshall oversaw a console in mission control and sent digital commands to *Skylab* and written instructions to the astronauts via a teleprinter.³¹

Marshall used similar procedures to help study Comet Kohoutek. Discovered in March 1973, astronomers expected it to be very bright. NASA developed a rush observation program using ATM instruments, and the four *Skylab* astronauts took into orbit the electronographic far-ultraviolet camera designed as backup for Apollo 16. Marshall managed the *Skylab* observations from November 1973 through February 1974, and Goddard coordinated NASA’s work with other institutions. Marshall Center scientists contributed to studies of the comet’s anti-tail and brightness. If the public was disappointed because Kohoutek proved dimmer than the media predicted for “the comet of the century,” *Skylab*’s surveillance was a scientific success and showed the flexibility of a piloted orbital observatory. Kohoutek became “the best observed and studied comet in history,” and the ATM instruments proved sensitive enough even though designed to view the Sun. Spectral evidence supported current theories that comets were composed of ice and primordial materials.³²

POWER TO EXPLORE: HISTORY OF MSFC

After the missions ended, Marshall helped scientists interpret the data. The most elaborate support went to the astronomy experiments. With \$15 million from NASA, Marshall managed an ATM Data Analysis Program that funded data archives, analysis, reports, and conferences. Teams of scientists from around the world met in three solar workshops to discuss and report findings. The wide spectrum of ATM instruments, the scientists found, revealed new information about the transition region between the cooler chromosphere and the hotter corona, coronal holes at the solar poles, magnetic fields around the Sun and their effects on the earth's upper atmosphere, and the dynamics of solar change. Scientists analyzed these discoveries for more than a decade and the ATM became, according to Leo Goldberg of the Kitt Peak National Observatory, "one of the most important milestones in the history of solar astrophysics."³³

The success of *Skylab* and its science programs left a long legacy for Marshall. The contributions of Center scientists to *Skylab* made them "mainstream" and laid a foundation for cooperation with engineers on later projects.³⁴ Moreover *Skylab* formed the basis for later growth. Development of the workshop and the integration of its experiments helped Marshall become Lead Center for Spacelab and get a large role in Space Station efforts. Operations support during the missions set a precedent for Huntsville's science operations control facility for Spacelab. And the Center's work on *Skylab*'s scientific payloads, especially in solar astrophysics and materials processing, helped establish credibility among scientists and enabled diversification to continue.

The Satellite Business

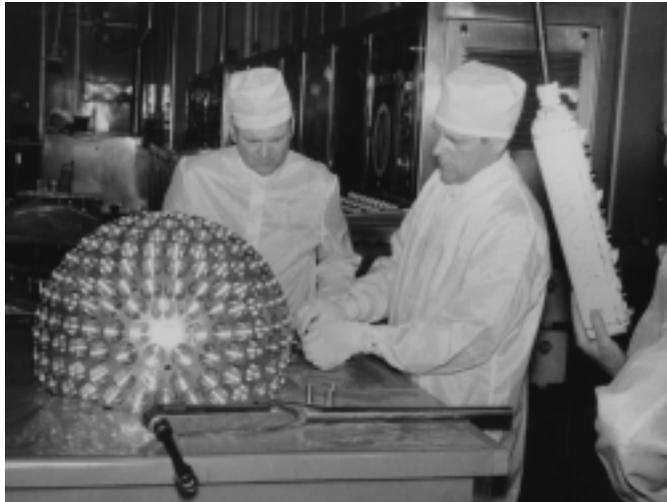
Even during research and development for *Skylab*, the Center was already working on several satellites and scientific probes. These payloads were automated, unlike *Skylab*'s ATM, and as a result Marshall had to work closely with other NASA Centers. The Center led successful efforts in high-energy astronomy, geophysics, and astrophysics.

One of the most elegant spacecraft was Marshall's Laser Geodynamic Satellite (LAGEOS). In 1964 geophysicists at the Smithsonian Astrophysical Observatory speculated that lasers aimed at a reflective satellite could help analyze the exact shape of the Earth and movements in its crust. They described their ideas in August 1969 at a NASA conference in Williamstown, Massachusetts, and later received support from Marshall. Since even the very thin atmosphere at

orbital altitude would disturb the satellite, the experts recognized that the mass-to-surface ratio of the satellite should be as large as possible. The more massive the satellite was, the more stable it would be. Therefore the scientists proposed Project Cannon Ball, a four-ton sphere to be launched by a Saturn I-B. The designers had thought too big, however, and NASA Headquarters rejected the proposal because of the configuration’s high cost.³⁵

Marshall and the investigators returned to the drawing board, and in 1973 Headquarters approved a scaled-down satellite designated as LAGEOS. The new design carefully optimized weight and diameter. The passive satellite weighed over 900 pounds and had no moving parts or instruments. Its aluminum shell and solid brass core optimized the mass-to-surface ratio. Brass alone would have been too heavy to launch cheaply, and aluminum alone too light to orbit stably. The designers of LAGEOS also had to choose a diameter large enough to maximize the number of mirrors and small enough to minimize drag. They chose a 24-inch diameter which allowed 426 fused silica retroreflectors, making the completed LAGEOS look like a “cosmic golf ball.” Because the sphere would stay in orbit for more than eight million years, NASA decided to mount a plaque inside to show its geologic mission.³⁶

Although LAGEOS development was a team effort, Marshall did most of the work in-house. Perkin-Elmer made the laser retroreflectors. Originally the Center intended to contract for a full-scale prototype and a flight model, but since machine shops in the Test Lab and the Quality Lab were working 30 percent below capacity, Center management decided to build the prototype in-house. Technicians machined



Assembly of LAGEOS at MSFC.

the holes and mounting rings for the retroreflectors and assembled the sphere even as a RIF was under way to lay them off.³⁷

Manufacturing LAGEOS was “a very precise high-tech job,” Marshall engineer Lowell Zoller noted, which “benefited from the very specialized manufacturing capabilities that we developed during the Saturn Program.” The Center’s prototype was so finely crafted and performed so well in tests that NASA made it the flight model. “The guys did such a great job with the first one,” said James Kingsbury, head of the Center’s Science and Engineering Directorate, “that we never built the second one. I think that it is the only program in the history of NASA that came in under fifty percent of cost and on schedule.”³⁸ Throughout the design and development phase, Marshall received scientific and technical support from the Smithsonian, Goddard Space Flight Center, and Bendix Corporation. Goddard also tested the mirrors, leading Marshall to alter the retroreflectors because six did not conform to design specifications. A Delta rocket launched LAGEOS in May 1976 and put it in a nearly perfect circular orbit.³⁹

Thereafter Goddard coordinated research using LAGEOS, which had an operational lifetime of 50 years. Laser ranging stations around the world projected lasers at the satellite and its mirrors reflected the beams back to Earth. By timing the round trip of the beams, geophysicists could compute a location on Earth within two inches of accuracy. This enabled measurement of shifts in polar ice, tectonic plates, and fault lines. In addition to improving knowledge about changes of the Earth’s crust, scientists hoped LAGEOS would help predict earthquakes.⁴⁰

In the early 1970s, Marshall also managed Gravity Probe-A (GP-A), which had science as elegant as LAGEOS and more exasperating engineering challenges. In the late 1960s, scientists—again from the Smithsonian Astrophysical Observatory—proposed a redshift experiment to explore the structure of space-time and test one of Einstein’s thought experiments in his theory of relativity. According to his “equivalence principle,” the effects of gravity and constantly applied acceleration could not be distinguished, a fact that would cause “warping” of cosmic space-time. Consequently, two clocks located at two different places with different gravity levels would tick at different rates. A higher gravity level would cause a slower rate. Thus by comparing the two clocks, one stationary on the surface of the Earth, and the other moving in

weightlessness onboard a free-coasting spacecraft, the earthbound clock would lag behind the spaceborne clock. The two-clock experiment would measure how several simultaneous effects contributed to the time difference: first, the classical Doppler effect between a stationary observer and a moving source; second, the relativistic Doppler effect between observer and source, described by one of the Lorentz equations in the special relativity theory; and third, the relativistic equivalence effect described in Einstein’s general relativity theory. Effects one and two were experimentally well proven and accurately known. Gravity Probe–A would allow measurement of the third and thereby test Einstein’s general theory. In late 1969, NASA Headquarters asked Marshall to help define this experiment. After rejecting a proposed satellite in an eccentric orbit for excessive cost, in 1971 NASA accepted Marshall’s proposal for a suborbital flight, Gravity Probe–A.⁴¹

GP–A was a joint project of the Smithsonian and the Center. The experiment required two super-accurate clocks, which the Smithsonian developed using atomic hydrogen technology. The clocks lost less than two seconds every one hundred million years and functioned within five thousandths of one percent of prediction. In addition to supporting the Smithsonian’s work, Marshall designed and built in-house the payload container and its power and communication systems. The Center also integrated the container with the clocks and instruments, tested the communications systems and the entire package. The finished probe was 45 inches long and 38 inches in diameter, weighed 225 pounds, and would spin during its hour-long flight.⁴²

Perhaps not surprising given the sensitivity and complexity of the equipment, the development of the probe was difficult. The Center and its partners encountered problems with its very stringent thermal-control system, electronic parts, the clock and leaks in its pressure vessel, and the probe’s spin dynamics and communication systems. The technical challenges, however, were exacerbated by people problems.

