Skylab Report: Man's Role in Space Research

Some results of the Skylab missions and ways in which man has optimized the scientific return are discussed.

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The flight activities of Skylab are now complete, with major effort shifting to data reduction and interpretation, a task expected to last for several years. Three-man crews have worked in Skylab for periods of approximately 1, 2, and 3 months, for a total of 6 months of manned operations (*1*). Since we can now view this experience from the new perspective of hindsight, it seems an appropriate time to outline briefly some of the more interesting results of the three flights and to review the ways in which crew members entered into the research activities onboard Skylab, in an attempt to understand more clearly how they may have contributed to the overall success of the scientific objectives. Such an understanding is important in planning for future space flight programs.

Skylab has been a multidisciplinary effort, perhaps to an extreme, with more numerous and varied scientific and technological objectives than in any previous single flight program or, for that matter, any program planned for the future. As one would expect, very difficult decisions on relative priority were often required in planning for each day's activities as a result of the differing interests of the several disciplines competing for time. About 100 different experiments were scheduled and carried out, with most of the crew time being devoted to (i) observations of the sun with a large collection of solar telescopes and instruments mounted on a single spar; (ii) medical objectives, focused principally on studies of man's response to long-duration "zero-gravity" exposure; and (iii) Earth Resources studies with an array of instruments looking back at the earth. Smaller amounts of time (although lesser importance is not implied) were devoted to individual experiments in stellar astronomy, technology, materials processing, and even a number of high school student experiments selected on a nationwide competitive basis.

I will describe first some of the early results reported by several investigators in the solar physics discipline as well as my subjective response to long-term zero-gravity exposure in several areas related to medical studies. A few of the more detailed papers by the principal investigator (PI) groups have now been published (*2–6*), and numerous papers have been presented or scheduled at special Skylab sessions of the appropriate national meetings of the various disciplines (*7*). A substantial tide, if not flood, of published work should become available within the next few years from the experts who have led this research.

Solar Observations

The array of solar instruments was called the Apollo telescope mount or ATM, terminology carried over from a much earlier design configuration (Fig. 1). Five PI groups conceived and guided the design of six major instruments (*8*) plus several auxiliary telescopes, including two hydrogen-alpha (the Balmer-alpha transition of hydrogen at 6563 angstroms) telescopes and one extreme ultraviolet (EUV) telescope used principally for pointing the array.

One of the most exciting discoveries made on Skylab is the dynamic behavior of the corona. This is shown most clearly in the appearance, frequency, and permanent distortion produced by large transients in the corona. Figure 2 shows the large "magnetic loop" observed on 10 August 1973, with the High Altitude Observatory coronagraph (*5*). A sequence of photographs shows the loop emerge from behind the instrument's occulting disks and then expand out through the corona at a velocity of about 400 kilometers per second. Before the flight it had been hoped that transient events of some sort might be observed on two or three occasions; in fact, over 60 events of this general type have been recorded, usually associated with eruptive prominences in the chromosphere. After a major transient, the coronal structure is completely altered within the volume of the event and a new structure is formed which may then persist for weeks or even longer.

The Harvard College Observatory photoelectric spectroheliometer operated in three principal modes. Most often, it was used in a "raster scan," in which an image of an area (5 by 5 arc minutes) of the disk was built up in about 5 minutes of time, and at seven different wavelengths simultaneously. Figure 3 shows mosaics of four rasters at three different wavelengths of an active region near the solar limb. The instrument also could be used to scan one line of the raster continuously in 5 seconds for high time resolution, or it could be placed at any desired point and a spectral scan obtained between 280 and 1350 Å (28 to 135 nanometers) (*9*).

The different wavelengths in a set of raster images such as Fig. 3 were usually selected in an effort to provide temperature, and therefore altitude, information within the chromosphere, transition region, and lower corona. For example, C III emission is produced near a temperature of 60,000°K, O VI emission near 300,000°K, and Mg X emission near 1.2×10^6 °K. Comparing the two lower-temperature images in Fig. 3, we can see that the chromospheric structure remains relatively unchanged up through much of the transition region, until at least above a temperature of 3×10^5 °K. However, in the lower corona (seen in Mg X emission) almost all chromospheric detail has been washed out (*3*).

An important exception is the case of "bright points," several of which

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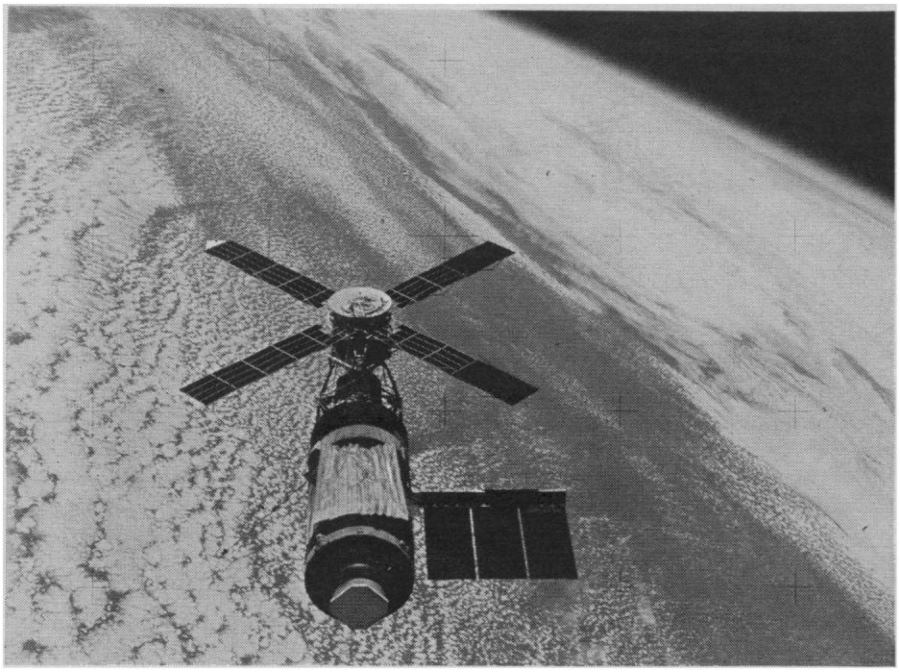