Initially Marshall blamed the Smithsonian for managerial failures which led to technical breakdowns. But Center managers admitted in August 1974 that “MSFC had underestimated the difficulty and complexity of the project” and failed to penetrate its contractor and provide enough resources. Therefore the Center had added more people and assigned a resident manager to the Smithsonian. It also required that the Smithsonian assign more people and improve its quality

practices. Nevertheless, by late November, NASA's Office of Space Science and Applications informed Marshall that it was "considering cancellation of the GP-A Project in view of the long series of incidents."⁴³

Problems continued, culminating in a test failure. In December the Systems Dynamics Laboratory ran a vibration test on the entire probe payload, unaware of its limited capacity to withstand lateral axis shock. The test was too strenuous and damaged parts of the probe, a serious error since Marshall was using a "protoflight" concept in which the qualification



Final check-out of Gravitational Redshift Probe-A at MSFC.

model used for testing would be refurbished and used in flight. An internal investigation revealed a "breakdown in communication" between the development and test organizations "similar to the problems that caused the loss of the meteoroid shield in *Skylab*." Center managers took technical responsibility from the project office and assigned it to the labs. Although communication problems did not recur, technical glitches slowed development. Gravity Probe-A went two million dollars over budget to cost nine million dollars and its schedule slipped over one year.⁴⁴

In June 1976 a four-stage Scout D rocket launched the probe from Wallops Island on a two-hour elliptical flight over the Atlantic. The probe attained a peak altitude of 6,200 miles and scientists compared readings from its clock with another at Cape Kennedy. The experiment was a full success and demonstrated the validity of this part of the General Relativity Theory to an accuracy never before attained. After the flight the principal investigators thanked the Center for helping "benefit the science of the experiment." They stated that Gravity Probe-A was "the first direct, high-accuracy test of the . . . [equivalence principle] and a beginning in the use of high accuracy clocks in space to measure relativistic phenomena."⁴⁵

The biggest satellite project Marshall managed between *Skylab* and Hubble was HEAO, the High Energy Astronomy Observatories. The new discipline of high-energy astronomy studied X and gamma radiation and cosmic-ray particles. To detect these forms of radiation, which have shorter wavelengths and higher frequencies than visible light, astronomers in the discipline depended on access to space. Initially they used instruments flown in sounding rockets or balloons, but recognized that satellites would be better. To get a satellite program, they formed a coalition in the late 1960s, drawing help mainly from the Harvard-Smithsonian Center for Astrophysics, Naval Research Laboratory, MIT, American Science and Engineering Corporation, and the Space Science Board of the National Academy of Sciences. Attracting support from NASA scientists, the coalition needed the backing of a field center.⁴⁶

Meanwhile, before the formation of the Program Development Directorate, Marshall’s Research Projects Lab was looking for new work. Stuhlinger met with the astronomers and wanted the project. Although the lab had no X-ray and gamma-ray astronomers, its Special Projects Division had radiation experts who had worked on NASA’s defunct nuclear propulsion program. Stuhlinger organized these people, under the leadership of Jim Downey, into an Electromagnetic Radiation (EMR) Project team.

The EMR team was less an instigator for the project and more an integrator, helping the scientists to conceive instruments and define technology for HEAO. Initial plans, similar to early concepts for the ATM, called for reconfiguring a lunar module to support X-ray instruments and using a Saturn V launch vehicle. From the beginning, the EMR team, Downey recalled, had many obstacles to overcome. First, since it had been put together on an ad hoc basis, the group lacked the sophistication and standing to build a coalition behind high-energy astronomy. “We were just trying to get some ideas so that we would have a respectable proposition” to present to Headquarters. The team “bootlegged the work” for more than a year, he said, on a strictly “catch-as-catch-can” basis. Even though the EMR team was moving the Center into a new area, support from von Braun and lack of bureaucracy created “an environment of innovation and creativity.” “We just didn’t know what we were supposed to be able to do,” Downey thought. “Maybe we were just too young to be as easily constrained to a system. I don’t know, but I don’t think we could do it today” because a project has to become “kind of official before you can start working on it now. To me in those earlier days, we would create the project.”⁴⁷

Even though Goddard had more experience in astronomy, Marshall got NASA's formal support for the HEAO proposals in late 1969. Several reasons accounted for this. Goddard was busy with other projects, and during austere times NASA could not provide more personnel. In contrast Marshall had a personnel surplus. Moreover Goddard supported the project because of its scientific merits and because Marshall's role would not threaten its dominance in astronomy. As Lead Center for development, Marshall would "provide assurance that the HEAO Project is technically sound, remains on schedule, and is accomplished within available resources." This mated Huntsville to another Center, with Marshall managing the design and development of launch vehicles, spacecraft, experiments, support facilities, and vehicle operations. Goddard would be Lead Center for science, having charge of mission planning and data analysis; project scientists for the first HEAO missions would be Goddard experts.⁴⁸

Based on this division of labor, Marshall established a project team in Program Development to make detailed experiment plans and vehicle designs. In March 1970, NASA released an Announcement of Opportunity for four HEAO missions and by November had already selected experiments for the first two satellites. TRW became the prime contractor for the spacecraft. HEAO plans called for "the largest payloads ever considered for an automatically operated US spacecraft," weighing 21,000 pounds and stretching 40 feet. Downey believed that Marshall encouraged the astronomers to "think bigger than they had been thinking" because the Center "had the big rockets" and "we thought big." Unfortunately Marshall's plans may have been too big, because NASA suspended HEAO in January 1973.⁴⁹

Budget cuts by the Nixon administration led the Agency to slash funding for automated projects and to "descope" (NASA's term for downgrade) the HEAO series. HEAO would have to be redesigned to cost one-third to one-half as much. In dealing with monetary constraints, Marshall faced management challenges far different from the lush funding of Saturn or even *Skylab*. Survival of HEAO, observed Dr. Fred A. Speer, Marshall's program manager, "depends upon our success here at Marshall in outlining a lower cost program which will obtain a major part of the scientific results sought in the original HEAO plan."⁵⁰ In the first months of 1973, Marshall's project office planned the reductions with the HEAO astronomers and contractors. They decided to postpone the beginning of the missions, setting back the launch of the first satellite from 1975 to 1977, and to economize by shortening the mission. Three small satellites

replaced the original four large ones. At three tons each, they were one-third the weight of the originals, but nonetheless very heavy scientific satellites. Atlas-Centaur boosters, rather than Titan IIIs, would launch the spacecraft. More than half the original experiments stayed; the X-ray instruments were light enough, but the cosmic- and gamma-ray instruments were too heavy and had to be redesigned. To keep costs low, Marshall also decided to use as much off-the-shelf hardware as possible.⁵¹

Using old hardware led to some awkwardness when the Grumman Corporation claimed that it could readily make HEAOs using hardware from Orbiting Astronomical Observatory satellites, a NASA program dating from the 1960s. As a result, Marshall decided to retain TRW as prime contractor. Although the Center justified its decision on legal and technical grounds, it also worried that the Grumman alternative would cost more money; moreover, building a new satellite would provide Marshall with more work than merely adapting an old one. At one point Center Director Petrone kept Grumman executives at bay by claiming his calendar was full for an entire month.⁵²

Meanwhile Marshall tried to maintain support behind the HEAO program. The Center stuck with HEAO, Speer recalled, because getting work “was always a consideration after Apollo.” To maintain support, Speer at the time counseled the investigators in “the need to act quickly and in keeping criticism on actions taken under control.” Although at least one scientist referred to the descoping as NASA’s “massive insult to science,” most contained their resentment. Realizing that their specialty bound them to the Agency, the scientists launched a campaign for HEAO in NASA and Congress. Success of UHURU, the first X-ray satellite, made their lobbying easier. In October 1974, NASA Administrator James C. Fletcher promised that HEAO would be the Agency’s “Number One priority” between Apollo-Soyuz and Shuttle, and in July 1974 development funding for HEAO resumed.⁵³

In the restructured program, each HEAO satellite had a specialized mission. HEAO–A and HEAO–C scanned the heavens to make maps of the whole sky. Each rotated end-over-end every half-hour but kept its solar arrays pointed at the Sun for power. HEAO–A scanned for X-ray sources and low-energy gamma flux and HEAO–C for gamma-ray emissions and cosmic-ray particles. HEAO–B pointed at sources identified by HEAO–A and had the first pointed X-ray telescope ever built. Its instruments, 1,000 times more sensitive than any

before, turned on a “lazy Susan,” rotating in the focal plane of the telescope mirror.⁵⁴

To achieve HEAO’s scientific goals, Marshall realized that budget and schedule constraints had to be maintained. If the Center and its partners did not use their resources wisely, the scientific instruments would never reach orbit. “The cost and schedule” of HEAO, Speer said in 1980, were “tightly controlled right from the beginning.”⁵⁵ Accordingly time and money determined many technical decisions during the development phase of the mid-seventies.

To minimize testing, Marshall and TRW used off-the-shelf space hardware like gyroscopes and star sensors. Almost 80 percent of the components for the HEAO—A spacecraft came from Pioneer, OSO, GEOS, and other satellites. The Center and its partners also standardized the three HEAO spacecraft with common computers, solar arrays, and equipment modules to support instruments.⁵⁶ Another way of saving development money was substituting “protoflight” for “prototype” testing. The traditional Marshall engineering approach was to build a prototype, or qualification model, for testing, and then use the lessons learned to build an improved flight article. Protoflight used a single piece of hardware for tests and flight. Richard E. Halpern, director of high-energy astrophysics at NASA Headquarters, told the Center to take a protoflight approach because the project lacked the money to build both a prototype and a flight model. HEAO’s budget shortfall, Speer remembered, led his team “to rethink some of these Marshall traditions. One of the first campaigns I took was to persuade my lab directors and my Center Director to give up on this prototype concept.” Marshall accepted protoflight partly because Goddard had used it successfully, but mainly because it helped “bring the price tag down.” In the end protoflight reduced costs 30 percent below original cost estimates of prototype-based development.⁵⁷ Marshall’s efforts to maintain budgets and schedules sometimes triggered conflicts with the scientists and their contractors. Protoflight reduced costs only if Marshall minimized hardware changes. The astronomers, however, often worried that resistance to change could prevent improvements and ultimately jeopardize research. Dan Schwartz of the Center for Astrophysics argued that “if you don’t do it with a certain quality, you get nothing. I felt that NASA was always pushing that threshold.” Another investigator believed that Marshall thought like a “bridge builder.” “It would be a disaster to build a bridge an inch too short, it would be silly to make it a foot too long. They very much stuck to the minimum requirements, when a little

extra might have yielded a substantial gain in quality.” In one case the scientists resorted to subterfuge to get improvement. When Marshall turned down a telemetry system checker that monitored data errors, the scientists resubmitted the same device as a “block encoder” and Marshall allowed it.⁵⁸

The Center’s close management of contractors and insistence on proper records also caused conflict. To the scientists, government record keeping was oppressive red tape. They later griped that if they had done all the paperwork, “the thing would still not be in orbit.” Disagreements culminated on HEAO–B experiments in 1975, when the Center blamed the scientists and American Science and Engineering for being lax and raising costs. This charge incensed Dr. Riccardo Giacconi, the pioneer in high energy astronomy, who protested to Headquarters that the scientists had more “carefully husbanded” resources than Marshall, and that “the level of visibility was neither sufficient for MSFC to closely monitor expenditures, nor adequate to foresee difficulties before they occurred.”⁵⁹

When the issue resurfaced in 1976, the president of American Science and Engineering complained to Speer about Marshall’s excessive oversight of the project. Marshall’s management, he argued, had “deteriorated to the point where it is not useful and is, in fact, detrimental to the program.” He believed that Marshall was making so many requests for so many kinds of information from so many people that responses “often require the expenditure of effort in conflict with our internal priorities.” The controls, he said, prevented his firm from “meeting our contractual requirements on schedule and with minimum costs.” Speer agreed that the goal should be “more efficient communication, not less” and that Marshall would change its practices and seek only meaningful information through as few channels as possible.⁶⁰