Fig. 1. Final view of Skylab as the third mission crew departed for home on 8 February 1974. One large workshop solar panel is missing at the lower left, and a sunshade shields much of the workshop from incident sunlight. The ATM assembly is contained in a large cylinder behind another sunshield at the center of the crossed array of solar panels.

can be seen in Fig. 3. Starting at the lower left corner of the Mg X image, the fractional distance to one of the better examples is: up, 0.25; right, 0.2. These points were found to have little or no signature in the visible wavelength of hydrogen-alpha (6563 Å) yet are very prominent in the EUV and x-ray wavelengths. Their lifetimes are typically about 8 hours (*6*), and their intensities were found to be quite variable (perhaps ± 25 percent) on a scale of minutes. Although these points were often located in Mg X, their signature can be found in the chromospheric lines also. The radiation from Mg X and O VI ions were both found quite helpful in flight because it could be used to locate precisely the point of maximum intensity for data collection.

The Naval Research Laboratory provided two EUV instruments. The spectroheliograph dispersed the image of the entire solar disk in two ranges between about 170 and 630 Å. An example of one of their more spectacular photographs is shown in Fig. 4, recorded on 9 August 1973. A portion of the solar disk is shown and a large cloud of gas which has been ejected to great heights above the limb of the sun. It is observed here principally in the emission of He II ions at 304 Å. The gas extends more than half a million kilometers into the corona, it is much cooler than the surrounding coronal material, and the looplike structure appears to have been partially blocked in its outward expansion. The second instrument is a narrow-slit spectrograph which operated in two ranges between about 1000 and 4000 Å and required very precise pointing and coalignment with the Harvard instrument. The returned data will be useful in constructing new models of the quiet solar atmosphere and, in addition, are expected to provide information on more unique features and transients, including filaments, prominences, active regions, and flares.

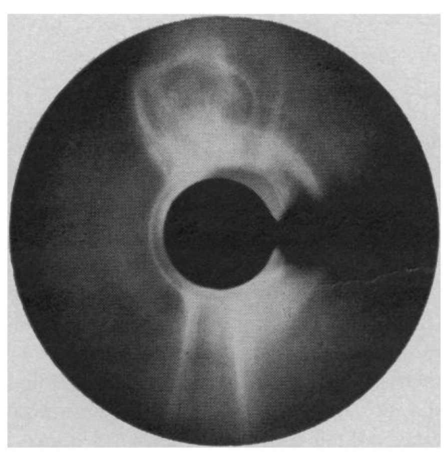

Fig. 2. Large coronal transient observed at 1448 U.T., 10 August 1973, with the white light coronagraph of the High Altitude Observatory. This "magnetic loop" was observed to emerge from behind the occulting disks in the center of the photograph and move outward through the corona at a velocity of about 400 kilometers per second.

American Science and Engineering and Marshall Space Flight Center each provided a grazing-incidence x-ray telescope. Figure 5 is an American Science and Engineering photograph showing the appearance of the sun in soft x-rays. The emission is, of course, substantially all from the very hot corona and reveals a great amount of detail about the structure of active regions. Bright points are again quite visible and they may increase in intensity by more than a factor of 10 in only a few minutes, producing a miniature "flare." Some 1500 new bright points emerge on the sun's disk every day and appear to contribute more flux to the solar magnetic field than even the active regions. An explanation of these points "may be of fundamental importance to our understanding of solar dynamo theories and of the solar cycle" (*6*).

Other interesting features include "coronal holes" from which x-ray emission is virtually absent and which are believed to represent regions in which the magnetic field lines are "open," or, more precisely, extend far out into the interplanetary medium. This could, therefore, be the source of the solar wind, whose relationship to the interplanetary magnetic field is being studied intensively, as is the possible relationship between the interplanetary magnetic field sector structure and the earth's weather (*10*).

Medical Studies

Since the evaluation of man's capability to live and work for long intervals in zero-gravity was one of the main objectives of Skylab, there were many medical experiments conducted on the crewmen. These included cardiovascular response to several kinds of challenge, exercise tolerance, vestibular functioning, mineral balance (requiring quantitative knowledge of all food and liquid intake plus all body wastes from 3 weeks before the flight until 3 weeks after the flight), sleep quality, and blood analyses. Without going into the details of each area, most of which are not yet available in final published form, the general conclusion has been reached that man can indeed function effectively for very long intervals in zero-gravity and then return to Earth. It is necessary to take certain precautions to avoid deconditioning, but a balanced and vigorous exercise program of 1 to 1½ hours per day seems to be quite adequate and effective. A review of all the Skylab medical experiments was held at the NASA Johnson Space Center, Houston, in August 1974, and publication of the symposium papers is planned by NASA (*11*).

Since individual subjective impressions are often missing in medical reports, a few brief comments of a more personal nature from one of the subjects might be appropriate. To begin with, I found life in zero-gravity quite pleasant, enjoyable, and absolutely fascinating. In the first few days, most persons do not feel completely comfortable, in much the same way that some people are bothered (more or less) on the first few days at sea. Of the nine Skylab crewmen, two did reach the point of vomiting on the first or second day in orbit, but at no time were they unable to carry out any essential activities. A quantitative evaluation of the crew's performance during the three activation intervals shows that less than 12 man-hours were lost as a result of motion sensitivity, while the crew was delivering about 200 man-hours of work (*12*). A very substantial improvement in work rate was noticed, however, for tasks of a repetitive nature as the crewmen gained experience in zero-gravity operations. After an initial period of 2 or 3 days, appetites and the feeling of well-being returned to normal for those who had noticed any symptoms at all.

The vestibular testing was particularly interesting (*13*). All the tests (before, after, and during the flight) were carried out in a rotating chair, with the crewman being asked to perform nodding and sidewise head movements until approaching "malaise." An attempt was made to reach the same level of symptoms in each test. Before the flight, most crewmen rotated at between 10 and 20 revolutions per minute and executed 50 to 75 head movements before reaching malaise. However, on all in-flight tests, symptoms were nearly absent. Soon all of us were rotating at the maximum possible rate of 30 rev/min and delivering the full protocol of 150 head movements with few or no symptoms. After return to Earth, this immunity to motion sensitivity appeared to persist for several weeks before returning to normal. Although quite an unexpected finding, this is one of the few areas in which all crewmen exhibited the same pattern.

Tests of cardiovascular response and exercise tolerance were usually conducted sequentially, starting with the crewman instrumented for automatic blood pressure, vector cardiogram, and calf circumference measurements (*14*). With the crewman sealed up to his waist in a cylinder, a partial vacuum was drawn on his lower limbs and torso, producing blood pooling in the legs. A pressure reduction of up to 50 millimeters of mercury was reached, corresponding to the pressure exerted by a 2.2-foot (68-centimeter) column of water in Earth's gravity, thereby challenging the cardiovascular system in a manner comparable to standing erect on Earth. After this "lower body negative pressure" (LBNP) test, the crewman moved to a bicycle ergometer for exercise. The usual tests were run at 25, 50, and 75 percent of the individual's preflight maximum capacity, for 5 minutes at each level.

We found that the LBNP test became a significant challenge in orbit, although it had never been a problem on the ground. This is apparently due to a combination of reduced total blood volume in orbit and pooling in the legs during the period of negative pressure. Some of the tests were terminated prior to reaching 50 mm-Hg because of the approach of syncope (fainting). However, exercise capability is little changed in flight, although it takes some time to learn how to work in zero-gravity. In order to pedal efficiently with the feet firmly attached to the pedals it is a help

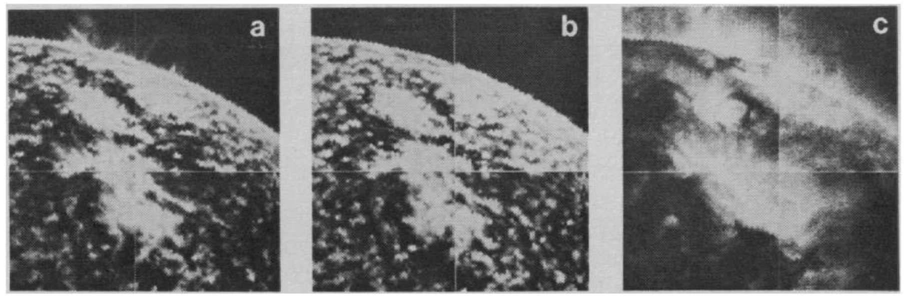

Fig. 3. Mosaic of four rasters taken at three wavelengths within about 25 minutes at 1600 G.M.T. on 11 September 1973, with the Harvard College Observatory spectroheliometer: (a) O VI, 1031.9 Å; (b) C III, 977.0 Å; (c) Mg X, 625.3 Å. These images of an active region span the temperature and height ranges from the chromosphere through the lower corona.