Generally, however, Marshall people defended the way they managed HEAO, pointing out the differences between the approaches of scientists and engineers. Astronomers, Speer observed, “didn’t particularly enjoy being X-rayed on their design project. . . . The PI (principal investigator) felt that he was in control of his experiment and he knew better than anyone in the world what it should do and how it should be built. He minded somebody from Marshall whom he considered not on par with his scientific capabilities to start questioning him on some things.” But Speer thought that success of HEAO caused the scientists to admit that, “Yeah, we didn’t particularly like it, but we agree now that it probably was not a bad idea to go through this sort of scrutiny.”⁶¹

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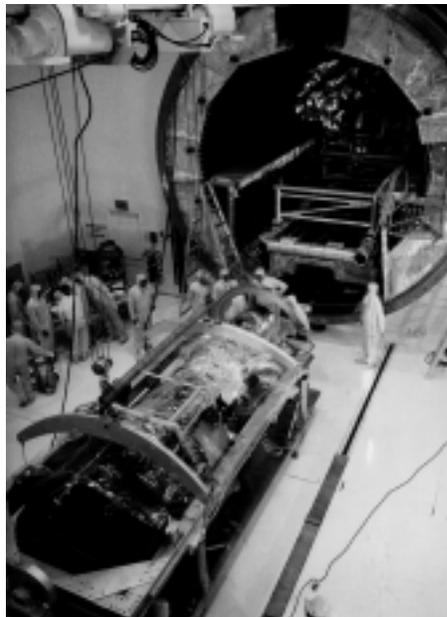
Dr. Thomas Parnell, a Marshall employee and project scientist for HEAO-C, said that Marshall's penetration was "a real shock to people who haven't been through it. We must prethink everything in nagging detail, everything that could go wrong and prepare for it. Also we have to worry about cost. The paperwork raises the cost, but it guarantees that, when we launch, everything we can do to ensure success is done." By the same token, working on scientific instruments led Center engineers to change their attitudes. Parnell believed that in the beginning, engineers thought a scientist was "esoteric and not very practical" and "should write his requirements out on paper initially and then get out of the way." But whenever problems emerged in development, the engineers had to abandon preconceived paper requirements and seek the advice of scientists. Thus HEAO's technical challenges, Parnell concluded, forced Center engineers to become more flexible in how they managed scientific projects.⁶²

Marshall also tried to save money by performing some tasks in-house. Arsenal capabilities, however, were mostly gone by the middle 1970s and the Center built no HEAO components. Marshall contributed to development more as designer and manager than as manufacturer. The Center's labs helped with spacecraft design, especially with troublesome gyroscopes. The Quality Laboratory ran a control center for electronics parts, and other labs helped with systems engineering and testing. The most lofty tests occurred aboard high altitude balloons. Marshall coordinated tests of cosmic- and gamma-ray detectors conducted aboard five balloons between September 1974 and May 1977.⁶³



Marshall employees recover Stratoscope II telescope after balloon flight near Bald Knob, Arkansas, in September 1971.

A more lowly but lengthy test of HEAO instruments occurred in the summer of 1977 in Marshall’s X-ray Calibration Facility. Marshall built the facility in 1975–1976 to simulate X-rays from distant celestial objects and thus test an American Science and Engineering telescope for HEAO–B. The Center estimated that construction would cost \$7.5 million but used surplus equipment from previous programs and cut costs to \$3.9 million. The facility consisted of a variable X-ray source connected by a pipe 1,000 feet long and 3 feet in diameter to a chamber that housed the telescope. The source, pipe, and chamber had to be evacuated together. The long distance was needed to test the telescope focus and produce an X-ray beam of very small angular divergence, approximating the parallel X-rays arriving from celestial sources.



HEAO–B telescope in MSFC’s X-Ray Calibration Facility.

Original planning called for a six-month test period, but a lag in the construction schedule forced Marshall to condense the tests into one month. Marshall technicians and the principal investigators worked 24 hours a day in two overlapping 13-hour shifts. They conducted nearly 1,400 tests and found problems that led to reworking the telescope hardware. The computer software developed for data retrieval during testing was later used for the same purpose during flight.⁶⁴

Marshall’s management of HEAO costs was very successful. During a time in which the consumer price index rose more than 50 percent, the high technology program finished within 20 percent of the original cost projection. Center Director Lucas told a HEAO Science Symposium in 1979 that HEAO–A had been built “at a lower cost per pound than any other NASA automated spacecraft.”⁶⁵

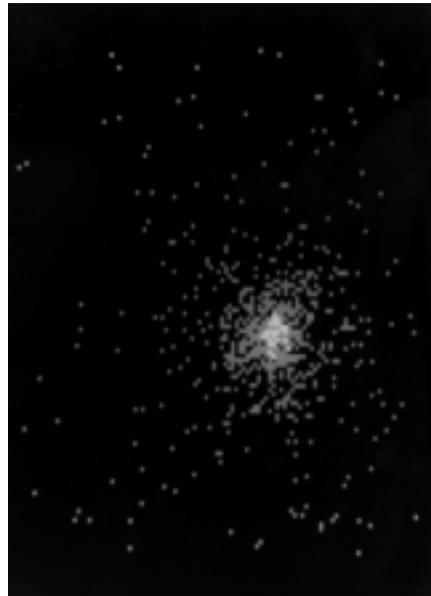
The Center co-managed operations for the three HEAO satellites launched from 1977 to 1979. Marshall established an HEAO operations office at Goddard

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and the two Centers divided authority. GSFC's role was mainly scientific, supervising mission planning, scientific observation, and data analysis. Marshall's role was primarily engineering. Although MSFC personnel helped plan observations with Goddard and the investigators, they primarily directed spacecraft communication and control.⁶⁶ The partnership played to the strengths of both Centers.

The operations role lasted longer than expected because NASA extended the lifetime of the HEAO missions. NASA had anticipated that the lifetime of the satellites would be limited by the amount of thruster gas needed for attitude control. But the earth's upper atmosphere proved less dense and the satellite control systems more flexible than expected. Marshall and contractor technicians developed techniques to maximize scientific observations while minimizing attitude changes, and to use computer programs and spacecraft gyroscopes to economize on thruster gas. These methods allowed for dramatic mission extensions; HEAO-2, expected to last only 15 months before its fuel ran out, kept going for nearly 30 months.⁶⁷

With the help of Marshall managers and technicians, the HEAO program became a great scientific success. For the first time, astronomers had clear images of high-energy radiation sources. HEAO-A found more than 1,200 new celestial X-ray sources. The focusing telescope on HEAO-B found thousands more sources and made detailed studies of the brightest ones. The first X-ray image of Cygnus X-1 from HEAO-B, one scientist said, was "almost like a religious experience." By providing new insights on supernovas, cosmic rays and heavy elements, superbubbles, flare stars and stellar coronas, neutron stars, black holes, pulsars, degenerate dwarfs, and quasars, the satellites showed the limitations of optical astronomy and the significance



First picture of the X-ray star Cygnus X-1, by HEAO-B, also known as the Einstein Observatory, November 1978.

of studying high-energy emissions. Thus, according to Wallace Tucker, an astrophysicist and a historian of the project, HEAO “not only changed our knowledge of the astronomical universe, it has changed the way that astronomy is done.”⁶⁸

The satellites of the seventies not only produced important scientific results, but also contributed to Marshall’s growing reputation as a multiproject Center. The projects created opportunities such as the astronomy facility Astro-1 on Spacelab, and the relativity experiment Gravity Probe-B. Especially the HEAO series, Fred Speer observed, “opened the door to a new dimension of our business,” establishing the Center as “a member of the Space Science club.” In part because of the project, Marshall would become Lead Center for AXAF, the Advanced X-ray Astrophysics Facility, with instruments 1,000 times more powerful than HEAO.⁶⁹

Space Materials and Microgravity Research

When Marshall began diversifying, its arsenal system engineering culture and propulsion specialty made the materials studies of microgravity science and applications a fertile field. Developing space hardware meant that Center engineers had to be experts on the properties of materials in space and allies of physical scientists studying the effects of microgravity. This collaboration pushed back the frontiers of a new science and would draw the Center into national debates about NASA’s mission and the commercialization of space.

Under ABMA and in the early NASA years, the rocket engineers contributed to materials research, because developing boosters required producing new materials and knowledge about the effects of the space environment. For the Explorer satellites, the Research Projects Lab discovered how to protect spacecraft from large temperature swings with thermal control coatings. The rocket engineers, especially in the Materials Laboratory, certified that materials met requirements. The Center’s labs developed Redstone graphite jet vanes, ablative nose cones, aluminum alloys for liquid oxygen and liquid hydrogen engines, and methods for welding and inspecting aluminum. They used the Pegasus satellites to gather information on the effects of striking particles on spacecraft. They learned how to manage liquids in low gravity and control liquid fuel floating in partially filled Saturn tanks. For *Skylab*’s crew waste and shower systems, Center technicians experimented on liquid dynamics in space.⁷⁰

POWER TO EXPLORE: HISTORY OF MSFC

During the late sixties, furthermore, the Center helped NASA make a transition from materials engineering into the new field of microgravity research. Inevitably early research in a new discipline was exploratory and involved trial and error. In 1965 Marshall personnel established a drop tower in the Saturn V Dynamic Test Stand in which they could release containers for several seconds of weightless freefall. Although initially used to study the effects of low gravity on fuel in rocket tanks, Marshall also used the drop tower for scientific experiments in microgravity research. During and after the *Skylab* program it helped test procedures and develop equipment.⁷¹

For Apollo 14 and 16 Marshall also helped devise “suitcase” experiments which studied how low gravity lessened convection, causing materials to mix and heat in other ways than on Earth. The investigations, recalled Dr. Robert Naumann, one of Marshall’s leading materials scientists, were “try-and-see” experiments that lacked the controls necessary for solid science. Nonetheless the Apollo experiments showed clearly that spacecraft did not experience real zero-gravity; gravity gradients, thruster firings, atmospheric drag, and crew motion created sources of small acceleration vectors which disturbed fluid motion and caused other small, but perceptible effects in materials processes.⁷² These discoveries caused scientists to change the designation from “zero-gravity research” to “microgravity research.”