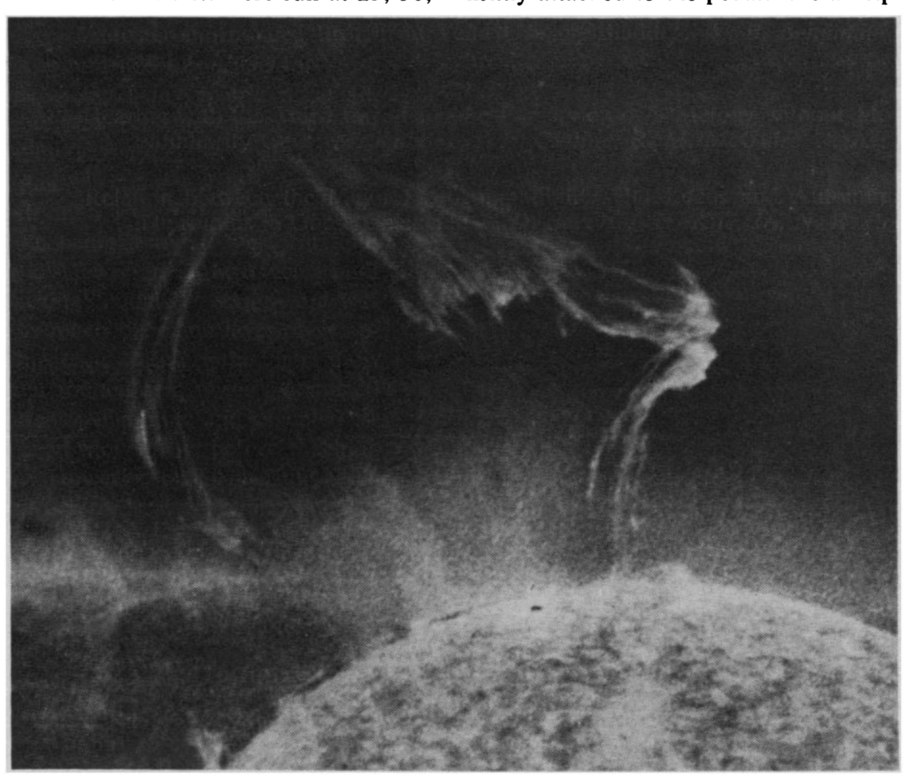

Fig. 4. Large looplike structure ejected into the solar corona, observed here on 9 August 1973, principally in the emission of He II ions. The eruptive gas cloud is much cooler than the surrounding million-degree corona and appears to have been partially blocked in its outward expansion. [Courtesy of the Naval Research Laboratory, Washington, D.C.]

to deliver a good part of the torque on the upstroke, and it takes a few weeks for an amateur cyclist to learn this and condition the different set of muscles.

For all the Skylab crewmen the sensors of taste, smell, touch, and vision seem to perform in zero-gravity just as they do on Earth. Appetite, after the first few days, also seemed to be normal. Since our menu was repeated every 6 days for the full flight duration, and with only slight modifications in the pre- and postflight intervals as well, there were a few individual items that various crewmen found unpalatable. Several crewmen continued to experience a slow weight loss throughout their flight. Had an "open pantry" been possible, the satisfaction of normal hunger might well have halted this trend.

There appear to be no psychological problems associated with the lack of clearly established "vertical" or "horizontal" orientations. In fact, one automatically adjusts his impression of "up" to conform to his own body orientation quite readily. I found sleep a very pleasant experience, achieved easily and fully restful. Complete electroencephalogram analyses of many sleep periods showed little change in the patterns that had been observed before the flight (*15*).

Manual coordination functions posed no problems at all for the crewmen with one notable exception. Reaching or handling objects was entirely normal, as long as visual contact was maintained. However, in the sleep compartment with all the lights out, we found it almost impossible to directly reach out and touch the light switch, located less than 2 feet "above" and in front of our heads! The result was not just a near miss—we found that our hands might first encounter a locker as much as 45° away from the correct direction. Although I tried to "practice" this move on a number of occasions, I still could not do it well after 2 months.

Upon return to Earth, all nine crewmen were in good condition and able to walk unaided. However, the sense of balance of each crewman was clearly not functioning normally yet, which should not be too surprising since the otoliths had experienced no gravitational forces and the gravity-responsive proprioceptive functions of the extremities (roughly, one's sense of "feeling" the forces supporting the body against gravity) had not been used for 1 to 3 months. As a result, each crewman exhibited a rather unsteady gait for 3 or 4 days, after which a normal sense of balance returned. Although my muscle strength after the flight was near preflight levels (*16*), my exercise capability was reduced for at least 3 months as measured by my jogging performance. Some of us noticed tenderness in the knee and ankle joints and some muscle soreness for a few weeks, but this condition then gradually disappeared. After a few months, there appeared to be no residual symptoms of any kind.

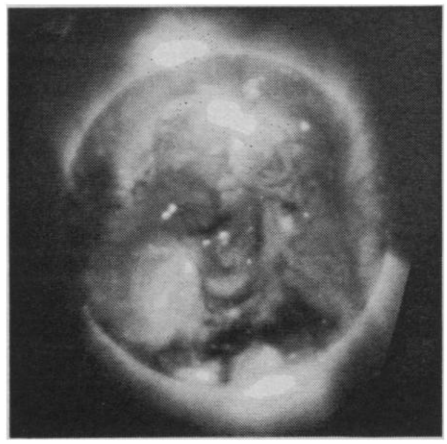

Fig. 5. Soft x-ray image of the solar corona obtained at 0336 U.T. on 28 May 1973, with the American Science and Engineering telescope. Notice especially the numerous bright points as well as coronal holes and the magnetic connections between separate active regions.

In order to achieve the objectives of the solar and medical experiments which have been only briefly reviewed or sketched above, close cooperation between ground and flight personnel was essential. Cooperative work began very early in the Skylab program, as experiment designs were being reviewed and procedures developed, well before the final crew selections were made about 1½ years before launch. In the course of these reviews, some new displays were added, such as for the white light coronagraph, to permit more effective use of various instruments. In the later phases of preparation, numerous simulations were conducted, involving all members of the scientific, flight control, and astronaut crew teams. Although these exercises were very time-consuming and even exhausting, they uncovered many unforeseen problems and interdisciplinary conflicts, of which a substantial fraction could be resolved before flight. Now that the flight program is complete, we may examine the Skylab operations in retrospect to identify those roles in which the crewmen were most effective in maximizing the scientific return.

Alter Ego of the Principal Investigator

On a multidisciplinary space flight, with only three crewmen available, it is an obvious impossibility to have even a few of the principal investigators personally at the sensors and controls of their instruments. All of the crewmen on Skylab had received several years of training oriented specifically to these flights. Much of it related to operations of the spacecraft, but about an equal fraction was devoted to experimental objectives in trainers and simulators, on some occasions with a principal investigator in attendance or even conducted at his home institution. As a result, a close personal rapport was established between flight crewmen and the ground-based scientific staff, which greatly increased mutual confidence and the ability to work together to achieve the experimental objectives.

One example of the fruit of this effort was the development of "shopping lists" which were devised after the first manned flight (Skylab I) to allow the crewmen to work independently of ground advice in selecting targets and objectives for the solar observations. These lists were originally devised to suggest to the crewmen a variety of short objectives that could be met if an extra 5 or 10 minutes of observing time should become available. The data collected in these intervals were found to be so useful that soon the ground team was requesting specific allotments of time to be used entirely at crewman option. Because the crewman had the current sensor outputs (and at EUV and x-ray wavelengths, unavailable on the ground), he was in the best position to select the most interesting features and programs for study. In this activity the crewman truly performed as the alter ego of the solar science community.

Pointing and Alignment Tasks

The Earth Resources Experiments Package (EREP) contained a number of photographic, microwave, and multispectral visible and infrared (IR) sensors used principally for evaluating the most satisfactory set of instruments for future operational systems. In one of the experiments an IR spectrometer was used to locate and track specific targets, such as a particular agricultural field for which simultaneous aircraft and ground truth was being obtained. Since the field of view (FOV) of the spectrometer was only 1 milliradian, corresponding to a square 0.4 kilometer on a side at the nadir, very careful training and considerable experience were required to locate and track the desired target. Several different targets were sometimes acquired only a few minutes apart in time.

The array of solar instruments (Fig. 1) was also pointed by the crewman at various features on the sun with a precision of about 1 arc second. (Performance was better than the equipment specification requirement of 2.5 arc seconds.) Detailed structures on the sun, such as chromospheric network boundaries, filaments, spicules at the limb, bright points, and the "core" of solar flares could be examined with narrow-FOV instruments. As mentioned before, the Naval Research Laboratory EUV spectrograph had an astigmatic slit of 2 by 60 arc seconds and the Harvard College Observatory EUV spectrometer accepted a field of 5 by 5 arc seconds. Thus, pointing precision was an essential element in the collection of useful data.

On 10 November 1973, the spectrometer was positioned on the solar disk by ground command so that the passage of the planet Mercury would intercept the line of sight. This successful operation was accomplished during a period when Skylab was not manned and required a major effort in the Mission Control Center. It would have been a very simple operation had a crewman been available for direct control.

Since all the solar instruments were mounted to a common spar, it was essential that the instruments with a narrow FOV be kept in close coalignment. After orbital operations began, it was found that the Naval Research Laboratory spectrograph and the Harvard College Observatory spectrometer did differ from precise coalignment by about 80 arc seconds. The Harvard College Observatory instrument was adjusted (in its spectrometer mode) to restore coalignment, and periodic checks were made thereafter to assure continued satisfactory alignment.

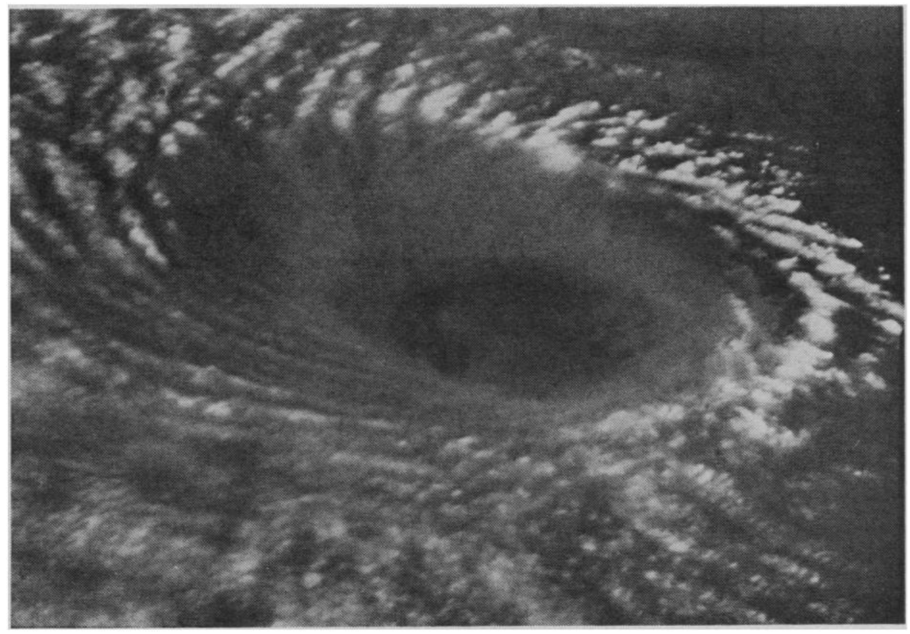

Fig. 6. Photograph of the eye of hurricane Irah, taken with a hand-held camera about 900 kilometers west of Acapulco at about 1230 U.T., 23 September 1973. Of particular interest is the alignment of long cloud strings and the funnel shape of the eye wall as it descends to the open water.