The real breakthrough for microgravity science, however, came with *Skylab*. NASA added materials studies late in *Skylab* planning, largely because Dr. Mathias Siebel, director of the MSFC Manufacturing Engineering Lab, persuaded Headquarters to include them. For these experiments the Center also designed and developed a materials processing facility with a work chamber that included an electron heating gun and a Westinghouse-developed electric furnace. The late addition of this research program, Naumann remembered, meant that “We had something like eighteen months from the time that it was decided to add these experiments to the *Skylab* until the hardware was actually delivered. Given what it takes in time to do things today, that’s a pretty remarkable feat!”⁷³

Marshall personnel acted either as managers or principal investigators for three general types of materials experiments on *Skylab*. They examined construction methods in space and tested welding and brazing as means of joining structures. Demonstration experiments studied various effects of microgravity, such

as the melting of ice or the mixing of oil and water. Finally Marshall helped investigate metallurgical, chemical, and biological processes in microgravity and the potential of manufacturing novel materials in space, for example producing homogeneous alloys and growing pure crystals for electronics.

The experiments showed how gravity affected materials through convection, buoyancy, sedimentation, and hydrostatic pressure. Since materials processing in space was such a new field, results from *Skylab* were often isolated and unpredictable, yielding more questions than facts. Nonetheless Siebel observed that “the longest journey begins with a single step. This first step has been successful. We’re all ecstatic.”⁷⁴

Unfortunately after *Skylab*’s first big step, Marshall and NASA were forced to take only little ones because of funding constraints. Progress in microgravity research slowed because no regular, sustained access to space for the scientists existed until the shuttle. Moreover the Agency gave the research low priority. A General Accounting Office study in 1979 showed that annual funding for microgravity studies amounted to one-half of one percent of the terrestrial applications spending which itself was only eight percent of the total NASA budget.⁷⁵

Some progress came in the only manned orbital mission between *Skylab* and shuttle, the Apollo-Soyuz Test Project. For the mission in 1975, Westinghouse and Marshall improved *Skylab*’s processing furnace and the Center managed eight materials experiments that followed those done on *Skylab*. An electrophoresis experiment was particularly successful, separating biological cells by type and function and demonstrating the utility of microgravity research for medicine. Nevertheless, Naumann believed that Apollo-Soyuz was “about a level of sophistication lower” than *Skylab*. Not only did Apollo-Soyuz have less power, stability, and longevity than *Skylab*, but the short two-year interval between missions meant that NASA and materials scientists had little time to learn lessons from *Skylab* and introduce changes.⁷⁶

Through the late 1970s, materials specialists at Marshall searched for creative ways to continue their research. They conducted experiments in NASA’s KC-135 aircraft, the Center’s labs, and in the drop tower. Struggling against restricted budgets, the Center created a new facility, a drop tube for containerless experiments. Lew Lacy of the Space Sciences Lab scrounged materials for the

tube, finding in a warehouse one-foot diameter liquid oxygen pipes from Saturn rockets that had failed to meet specifications. Still facilities on the ground or in KC-135 airplanes were at best poor man's microgravity, offering only seconds of free fall in which to do research.⁷⁷ Accordingly, Marshall proposed and managed a sounding rocket program. The Space Processing Applications Rockets (SPAR) Program had 10 flights from 1975 to 1983, each with five minutes of research time as the rocket returned to Earth on a suborbital flight. Marshall ran SPAR on tight budgets with each flight costing about one million dollars. To save money, the Center worked with Goddard, which already had a sounding rocket program at White Sands Missile Range. Goddard supplied the Black Brant VC vehicles and directed launch and payload recovery. Marshall also saved money with in-house development of some investigators' hardware; the Center's labs designed, manufactured, integrated, and checked out about half of the experiment payloads. Roger Chassay, SPAR project manager, recalled that he was a "one-person project office" who chose the project name, wrote its plan, and in the first year wore through the soles of two pairs of shoes walking from lab to lab.⁷⁸

Managing a low cost program like SPAR forced NASA to tolerate higher than customary technical risks. Chassay said he had to convince lab personnel to use different technical standards because SPAR could not afford to follow the Center's traditional quality standards for manned missions. "That was always difficult for me," he said, "to have our management and our engineers relax their standards, their technical standards, to allow them to be compatible with the tight schedule and the tight budget of SPAR."⁷⁹

Headquarters had to be convinced as well. When all four experiments on SPAR IV failed, John Carruthers, Headquarters' director of materials science, acknowledged that the scientists were responsible for their hardware, but nonetheless recommended that Marshall increase its testing and penetration. In response Marshall objected to Carruthers "overstepping his bounds and telling us how to do our job" and thought "returning to the 'Apollo mode' of integration and penetration" would be "a big mistake." Marshall Director Lucas appointed a chief scientist to improve communication between external scientists and Center engineers and promised the Center would use more testing and simpler technology to avoid failure and "unnecessary criticism." But he also thought Headquarters should lower its ambitions for an experimental program and recognize that "scientific objectives can best be achieved after the apparatus has been proved in flight."⁸⁰

The SPAR flights had scientific, technical, and organizational payoffs. Microgravity specialists continued their research and improved their instruments. They developed containerless processors that suspended materials in an acoustic or magnetic field. SPAR also tested equipment for the Shuttle and Spacelab. Moreover, scheduling and integrating scientific experiments for a succession of flights taught Marshall payload managers lessons that proved useful for the Shuttle program.



Material processing experiments for a SPAR flight.

Project Manager Chassay remembered that Center Director Lucas enjoyed SPAR briefings, probably because the reports were “a pleasant diversion from some of the Shuttle problems for our Center management. They could see something positive going on. We would fly anywhere from four to nine experiments on a single flight and do that successfully.”⁸¹

Despite impressive early achievements, microgravity research and applications suffered the growing pains of an immature field. To grow, the field needed scientific credibility, a political constituency, and lots of money. NASA needed these things too in the lean years after Apollo. The Agency sought programs that could yield beneficial results and bring political support for space exploration and corporate backing for the Shuttle. By the mid-seventies, the Agency decided to fund microgravity materials research in major corporations. Consequently NASA defined microgravity research as an applications program and promoted it as investment in “the industrialization of space.” The common title for the field, “materials processing in space,” emphasized its practicality.⁸²

By the late 1970s, Marshall had assumed the leading role in promoting the commercialization of space processing. Press releases held out the promise that the research would eventually produce new materials, improvements in tools, electronics, and medicine, and ultimately “space manufacturing.” The goal of the publicity, according to Marshall’s Director of Program Development, was to create “a broad-based interest, and the climate and structure needed to sustain it within the context of our economic and political system.” Then the field could become commercial, and the NASA-business partnership could “add material benefits to man’s life style, satisfaction, and enjoyment, as well as make a positive economic contribution.”⁸³

Technological progress and material benefits, of course, had been a justification for the space program since its inception.⁸⁴ But NASA’s claims about materials processing in space would later become very controversial because NASA claimed it might also become commercially viable. The merits of this claim became part of discussions about the utility of the Shuttle, Spacelab, and a proposed Space Station. Thus Marshall’s efforts to commercialize materials processing in space helped provoke debates about the mission of NASA and the role of the government in the economy. What were the proper relations between business and government? Should government fund commercial R&D projects that had little business support? Could government officials anticipate the marketplace and pick commercially viable areas for research?

Whether the Agency was financing a boondoggle or a bonanza was unclear, and even optimistic Center engineers predicted a payoff only years in the future. But even as Center engineers envisioned commercial ventures in space, others worked on Marshall’s down-to-earth energy enterprise.

The Energy Business

By the early 1970s, a national economic slump deepened post-Apollo cutbacks. NASA’s plight became more serious when the 1973 Arab oil embargo touched off an energy crisis and a severe recession. Americans questioned the value of the space program. With the first Shuttle flight years away and the Apollo Applications program nearing an end, the Agency had few ways to capture public attention, and had to compete for scarce resources with other federal agencies. The new environment led NASA Centers to compete for the first time in space spinoff projects. NASA had worked with the Defense Department since its inception, but in previous contacts with other agencies NASA had always

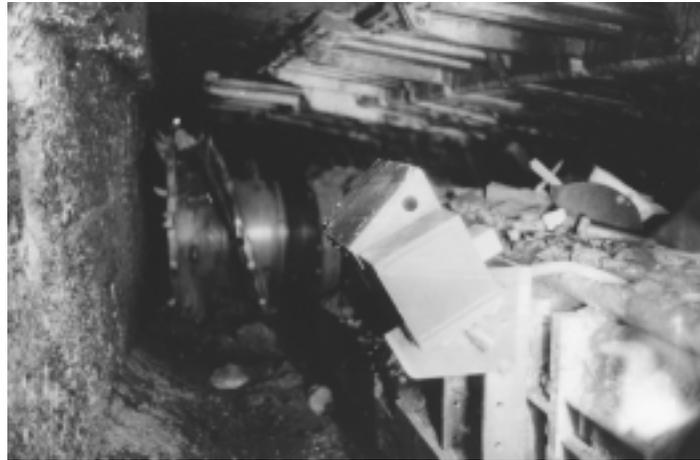
taken the lead. Now for the first time NASA would become subordinate to the Departments of Energy, Interior, and Housing and Urban Development. “We were used to doing things where we were the customers,” according to Bill Sneed of Program Development. But now the Center was developing technology for commercial companies, homeowners, or other government agencies, and “we had difficulty acclimating to that.”⁸⁵ Marshall and other Centers struggled to define new relationships with each other, with Headquarters, with other federal agencies, and with contractors in unfamiliar industries.

Diversification reached its limit when Marshall helped develop new coal mining technology. In 1974 a coincidence of interests between NASA and the Department of the Interior led Marshall to turn from the heavens to the earth’s interior. NASA sought ways to keep its name before the public during the flightless years of shuttle development, and Interior’s Bureau of Mines wanted fresh ideas to stimulate a flagging industry. New safety regulations and outmoded equipment had reduced mining productivity by 25 percent over a five-year period, and miners hoped new technology might stimulate the industry. Secretary of the Interior Rogers C. B. Morton challenged NASA Administrator Fletcher to apply NASA’s engineering talent to develop automated mining technology that would increase mining safety, minimize environmental damage, and increase productivity.⁸⁶

Notwithstanding the irony of the Space Agency setting its sights below the Earth’s surface, the proposal had merit. NASA hoped to justify more generous appropriations by demonstrating that it could deliver more than space spectacles. Coal mining offered a unique opportunity for NASA to help solve the national energy emergency.

That Fletcher selected Marshall as the Lead Center for NASA’s coal mining work was not surprising. The Center’s diversification plans had already led to active involvement in Earth resources programs in the Southeast. In the early 1970s Marshall had worked with state governments to develop a land classification system, to provide remote sensing for land surveys, to detect trees infested with the Southern Pine Beetle, and to develop a satellite-assisted system for the management of information on resources.⁸⁷ In January 1975, the Department of the Interior and NASA announced an interagency agreement for coal extraction. Marshall’s Program Development organized a task team to coordinate work with contractors, Interior, and NASA Support Centers.⁸⁸

Marshall identified the automated extraction of coal from deep mines as the area most likely to benefit from NASA's expertise. Automated mining techniques were replacing the traditional room-and-pillar method, which



Down-to-earth application of space technology for mining industry.

required that much quality coal be left behind for roof support. The new longwall shear system allowed miners to carve out entire seams, making mining both faster and more efficient. The greatest obstacle to automated longwall mining was the lack of an effective means of adjusting shearing equipment. Cutters needed to take as much coal as possible without penetrating into the roof or floor beyond the seam, and thereby diluting the quality of the coal or leaving too little coal for support. An improved system thus needed both sensors and a control system to guide cutting drums. Preliminary studies indicated that such equipment could extract as much as 95 percent of the coal from a seam while reducing the rock collected from five to one percent.⁸⁹

The task team found parallels to their customary work. Like space, mines were a hostile environment. "Everything about it is hostile. There's dust, shock, vibration," remembered Peter Broussard. "In space it's really in a way more benign." This meant that aerospace engineers had to adapt to the way miners worked. "A lot of it is sledgehammer stuff," explained Broussard. "You have to be able to make things so they will withstand the thousand natural shocks they're going to get either from the environment or the miners."⁹⁰

Marshall's fresh perspective produced profits. Using space-derived technology, the task team demonstrated that devices using gamma rays, radar beams, impact devices, or reflected light could improve performance of longwall shearing equipment. A Wyoming mining company used a Marshall depth-measuring device to save an estimated \$250,000 a month. Industry praised the Center's

achievements. The Department of Energy, created since initiation of the project and now responsible for its administration, hoped to see it continue.⁹¹

At the same time as it assisted the coal industry, Marshall broadened its energy research to include solar heating and cooling for residential and commercial use. Marshall and Lewis Research Center initiated Earth-based solar studies before other Centers and won the backing of Headquarters for their efforts. When NASA made a bid to gain the lead government role in solar energy research in the fall of 1972, Marshall was already planning solar energy prototypes. NASA won only a supporting role, but early involvement ensured that Marshall and Lewis would be the focus of the Agency’s solar energy activity.⁹²



Test of a solar collector in simulated sunshine at the Marshall Center, 1978.

As its first solar energy project, Marshall proposed developing a demonstration building heated and cooled by solar energy.⁹³ Headquarters approved plans in October 1973, and by December engineers had constructed a prototype solar collector, the “heart of the test article,” mounted at a 45-degree angle to simulate a roof. Nearby they positioned three surplus house trailers with 2,500 square feet of floor space to serve as the model solar house. The demonstration project went into operation in June 1974. Marshall’s *Skylab* experience helped advance the state of the art: a solar absorptive coating replaced black paint on the collector panels and absorbed 93 percent of the available solar heat, and computer simulations aided design and performance predictions.⁹⁴

Federal agencies jockeyed for energy funds with the advent of the energy crisis. Marshall’s position became clearer in the fall. In September Congress passed the Solar Energy Heating and Cooling Demonstration Act, which established the Energy Research and Development Administration (ERDA). NASA named Marshall as the Lead Center for the Agency’s responsibilities under the act, but

advised that other Centers must be encouraged to participate. As Lead center, Marshall would develop solar heating and cooling equipment and manage the ERDA Commercial Demonstration Program.⁹⁵

The Lead Center assignment in solar energy research testified to the dynamism of Marshall's diversification and the energy of Program Development. Marshall led the Agency into applied fields and charted a new entrepreneurial course for NASA. With Headquarters discussing the possible closing of Centers, however, Center Director Lucas knew that Marshall remained in a perilous position. Moreover, the Lead Center assignment in solar energy differed from one in development of space technology where the Lead Center could draw on other Centers to produce hardware for NASA. In applied fields, interagency contacts and institutional commitments constantly shifted, making the entrepreneurial environment even more competitive than normal Center relations, which were combative enough.

Consequently Lucas vigilantly guarded Marshall's lead in solar energy. When Langley Research Center asked for Marshall participation in an "Energy Conservation House" project, Lucas worried about "what appears to be our lack of initiative and resourcefulness in maintaining our apparent lead in developing ways of utilizing solar energy in residential and commercial activities."⁹⁶ Program Development offered participation to other Centers, but promised Lucas that "we will be very selective in our acceptance of their proposals."⁹⁷ Lucas offered participation to Johnson Space Center and Lewis Research Center only after Headquarters exerted considerable pressure.⁹⁸ Other agencies exploited the rivalry between NASA Centers; when Marshall complained that a Department of Housing and Urban Development procurement plan would make NASA technically responsible without management authority, HUD replied that the decision would be made at NASA Headquarters, not Marshall, and in any case Johnson could support them if Marshall would not.⁹⁹

Indeed much of Lucas's concern stemmed from his belief that Headquarters had retained more control over the solar energy program than space programs. The organization chart placed two management control levels above the Lead Center program manager while other NASA programs had only one. Harrison Schmitt, who administered NASA's energy programs at Headquarters, acknowledged a new environment in which "traditional words of management may

have to be applied in new ways.” Schmitt confirmed Marshall’s lead on technical matters, but insisted that Headquarters would lead in contacts with other federal agencies.¹⁰⁰

Marshall’s contributions to the nation’s solar energy program grew, and during the second half of the decade the Center seemed destined to fulfill von Braun’s promise: “Huntsville helped give you the moon and I don’t see why Huntsville can’t also help give you the sun.”¹⁰¹ After NASA negotiated an agreement with the Energy Research and Development Administration (ERDA) in March 1975, the Center helped select and manage ERDA commercial demonstration projects.¹⁰² Marshall assumed technical management for a Department of Energy project to introduce solar energy into federal buildings.¹⁰³ By 1980, Marshall had responsibility for 106 of the 285 commercial solar energy projects selected by ERDA and the Department of Energy. Center personnel assisted the solar industry with over 150 system design reviews.¹⁰⁴ The Center developed a system to record sunfall for solar energy programs. Marshall engineers developed a solar collector that used air instead of water for heat transfer.¹⁰⁵

The energy projects helped the Center grow beyond propulsion and apply its space expertise to Earth uses. It also protected personnel slots. In April 1979, NASA Administrator Robert Frosch agreed to allow Marshall to increase its manpower commitment to energy programs from 135 to 235 over the next three years if the Center’s civil service manpower allotment could accommodate the increase.¹⁰⁶ Six months later, Frosch suggested that NASA might increase its commitment to energy from 3 percent of its manpower to 10 percent.¹⁰⁷ A GAO survey in 1980 found “diversification into expanded energy work a positive force in maintaining Center vitality.”¹⁰⁸

Despite Marshall’s success, by 1981 NASA began reconsidering its energy programs. Opposition came both from within the Center and from Washington. Kingsbury, director of the Science and Engineering Laboratory, had never warmed to the idea of the Center devoting efforts to mining, an activity so removed from NASA’s central mission. Center Director Lucas believed NASA should have a role in energy programs, but it should have its own mission rather than be responsible to other agencies.¹⁰⁹

Political winds in Washington had also shifted. In spite of the Carter administration’s limited support for NASA, energy seemed to be one area in

which growth was assured. The Reagan administration, however, disapproved of technological development projects by federal agencies that could be conducted as well by private industry. Soon after Reagan's inauguration, Budget Director David Stockman announced plans to trim the Carter solar energy budget by 23 percent in 1981 and 62 percent the following year. Both solar energy and coal would be limited to long-term studies with the potential for large returns.¹¹⁰

With NASA manpower undergoing another reduction, energy programs became expendable. A budget amendment in May 1981 slashed NASA's direct energy research and development appropriation in half. NASA Headquarters directed Marshall to transfer its energy project to the Department of Energy by the end of the year.¹¹¹ The Center received permission to continue its coal research until February 1982 to complete work already underway, but then the Center's eight-year entrepreneurial energy ventures came to an end.¹¹²

However unlikely, Marshall's contributions to the earth-bound energy business were successful. Rather than waiting for private industry to apply ideas from the space program, Marshall directly sought space spinoffs. The mining inventions profited an old industry, and solar innovations yielded useful knowledge in a new field.

When Marshall's energy work was complete, its commercial undertakings were not. The experience influenced the way Marshall did business. Zoller recalled that the energy projects "certainly influenced how we dealt with the scientific community," and led the Center to involve industry and the scientific community in decision making. "We developed a working relationship first of all with industry in the solar business, then through commercialization, then through the scientific community to make them more part of the engineering management team," Zoller explained.¹¹³

Conclusion

Marshall's diversification took the Center far from propulsion and created problems as well as possibilities. The greatest problems of diversification were managerial. The Center had to manage, in addition to the science projects described here, the Shuttle, Spacelab, and the Hubble Space Telescope. At the same time that projects were increasing, personnel lines were decreasing.

Thus a flexible organization using ad hoc teams of specialists became a necessity. “Matrix management had been talked about in the Apollo Era,” Bob Marshall said, but now it “had to happen.” Rather than many engineers from one lab specializing on a problem, a handful of people worked full time and received support from dozens of part-timers who were working on several other projects. Critical staff shortages in some key technical specialties compounded the problems. Funding limitations and personnel caps prevented the Center from hiring experts for all its new fields.¹¹⁴

Naturally Center managers worried about having too few people with too little experience on too many projects. George McDonough, head of Science and Engineering in the late 1980s, complained that “you try to matrix people and there aren’t enough people to go around, you are always bouncing from here to there. There are fire drills and panics.” Sometimes penetration of projects suffered. “With the decline of people and a diversification of projects,” Sneed lamented, “automatic responsibility for project integrity diminished somewhat and we tended to get more in a reactive, as opposed to a proactive, mode of operation.” Engineers tended to get most involved “when problems occurred or at critical points in the development process such as the key technical design reviews. This mode of operation was not conducive to the most effective management of our projects.”¹¹⁵

Despite being stretched thin, Marshall recorded important accomplishments. Center personnel diversified a government installation during an era of austerity. This remarkable feat helped preserve an experienced and versatile technical team as a national resource. Marshall’s diversification also had social side effects in North Alabama, encouraging Huntsville’s economy to become more varied as well.¹¹⁶

In addition, the Center made changes in its culture, discovering ways for engineers and scientists to work together. The Center’s diversification also contributed to scientific and technological progress. Its hardware and services made possible new discoveries in solar physics, astrophysics, space physics, theoretical physics, chemistry, metallurgy, and biology. Such successes helped the Center gain future projects and operational responsibilities.