Transient Identification and Response

There are a wide variety of events almost certain to occur during a flight of 6 months, but whose precise times of occurrence cannot be planned. Examples are solar flares, coronal transients, hurricanes (Fig. 6), auroras, volcanic activity, and even astronomical phenomena such as comets. Preflight plans were made to observe all of these events, but crew or ground-coordinated action was required to establish that a transient was in progress (or, better yet, was imminent) and to select the appropriate mode of data collection.

In the case of solar flares, the crew usually had the first evidence of flare activity from the ATM instruments, particularly from x-ray flux measurements and the Naval Research Laboratory EUV monitor display, which provided an image of the sun in light integrated over the range of 170 to 550 Å (17 to 55 nm). It was then necessary to decide whether the current observing program should be interrupted and the instruments repointed to observe the flare. This was usually a difficult decision, because fluctuations in EUV and x-ray intensity were not infrequent, which could lead to a "false alarm," whereas it was also very important to observe the very early phase of an "explosive" flare when much of the energy is apparently released. More will be mentioned of this problem in a later section.

Coronal transients required similar identification and response, although there was usually little doubt about whether one was in progress (Fig. 2). Some were first discovered by the crew, whereas others were observed after the ground had received and relayed evidence of a possible transient from radio or coronameter (an instrument that measures the brightness of the corona) measurements.

Because hurricanes, auroras, and volcanic activity were predictable with about 24 hours' notice, revisions in the flight plan could be made for these phenomena, if required. Usually, data were collected only with hand-held cameras, although more sophisticated experiments will certainly be desirable in the future.

Comet Kohoutek was discovered well after all flight plans and experiment operations for Skylab had been formulated. Nevertheless, even as the Skylab I crew were completing their tasks, new plans were made to allow an extension of the flight of Skylab III from the planned 2 to 3 months, to adjust its launch date to optimize comet observations, and even to add new cameras to be operated during extravehicular activity (EVA), that is, with the crew outside the spacecraft. Although the ground views of Kohoutek were something less than spectacular, the views in space were certainly more impressive, and the coronagraph and EUV photography near perihelion promises to be of considerable value. Man's participation was the essential element in allowing the existing instruments to be used in a way not envisaged at the time of their design.

Data Quality

Monitoring the quality of the collected data is one of the more obvious uses for man in space research. On the basis of Skylab experience, it seems to be also one of the most important. The principal advantage to having a man in space employed in this way is that he is nearest to the sensors and can, therefore, most readily identify the source of any problem that might arise and, hopefully, correct it. In the medical area, the impedance between body electrodes, the performance of gas analyzers and mass spectrometers, and the reasonableness of heart rate and pulse pressure as related to observations of the subject are examples of this use. The astronomical instruments require monitoring for pointing stability, proper focus, reasonable sensor output, and normal sequencing of automated modes. Many of these tasks appear more reliably and economically monitored by man than by automatic systems telemetered to the ground.

One of the more complex Earth Resources instruments was a visible IR multispectral scanner, which recorded its images on magnetic tape for return to Earth. Neither the crew nor the ground could verify data quality in real time. As a result, intense low-frequency noise generated in the low-temperature detector system was not discovered until after the flight of Skylab I and the detector could not be replaced until the Skylab III flight. Much additional computer data processing is now required to restore the images, even at reduced quality. Obviously, real-time monitoring and repair capability would have been immensely helpful.

Experiment Setup

The design of many experiments was made more simple by launching them in an environment protected from launch loads and then having the crew reconfigure the experiment for orbital operation. This also permitted frequent film exchange in many cases and the interchange of experiments at a single scientific air lock for direct exposure to space. In several optical experiments the same external articulating mirror system was used, thereby achieving greater flexibility and capability without extra expense.

Innovation and Flexibility

Almost every discipline has provided examples of innovation and flexibility in their observational programs. Very little study of ocean currents in the Southern Hemisphere has yet been undertaken, and oceanography was not a part of Skylab's experimental program. Yet, the crew of Skylab III found that the Falkland current in the South Atlantic was well delineated by color contrast and its route over hundreds of kilometers can be traced in photographs that they took. The pictures also show areas of a "red tide" and algae blooms far at sea, most often brought to our attention in association with fish kills nearer the shore. These observations, along with others in meteorology (such as the intermediate scale structure of hurricane systems shown in Fig. 6) suggest new fields of study for later flight activities.