Moreover, the dynamism and creativity of Marshall led NASA in new directions. Its entrepreneurship spawned competition and cooperation among field Centers

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and connected the Agency to other government institutions. The Center undertook commercial ventures, developing marketable technology for mining and performing solar energy research. It also sought to lay foundations for a new industrial sector of materials processing in space. Thus the Center's diversification forced NASA officials and national leaders to define the Agency's mission and refine the role of government in the economy. Within a decade after the first launch of a Saturn V, Marshall had helped conduct many different explorations of outer space.

- 1 Ernst Stuhlinger, OHI by SPW, Huntsville, 8 January 1991, p. 4.
- 2 William Lucas, OHI by AJD and SPW, UAH, 19 June 1989, p. 26.
- 3 Barry J. Casebolt, "MSFC to Continue Hunt for Scientific Work," *Huntsville Times* (30 September 1973).
- 4 Spacelab and Hubble will be discussed in Chapter 9.
- 5 Andrew J. Stofan, OHI by Adam L. Gruen, 13 November 1987, Space Station History Project, p. 35.
- 6 Stuhlinger OHI 1991, pp. 18–19; E. Stuhlinger to M. Wright, 29 September 1992, MSFC History Office.
- 7 David H. DeVorkin, *Science with a Vengeance: How the Military Created the US Space Sciences after World War II* (New York: Springer-Verlag, 1992).
- 8 John E. Naugle, *First Among Equals: The Selection of NASA Space Science Experiments* (Washington, DC, National Aeronautics and Space Administration Special Publication–4215, 1991), pp. 14–17; Frederick I. Ordway and Mitchell Sharpe, *The Rocket Team: From the V–2 to the Saturn Moon Rocket* (New York: Thomas Y. Crowell, 1979), pp. 354, 383; Stuhlinger OHI 1991, pp. 2–4; Charles A. Lundquist, OHI by SPW, Huntsville, 21 September 1990, pp. 10–11.
- 9 Roger Bilstein, *Stages to Saturn: A Technological History of the Apollo/Saturn Launch Vehicles* (Washington, DC, National Aeronautics and Space Administration Special Publication–4206, 1980), Appendix H, p. 452.
- 10 *Marshall Space Flight Center, 1960–1985: 25th Anniversary Report* (MSFC, 1985), pp. 35–36; "Space Science Laboratory," January 1973, Stuhlinger Collection, Record File, Folder 181, Box 3 & 4, ASRC.
- 11 Dr. George Fichtl, OHI by SPW, 21 July 1992, MSFC, pp. 14–15; William C. Snoddy, OHI by AJD and SPW, 22 July 1992, MSFC, pp. 15, 38–39; ABMA Organization Charts, 14 January 1958, 1 January 1960, MSFC History Office.
- 12 Quote from Bilstein, p. 325; quote from NASA Press Release 62–237, 13 November 1962; K. Debus, et. al., "Saturn SA–2 Water Experiment," scientific paper, XIII International Astronautical Congress, Sophia, Bulgaria, September 1962; David Woodbridge, et al., "An Analysis of the Second Project High Water Data," NASA Report 02.01, 25 October 1963; E. Stuhlinger OHI, n.d., UAH Saturn Collection, pp. 1–4; G. Bucher OHI, n.d., UAH Saturn Collection, pp. 3–4, 9–10; Wernher von Braun OHI, 30 November 1971, 38–39.

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- 13 NASA Facts: Pegasus, Vol. II, No. 15; MSFC Press Release 66-264, 2 November 1966, Pegasus General folder, NHDD; “Three Pegasus Satellites Tuned Out and Turned Off,” *Marshall Star* (21 August 1968), pp. 1, 10; Bilstein, pp. 329–36; Stuhlinger OHI n.d., pp. 4–8, 11.
- 14 William J. Hines, “An Exercise in Space Futility,” *Washington Evening Star* (22 July 1965); Robert J. Naumann, “Pegasus Satellite Measurements of Meteoroid Penetration” scientific paper for Smithsonian Astrophysical Observatory, Cambridge, Mass., 9–13 August 1965, Pegasus General, NHDD; von Braun, p. 39; Bill Snoddy to Mike Wright, 17 December 1992, MSFC History Office; Bilstein, pp. 329–36.
- 15 E. Stuhlinger, Weekly Note, 18 August 1969, Box 12 & 13, Notes File; R. Shelton, “Science at MSFC,” 5 December 1966, Box 1, R&D Administrative File, Stuhlinger Collection, ASRC.
- 16 See Chapter VI herein.
- 17 See Chapter V herein.
- 18 Von Braun, “Adjustment to Marshall Organization, Announcement No. 4,” 16 January 1969, Apollo Program Chronological File, Box 70–62, JSC History Office; “Major Reorganization Underway at NASA-Marshall,” *Space Daily* (10 December 1968), p. 171.
- 19 Stuhlinger OHI 1991, p. 1; Stuhlinger to Wright, 29 September 1992, MSFC History Office; E. Rees to H. Gorman, 13 August 1971, Stuhlinger Collection, Record File, Box 2, ASRC.
- 20 Statistic compiled from information furnished by Jerre Wright, Equal Opportunity Office, MSFC.
- 21 Unclear authorship, but whomever Lucas as head of Program Development reported to, probably von Braun or Rees, “Discussion regarding Dr. Newell’s visit to Marshall on October 24, 1968,” 14 November 1968, Box 5–35, Shuttle Chronological Series, JSC History Office.
- 22 Dr. Charles R. Chappell, OHI by SPW, MSFC, 23 August 1990, pp. 7, 9, 10, 15; Barry Rutizer, “The Lunar and Planetary Missions Board” (NASA-HHN-138, 30 August 1978), cited in Arnold S. Levine, *Managing NASA in the Apollo Era* (Washington, DC, National Aeronautics and Space Administration Special Publication-4102, 1982), p. 251; Dr. Thomas Parnell, OHI by SPW, MSFC, 11 September 1990, pp. 21–22; Fichtl OHI, pp. 15–16.
- 23 Stuhlinger to Wright, 29 September 1992, MSFC History Office; Stuhlinger, “Relations between NASA and outside scientists,” 3 June 1966, R&D Administrative File, Box 1, Stuhlinger Collection, ASRC.
- 24 F. J. Magliato, “Management of Experiments at MSFC—Draft,” 1 November 1965, AAP November-December 1965 folder, MSFC Director’s Files; MSFC, “MSFC *Skylab* Corollary Experiment Systems Mission Evaluation,” NASA TM X-64820, September 1974, folder 517, MSFC History Office; L. Belew and E. Stuhlinger, *Skylab: A Guidebook* (NASA EP-107, 1973), pp. 114–226; R. J. Naumann, “*Skylab* Induced Environment,” in M. I. Kent, et al., eds., *Scientific Investigations of the Skylab Satellite* (New York, AIAA, 1976), pp. 383–96.
- 25 MSFC, “*Skylab* Student Project: Project Definition Report,” 7 May 1972, MSFC History Office, folder 517; H. B. Floyd, “Student Experiments on *Skylab*,” in Kent, pp. 471–94;

POWER TO EXPLORE: HISTORY OF MSFC

- H. B. Floyd, OHI, by W. D. Compton, MSFC, 5 November 1974, Rice University, pp. 14–15.
- 26 T. Bannister, “Postflight Analysis of Science Demonstrations,” in Kent, pp. 531–50; NASA TM X–64820, Section VII; Dr. Charles Lundquist, OHI by SPW, UAH, 7 July 1991, p. 13.
- 27 E. Stuhlinger to Mike Wright, MSFC Historian, Comments on MSFC History Draft, Chapter Five, September 1992, p. 4.
- 28 L. Belew to W. Lucas, “Key Assignments for *Skylab* Experiments,” 24 September 1971, AAP 1971 folder, MSFC Director’s Files; Ise interview, pp. 10–12; Snoddy OHI, pp. 15–16; Stuhlinger to Wright, p. 4.
- 29 E. Stuhlinger, Memo for Record, 28 February 1968, E. Stuhlinger to F. Williams, 15 February 1968, Historical File, Boxes 12 & 13, Stuhlinger Collection, ASRC.
- 30 W. D. Compton and C. D. Benson, *Living and Working in Space: A History of Skylab* (Washington, DC, National Aeronautics and Space Administration Special Publication–4208, 1983), pp. 174–79.
- 31 NASA OMSF and OSSA, “*Skylab* and the Sun: ATM,” July 1973, MSFC Technical Library, 30–34, 38–39; Dr. Anthony DeLoach, OHI by SPW, MSFC, 11 May 1992, pp. 1–8; Lundquist 1992 OHI, pp. 9–10; Snoddy OHI, pp. 17–23.
- 32 MSFC *Skylab* Program Office, “MSFC *Skylab* Kohoutek Experiments Mission Evaluation,” NASA TM X–64879 (September 1974), pp. 1, 3; R. D. Chapman, “Comet Kohoutek,” *Space Science and Technology Today I* (September 1973), pp. 30–32; W. C. Snoddy and R. J. Barry, “Comet Kohoutek Observations from *Skylab*,” in W. C. Schneider and T. E. Hanes, eds., *The Skylab Results: Advances in the Astronautical Sciences*, Volume 31, Part 2 (Tarzana, CA: American Astronautical Society), pp. 871–94; C. A. Lundquist, ed., *Skylab’s Astronomy and Space Sciences* (Washington, DC, National Aeronautics and Space Administration Special Publication–404, 1979), pp. 47–48, quoted, pp. 59–60; Compton and Benson, pp. 390–94.
- 33 Lundquist 1992 OHI, pp. 2–8, 15; J. A. Eddy, *A New Sun: The Solar Results from Skylab* (Washington, DC, National Aeronautics and Space Administration Special Publication–402, 1979), pp. 67–180, quoted p. vii; J. B. Zirker, *Coronal Holes and High Speed Wind Streams: A Monograph from Skylab Solar Workshop I* (Boulder, CO: Colorado Associated University Press, 1977); P. A. Sturrock, *Solar Flares: A Monograph from Skylab Solar Workshop II* (Boulder, CO: Colorado Associated University Press, 1980); F. Q. Orral, ed., *Solar Active Regions: A Monograph from Skylab Solar Workshop III* (Boulder, CO: Colorado Associated University Press, 1981); Snoddy OHI, pp. 32–34.
- 34 Snoddy OHI, pp. 15, 34–35.
- 35 Craig Covault, “Help Abroad Key to Laser Mission Goals,” *Aviation Week and Space Technology* (12 May 1975), pp. 36–43; E. Rees to D. D. Meyers, “LAGEOS,” 25 January 1973, LAGEOS folder, MSFC Director’s Files; “Project LAGEOS Press Kit,” NASA Release 76–67, 14 April 1976, pp. 5–7, MSFC History Office Fiche No. 1345.
- 36 “LAGEOS Task Team formed at MSFC,” MSFC Release 73–171, 20 November 1973; Program Development, “Preliminary Project Plan for LAGEOS,” November 1973, RHT File No. 495; “LAGEOS Press Kit,” pp. 1–5, 9, 12–14; Covault, pp. 36–43.
- 37 Eugene H. Cagle, Deputy Director, Test Lab to R. G. Smith, “LAGEOS, n.d.”; “Summary of Add-on In-House LAGEOS Work for FY–1975,” 2 October 1974; R. G. Smith to W. Lucas, 4 October 1974, LAGEOS folder, MSFC Director’s Files.

- 38 Zoller OHI, pp. 5–9; James Kingsbury OHI, by SPW, 22 August 1990, Madison, AL, p. 30.
- 39 "MSFC/GSFC Memorandum of Agreement relative to the LAGEOS Project Spacecraft Development Support," 28 January 1976, LAGEOS folder, MSFC Director's files; MSFC Release 76–17, 76–82; Covault, pp. 36–43.
- 40 "LAGEOS: Scientific Results," *Journal of Geophysical Research* 90, B11 (30 August 1985), entire issue.
- 41 Stuhlinger to Wright, 29 September 1992, MSFC History Office; MSFC, "Project Plan for Gravitational Redshift Space Probe," March 1972; E. Rees to D. D. Myers, "Gravitational Redshift Space Probe," 3 October 1972, MSFC Director's Files.
- 42 "Relativity Gravity Probe Press Kit," NASA Release 76–106, Gravitational Probe-A folder, NHDD;
- 43 Quotation from "Discussion on GP–A Management," 11 August 1974; F. Speer, MSFC to A. Schardt, HQ, "Assessment of GP–A Project Requirements," 8 November 1974; quotation from F. Speer to W. Lucas, "Request for Additional GP–A Funding," 14 November 1974, MSFC Director's Files.
- 44 J. A. Lovingood to R. G. Smith, "Redshift Vibration and Loads Problems," 12 December 1974; quotation from L. Belew to W. Lucas, "Redshift (GP–A) Vibration and Loads Problem," 27 December 1974; "GP–A Dynamics Problem," December 1974; J. Stone to F. Speer, "GP–A Review at OSS," 28 February 1975; F. E. Vreuls to W. Lucas, "Monthly GP–A Review of November 21, 1975"; "Recapitulation of GP–A Funding and Manpower History," n.d.; J. A. Bethay to W. Lucas, routing slip, 2 December 1975; F. Speer to R. Halpern, HQ, "GP–A Reprogramming Recommendations," 12 March 1976, GP–A folder, MSFC Director's Files.
- 45 "Relativity-Gravity Space Probe Launched," MSFC Release 76–113, 18 June 1976, Gravity Probe-A folder, NHDD; MSFC, "GP–A: The Redshift Experiment," n.d., MSFC Public Affairs Office; R. F. C. Vessot and M. W. Levine to W. Lucas, 22 June 1976, GP–A folder, MSFC Director's Files; R. F. C. Vessot and M. W. Levine, "GP–A Redshift Space-Probe Experiment Project Report," April 1977, MSFC History Office Fiche No. 1768; R. F. C. Vessot and M. W. Levine, "A Test of the Equivalence Principle Using a Space-Borne Clock," *General Relativity and Gravitation* 10 (1979), pp. 181–204.
- 46 Wallace H. Tucker, *The Star Splitters: The High Energy Astronomy Observatories* (Washington, DC, National Aeronautics and Space Administration Special Publication–466, 1984), chap. 2, 3.
- 47 Jim Downey OHI, by SPW, Madison, AL, 14 December 1990, pp. 1–6, 9, 14; Herbert Friedman, "High-Energy Astronomy with HEAO," *Astronautics and Aeronautics* (April 1978), pp. 50–51.
- 48 R. D. Stewart, "HEAO Project Plan," March 1971, MSFC History Office, Fiche 707, quoted pp. 3–1; "HEAO Charter and Staffing Pattern," MSFC Director's Files, HEAO 1971; Downey OHI, pp. 7–8; Tucker, p. 20.
- 49 "Opportunity for Participation in Space Flight Investigations: HEAO," 3 March 1970, HEAO General Folder, NHDD; "NASA picks experiments for 2 HEAOs," *Huntsville Times* (8 November 1970); Downey, OHI, pp. 5, 10; Tucker, p. 21.
- 50 "NASA Program Reductions," NASA Press Release 73–3, 5 January 1973, HEAO General, NHDD; "HEAO Program Reoriented," *Space Business Daily* (8 February 1973), p. 1.

POWER TO EXPLORE: HISTORY OF MSFC

- 51 Dr. Fred Speer, OHI by SPW, 9 October 1990, UAH, pp. 8–11; John Naugle to Petrone, “Revised HEAO Program,” 5 March 1973, HEAO 1973 folder, MSFC Director’s Files; “Restructured HEAO Contracts Signed,” MSFC Press Release 29–74, 29 August 1974; Tucker, pp. 22–24.
- 52 Petrone memo, 30 March 1973; Speer to Petrone, 12 April 1973; Lucas to Petrone, 13 April 1973; J. P. Noland, “Rationale for retaining current HEAO contractors,” 14 March 1973, HEAO 1972–73 folder, MSFC Director’s Files.
- 53 Speer to Rees, “HEAO PI Meeting in Washington (16 January 1973),” 18 January 1973, HEAO 1972–73 folder, MSFC Director’s Files; Speer OHI, pp. 8–11; C. Covault, “HEAO Design Program Restarted,” *Aviation Week* (7 October 1974); Barry Casebolt, “HEAO to be NASA’s ‘Major Effort’ after 1975,” *Huntsville Times* (28 October 1974); Tucker, chap. 4.
- 54 MSFC, “HEAO Fact Sheet,” March 1979, MSFC History Office Fiche No. 819; Tucker, chap. 5.
- 55 F. A. Speer, “HEAO: Signature of a Successful Space Science Program,” 21 September 1980, MSFC History Office Fiche No. 751, p. 8.
- 56 Speer, “HEAO,” pp. 8–9, 11; F. A. Speer, “Prepared Statement on the HEAO Program” for the Subcommittee on Space Science and Applications, Committee of Science and Technology, House of Representatives, 7 February 1977, MSFC History Office Fiche No. 745, pp. 2–3.
- 57 Speer, “HEAO,” pp. 6–7, 10; Tucker, p. 44; Speer OHI, quoted p. 8.
- 58 Tucker, pp. 38, 44–45.
- 59 Tucker, p. 44; Speer to R. Halpern, “HEAO–B Experiment Cost Problem,” 14 October 1975; R. Giacconi to A. W. Schardt, NASA HQ, 31 October 1975, HEAO 1975 folder, MSFC Director’s Files.
- 60 Speer, “Management Review at AS&E,” 30 July 1976; A. Martin to Speer, 17 August 1976; Speer, “AS&E/MSFC Communication Contacts for the HEAO–B Experiment, draft,” n.d., HEAO 1976 folder, MSFC Director’s files.
- 61 Speer OHI, pp. 14–16.
- 62 Tucker, p. 44; Parnell OHI, pp. 8–9, 15–16.
- 63 Speer OHI, pp. 13–15; Speer to Lucas, “Central Parts Control for HEAO,” 2 February 1973, HEAO 1972–73 folder; HEAO Office, “Interim Assessment of the HEAO Central Parts Control,” 24 March 1975, HEAO 1975 folder, MSFC Director’s Files; Tucker, pp. 48–51; MSFC Press Releases 74–201, 75–100, 76–172, 77–93, 77–186.
- 64 MSFC, “A Guide to Space Simulators at MSFC,” n.d., p. 11, MSFC History Office; Speer, “Prepared Statement”; Tucker, pp. 68–70.
- 65 Tucker, pp. 75–76; W. Lucas, “Address to HEAO Science Symposium,” 8 May 1979, p. 7, HEAO 1979 folder, MSFC Director’s Files.
- 66 Speer to Petrone, “MSFC/GSFC Memorandum of Agreement on Mission Operations for the HEAO Project,” 28 September 1977, HEAO 1972–73 folder, MSFC Director’s Files; Speer OHI, pp. 11–13; HEAO–A Press Kit, 5 May 1977, p. 15, MSFC History Office, Folder No. 433.
- 67 “NASA Increases Lifetime Estimates of HEAO Missions,” *Aerospace Daily* (27 November 1978), p. 108; Tucker, p. 81, chap. 5.

- 68 Tucker, pp. 9, 72, chap. 8–23.
- 69 Speer OHI, pp. 17–18; Dave Dooling, “NASA Planning Large Telescope for X-Ray Astronomy,” *Space World* (February 1980), pp. 22–24.
- 70 Eugene C. McKannan, “A Brief History of the Materials and Processes Laboratory—As I Saw It,” n.d., MSFC History Office, Folder No. 14; Dr. Robert Naumann, OHI by SPW, 3 June 1991, UAH, pp. 3–6.
- 71 R. J. Naumann and H. W. Herring, *Materials Processing in Space: Early Experiments*, (Washington, DC, National Aeronautics and Space Administration Special Publication—443, 1980), pp. 33–34; “A Guide to Space Simulators at the Marshall Space Flight Center,” 1987, pp. 8–10; MSFC History Office, Fiche No. 1039; Naumann OHI, pp. 26–28.
- 72 McKannan, pp. 8–9; R. J. Naumann, “Materials Processing in Space: Review of the Early Experiments,” in *Applications and Science: Progress and Potential* (New York: IEEE, 1985), pp. 2–8.
- 73 Belew and Stuhlinger, pp. 187–196; Naumann OHI, pp. 9–11.
- 74 E. Stuhlinger, “Technical Processes under Weightlessness: *Skylab* Press Briefing,” 8 November 1973, MSFC History Office; E. Stuhlinger, “*Skylab* Results—Review and Outlook,” n.d., NASA Cospar S.P. I.4.4.8, MSFC Technical Library, pp. 7–8; C. Lundquist, “*Skylab* Experiments on Metals,” paper for ESRO Space Processing Symposium, Frascati, Italy, 25 March 1974; Naumann and Herring, pp. 64, 67, 71–71, 82–83, 86, 92–93, 97–98, 105–106; David Salisbury, “Factories in Orbit may Manufacture Alloys now called Impossible,” *Christian Science Monitor*, 14 February 1974; Materials Processing Panel, “*Skylab* Revisit: A Conference in Recognition of the Fifteenth Anniversary,” 11 May 1988, Huntsville, videotape, MSFC History Office.
- 75 L. Zoller to W. Lucas, “GAO Study of Materials Processing in Space,” 12 February 1979, MPS 1978–79 folder, MSFC Director’s Files.
- 76 “MSFC to Manage 8 ASTP Experiments,” MSFC Press Release 73–147, 15 October 1973; “ASTP Fact Sheet,” NASA Press Release 75–9, 1975; C. Covault, “ASTP Research Spurs Medical Benefits,” *Aviation Week and Space Technology* (17 November 1975), p. 53; MSFC Space Processing Applications Task Team, “ASTP—Composite of MSFC Final Science Report,” NASA TM X–73360, January 1977; Walter Froehlich, “Apollo-Soyuz,” NASA EP–109, 1976, pp. 79–80; Naumann OHI, p. 12.
- 77 Naumann OHI, pp. 28–31; MSFC Commercial Applications Office, “NASA Drop Tube: A Tool for Low-Gravity Research,” CMPS 302, n.d., MSFC History Office No. 79; L. Lacy, et. al., “Containerless Undercooling and Solidification in Drop Tubes,” *Journal of Crystal Growth* 51 (1981), pp. 47–60; J. Kingsbury, Weekly Note, 20 September 1982, MSFC History Office.
- 78 “Sounding Rocket Project for Space Processing Experiments,” November 1974, Space Processing, 1970–75 folder, MSFC Director’s Files; “S&E Labs Play Vital Role in SPAR Program at MSFC,” *Marshall Star* (15 December 1976); D. Dooling, “Rockets Test Space Processing: MSFC Engineers Direct Program,” n.p., 6 June 1977; Naumann OHI, pp. 12, 32; Roger Chassay, OHI by SPW, 24 July 1992, MSFC, pp. 14–17.
- 79 Chassay OHI, pp. 18, 21.
- 80 Chassay to Lucas, “SPAR IV Results,” 23 August 1977; J. R. Carruthers, Director MPS