In solar observations, flares and especially their "rise" phase were a major objective. It was known that the region of brightest plage in an active region, sometimes lying on either side of the magnetic neutral line, was the most probable location for a flare. However, no known forecasting techniques were useful in predicting their initiation on a scale of, say, 5 minutes to 1 hour. In flight, it was found that the brightest portion of the plage appears, on at least some occasions, to undergo a periodic fluctuation in EUV intensity, not necessarily noticeable in visible wavelengths such as hydrogen-alpha. This fluctuation was used on several occasions to alert the crewman observer to the possibility of an impending flare and to initiate experiment operation in the appropriate modes. As a result, a good many examples are presently being analyzed showing the flare activity within a few minutes of its earliest manifestation and well before it reached peak intensity.

It was also observed that many of the flares have a well-defined and rather small core, more brilliant in the EUV than the surrounding bright plage. We estimated the size to be 5 or 10 arc seconds in diameter from our displays, although more precise measurements will come from the Naval Research Laboratory spectroheliograph. This allowed the narrow-FOV instruments to be placed directly on the brightest segment of the flare for temporal and spectral investigations.

During the Skylab II flight the spatial and temporal character of coronal transients were observed for the first time and the ease of identification of these events was established (Fig. 2). Earlier telemetry from Orbiting Solar Observatory 7 had shown large clouds of plasma being ejected from the sun, but the sensitivity and resolution of the High Altitude Observatory coronagraph TV image appears to have revealed much more of their spatial structure as discussed earlier.

Ground-based "quick look" analysis also revealed the importance of examining other solar features in the light emitted from ionized atoms in the lower corona, such as Mg X at 625 Å which occurs at a temperature of about 1.2×10^6 °K. Bright points and coronal holes could be located with much improved contrast at this wavelength, since the chromospheric emission at other EUV wavelengths was excluded. Pointing techniques were devised with the use of the Harvard College Observatory EUV spectrometer, and new observations of the temporal fluctuations of bright points, some of which became extremely brilliant, and coronal hole boundaries and gradients were carried out.

In the medical area, there was considerable uncertainty before the Skylab I flight as to the probable condition of the crew upon return to Earth after 1 month in zero-gravity. As it developed, regular and vigorous exercise was found to be a quite satisfactory way of maintaining good physical condition, although there do appear to be a number of adaptive changes that take place during the first 4 to 6 weeks of exposure. After the effects of somewhat differing exercise loads on the Skylab I mission had been observed, the Skylab II crew added several new items of exercise equipment and increased the daily time spent in exercise from about 30 minutes to 1 hour. Their more rapid return to preflight base lines after recovery prompted even more exercise with the Skylab III crew. They added a lightweight treadmill exerciser and increased their daily exercise time investment to about 1½ hours. The Skylab III crew exhibited the most rapid return to normal base lines of all three crews. I mention this sequence to illustrate the flexibility with which Skylab experiments could be performed, allowing second- and third-generation objectives to be reached, as long as a preliminary interpretation of results was made concurrently with the conduct of the experiments.

Repair Activities

In-flight repair of Skylab not only saved the program from near disaster but also was an essential element in the completion of most of the experimental objectives. When Skylab was launched on 14 May 1973, a thin micrometeoroid shield was torn away by aerodynamic pressure just over 1 minute after liftoff. Although the shield was never needed for its original purpose, the incident led to two other major difficulties. (i) One of two large solar arrays on the workshop portion of Skylab was also torn away, and the second wing was pinned to the side of the workshop with a metal strap. This reduced the available power to about half that planned before the flight. (ii) The very careful thermal balance of the workshop was destroyed, with the result that internal temperature climbed as high as 60°C.

The launch date of Skylab I was delayed from 15 May to 25 May 1973, and several solutions to the thermal problem were conceived and designed, and flight hardware constructed prior to 25 May. All NASA centers and thousands of support contractors contributed to these efforts, which were ultimately successful. In the method finally adopted, the crew extended a "parasol" out through an airlock on the sun side of the workshop, originally intended to accommodate several scientific instruments. After the parasol had been fully extended, it unfolded and shaded the workshop where the micrometeoroid shield had been placed before (Fig. 1). Internal temperatures began to drop immediately toward the more comfortable 27°C range. The power problem was finally solved when two crewmen went outside the spacecraft (EVA) with a set of bolt cutters attached to a long rod. The metal strap was finally cut and the solar array wing erected manually.

In the next 8 months, a succession of repair tasks was required in orbit, only some of which will be mentioned here. For the ATM solar experiments, repairs or modifications were made to every one of the principal scientific instruments. The EVA tasks included (i) pinning open one telescope aperture door which had stuck closed, (ii) removal of the ramps on three other aperture doors to prevent their sticking closed, (iii) brushing away a small hair or whisker on the outer occulting disk of the coronagraph, and (iv) repair of a jammed wheel filter on an x-ray telescope. Within the pressurized volume, the timer-sequencer of one Naval Research Laboratory experiment was changed, based upon results of earlier flights, to optimize the exposure lengths and save film, and one TV monitor assembly was replaced.

A scanning microwave antenna, part of the Earth Resources equipment, was repaired during EVA as well as the visible IR detector of the multispectral scanner inside the spacecraft. A broken pedal was repaired and the handlebars on the bicycle ergometer were extended; this ergometer was a very critical item, as it was the principal exercise device and provided the measured workload for two of the medical experiments. Other spacecraft repairs included the placing of an extra sunshade over the top of the parasol (EVA), replacement of a set of six gyros controlling spacecraft attitude (both internal and EVA), refilling the coolant line, and repairing the battery module relay.