POWER TO EXPLORE: HISTORY OF MSFC

- HQ to MSFC Special Projects Office, "Programmatic and Management Recommendations for the SPAR Project," 26 August 1977; J. T. Murphy to Lucas, 15 September 1977 and 29 September 1977; Lucas to Leonard B. Jaffe, HQ, 20 October 1977, Space Processing 1976 folder, MSFC Director's Files.
- 81 SPAR clippings, Fiche No. 1103, MSFC History Office; Chassay OHI, pp. 15–16.
- 82 Statement of Dr. Robert A. Frosch, Administrator, NASA on the Space Industrialization Corporation Act of 1979 before the Subcommittee on Space Science and Applications, Committee on Science and Technology, U.S. House of Representatives, 11 May 1979, MPS, 1978–79 folder, MSFC Director's Files; R. Naumann, "Microgravity Science and Applications Program Description Document," February 1984, MSFC Technical Library, I.6–I.9; R. Naumann, "Historical Development," in B. Feuerbacher, et al., eds., *Materials Sciences in Space: A Contribution to the Scientific Basis of Space Processing* (Berlin: Springer-Verlag, 1986), pp. 27–28.
- 83 "Marshall Studies Materials Processing in Space," MSFC Press Release 74–47, 4 April 1974; J. T. Murphy, "RTOP Commercialization of MPS," 23 November 1974, MSFC History Office, Folder 14E.
- 84 See Walter A. McDougall, . . . *The Heavens and the Earth: A Political History of the Space Age* (New York: Basic Books, 1985).
- 85 Bill Sneed, OHI by SPW, 15 August 1990, Huntsville, Alabama, p. 21.
- 86 MSFC, "Program Plan for Underground Coal Extraction Technology," November 1974. Morton officially asked NASA's assistance in a letter to Fletcher on 9 January 1975, but Marshall's Peter Broussard remembered a story that the challenge first came at a Christmas party, when Morton said in effect, "If you fellows are so smart in automation, . . . why don't you help us in the coal mining business?" Peter Broussard, OHI by SPW, 20 September 1990, Huntsville, Alabama, p. 32. Morton to Fletcher, 9 January 1974, Assistance to Department of Interior (Coal Mining Problems) folder, MSFC Center Director's Files.
- 87 W. R. Lucas to Joseph P. Allen, "Regional Applications Transfer Activities at Marshall Space Flight Center," 3 November 1977, Fiche No. 1834, MSFC History Office.
- 88 John Goodrum, "Coal Energy Extraction Program and Related Coal Mining R&D Efforts," 27 June 1974, Coal Energy Extraction Program folder, MSFC Center Director's Files; NASA Release 75–17, 20 January 1975; MSFC Release 75–215, 7 October 1975.
- 89 MSFC, "Project Plan for Development of Longwall Guidance & Control Systems: Bureau of Mines Advanced Longwall Program," June 1976, pp. III–2 to III–8; Broussard OHI, pp. 15–16; David Cagle, "Space-Program Technology May Boost Coal Production," *Huntsville Times*, 21 October 1976.
- 90 Broussard, OHI, pp. 19–20.
- 91 MSFC 1978 Chronology, 9 January 1978; Broussard, OHI, pp. 2, 15–16.
- 92 Charles W. Mathews to Associate Administrator for Manned Space Flight, 28 June 1973, Solar Energy Heating and Cooling Demo folder, MSFC Center Director's Files. For Lewis involvement with solar energy programs, see Virginia Dawson, *Engines and Innovation: Lewis Laboratory and American Propulsion*, (Washington, DC, National Aeronautics and Space Administration Special Publication–4306, 1991), pp. 206–08.
- 93 James T. Murphy to Rocco Petrone, 17 October 1973, and Murphy to Petrone and William R. Lucas, 31 October 1973, Solar Energy Heating and Cooling Demo folder, MSFC Center Director's Files.

BEYOND “THE GATE OF HEAVEN”

- 94 MSFC, “Harnessing the Sun’s Energy for Heating and Cooling;” MSFC, “The Development of a Solar-Powered Residential Heating and Cooling System,” 10 May 1974; Richard G. Smith, Statement before Subcommittee on Science and Applications, Committee on Science and Astronautics, House of Representatives, May 1974; MSFC Public Affairs Office, “MSFC Solar Energy Demonstration,” 15 May 1974; 1974 MSFC Chronology, 22 April 1974, MSFC History Office.
- 95 Harrison H. Schmitt to Lucas, 18 September 1974, Solar Energy Heating and Cooling Demo folder, MSFC Center Director’s Files; MSFC, “Solar Energy for Heating and Cooling: Applied Technology.”
- 96 Lucas memo to Jim Murphy and Dick Smith, 7 November 1974, Solar Energy Heating and Cooling Demo folder, MSFC Center Director’s Files.
- 97 James T. Murphy to Lucas, 27 September 1974, Solar Energy Heating and Cooling Demo folder, MSFC Center Director’s Files.
- 98 Schmitt to Lucas, 18 September 1974; Schmitt to Chris Kraft, 11 November 1974; Lucas to Schmitt, 17 December 1974, Solar Energy Heating and Cooling Demo folder, MSFC Center Director’s Files.
- 99 Donald R. Bowden to Lucas, 19 February 1975, Solar Energy Heating and Cooling Demo folder, MSFC Center Director’s Files.
- 100 Lucas to Harrison H. Schmitt, 4 December 1974; Schmitt to Lucas, 17 December 1974, Solar Energy Heating and Cooling Demo folder, MSFC Center Director’s Files. Lucas was careful not to push headquarters too hard, however. He considered informing Washington that because of imminent reductions in force, Marshall would have to suspend its solar energy work unless it received a manpower augmentation, but reconsidered when he decided such a position seemed too much like an ultimatum. Lucas to Schmitt (unsent), 17 January 1975, Solar Energy Heating and Cooling Demo folder, MSFC Center Director’s Files.
- 101 Cited in Philip W. Smith, “‘Let Huntsville Give You the Sun,’ Urges Dr. Von Braun,” *Huntsville Times*, 12 March 1976. Von Braun was speaking to a group of southeastern senators.
- 102 MSFC, “Solar Heating and Cooling Development Program Plan,” SHC–1003, 9 April 1975, Solar Heating and Cooling, January to June 1975 folder, MSFC Center Director’s Files.
- 103 “Marshall is Assigned Solar Role,” *Huntsville Times*, 17 April 1979.
- 104 MSFC Release 76–42, 17 February 1976; MSFC Public Affairs Office Fact Sheet: “Solar Heating and Cooling Program,” 10 January 1980.
- 105 MSFC Release 75–168, 24 July 1976; MSFC Release 76–56, 2 April 1976.
- 106 Ray Kline, NASA Associate Administrator for Management Operations, to Lucas, 26 April 1979, Energy Research and Development 1979–1980 folder, MSFC Center Director’s Files.
- 107 Donald A. Beattie, Director, Energy Systems Division to Lucas, 5 November 1979, Energy Research and Development 1979–1980 folder, MSFC Center Director’s Files.
- 108 Mr. Sheley, Jr. (first name illegible), GAO Procurement and Systems Acquisitions Division, to Robert A. Frosch, 16, September 1980, Energy Research and Development 1979–1980 folder, MSFC Center Director’s Files.

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- 109 Mitzi E. Peterson, Memorandum for the Record Re: OAST Energy Management Council, 1 May 1981, Energy Program, Long Range Mining, 1981 folder, MSFC Center Director's Files; Broussard OHI, p. 23.
- 110 Burt Solomon, "Hatchet Job: Reagan's OMB Meets the Energy Budget," *The Energy Daily* 9 (Friday, 6 February 1981), p. 6.
- 111 The Appropriation dropped from \$3.9 million to \$1.9 million. Walter B. Olstad to Center Directors, 4 May 1981, Energy Program, Long Range Mining, 1981 folder, MSFC Center Director's Files; Jack L. Kerrebrock to NASA Administrator James Beggs, 23 September 1981, Energy Program, Long Range Mining, 1981 folder, MSFC Center Director's Files; A. M. Lovelace to Raymond Romatowski, 26 May 1981, 1981 Energy Program—Longwall Mining folder, MSFC Center Director's Files.
- 112 Jack L. Kerrebrock to Lucas, 7 October 1981, Energy Program, Long Range Mining, 1981 folder, MSFC Center Director's Files.
- 113 Lowell Zoller, OHI by SPW, 10 September 1990, Huntsville, Alabama, p. 34.
- 114 Marshall OHI, pp. 24–25; Parnell, OHI, p. 10.
- 115 George McDonough, OHI by SPW, 20 August 1990, MSFC, p. 24; Sneed OHI, pp. 16–17; Bill Sneed to Mike Wright, 5 January 1993, MSFC History Office.
- 116 Jack Hartsfield, "Diversifying is Aerospace Group Aim," *Huntsville Times* (5 April 1970).