It is important to keep in mind that out of this list, only one item (the ATM aperture door that was pinned open) was considered as potentially repairable prior to flight! Indeed, the spacecraft and most of the experiments had been designed with almost no thought of man's participation as a repairman. In spite of this, once a failure or problem presented itself during flight, solutions were usually generated and accomplished.

Implications for Shuttle

Many of the roles in which man has participated in research aboard Skylab will again be important in future space activities such as the Space Shuttle. Examples are pointing, alignment, transient identification and response, and assurance of data quality. We can extend these tasks to include a greater role in data management and interpretation, so that some selectivity or processing, or both, might be appropriate onboard the spacecraft, prior to transmission of the data to the ground.

Present plans call for somewhat larger Shuttle crews of four to seven persons, with either principal investigators or their direct representatives among them. Still, the role of an alter ego for one or more PI groups does not seem inappropriate, as a variety of experiments will surely be flown, even when they are within one or two disciplines, owing to the large payload capacity and desire for economy in the mission operations. Skylab made important advances in the intercommunication between flight crew and the ground science team, including occasions of direct verbal exchange between the principal investigators and crew. The Shuttle should certainly expand upon this, perhaps to the point of a dedicated voice channel for crew–science team communication.

The opportunity to innovate is presumably always a desirable objective, but it can be severely curtailed by inappropriate or inflexible experimental design. It is essential that the necessary sensor outputs be displayed to the crew, and some processing and data retrieval capability provided, in order that the opportunity to innovate is achieved. Much the same comment applies to repair activities, because many systems can be designed so that a desirable repair feature becomes virtually impossible. In the Shuttle, it will be necessary to evaluate these designs in light of the intended occasional return to Earth of most payloads for repair or refurbishment. In-flight repairs would be justified when it becomes economically advantageous to avoid a separate flight.

Finally, I would hope that this discussion will not be misinterpreted as another "contribution" to the largely unproductive arguments relative to manned versus automated space experimentation. Instead, I have intended to provide an outline of some of the fascinating new results coming from Skylab experiments, to show how man has been used to maximize the scientific return, and to extrapolate to his roles in the Shuttle era. Hopefully, the results presented here may spur the imaginations of those planning experiments for the Shuttle and result in a more optimum meld of personal and automatic control.

References and Notes

1. The three Skylab mission crews are listed below in the order of commander, scientist-pilot, and pilot, with the dates of their mission: Skylab I, Charles Conrad, Jr., Joseph P. Kerwin, Paul J. Weitz, 25 May to 22 June 1973; Skylab II, Alan L. Bean, Owen K. Garriott, Jack R. Lousma, 28 July to 25 September 1973; Skylab III, Gerald P. Carr, Edward G.

Gibson, William R. Pogue, 16 November 1973 to 8 February 1974.
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8. The principal investigators for the solar experiments (ATM) are as follows: R. M. MacQueen, High Altitude Observatory, Boulder, Colorado, white light coronagraph; R. Tousey, Naval Research Laboratory, Washington, D.C., EUV slit spectrograph and EUV spectroheliograph; E. M. Reeves, Harvard College Observatory, Cambridge, Massachusetts, EUV photoelectric spectroheliometer; G. S. Vaiana, American Science and Engineering, Cambridge, Massachusetts, x-ray spectrographic telescope; J. Milligan, Marshall Space Flight Center, Huntsville, Alabama, x-ray telescope.
9. E. M. Reeves, J. G. Timothy, M. C. E. Huber, paper presented at the Meeting of the Society of Photo-Optical Instrumentation Engineers, Tucson, Arizona, 4–6 March 1974.
10. J. M. Wilcox, P. H. Scherrer, L. Svalgaard, W. O. Roberts, R. H. Olson, R. L. Jenne, *J. Atmos. Sci.* **31**, 581 (1974).
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13. Principal investigators for the vestibular function experiment are A. Graybiel and E. F. Miller. Their initial results are summarized by Buchanan (*2*) and in papers presented as part of the 1974 annual scientific meeting of the Aerospace Medical Association, four sessions on Skylab II, Washington, D.C., 6–9 May 1974.
14. Principal investigators for the lower body negative pressure experiment are R. L. Johnson and G. W. Hoffler. The principal investigators for the metabolic activity experiment are E. L. Michel and J. A. Rummel. Some of their initial results are summarized by Buchanan (*2*) and in papers presented as part of the 1974 annual scientific meeting of the Aerospace Medical Association, four sessions on Skylab II, Washington, D.C., 6–9 May 1974.
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17. I thank my fellow astronauts for discussions which have contributed significantly to drafts of this paper, especially the suggestions of J. Allen, J. Kerwin, W. Lenoir, R. Parker, and P. Weitz. Also, I thank our Skylab II crew physician, Dr. P. Buchanan, for his very helpful comments and advice.

High-Pressure Ion Exchange Chromatography

New systems for analyzing large numbers of body fluid components can be used in the clinical laboratory.

Charles D. Scott

There is an increasing interest among medical scientists in new systems being developed for the automatic analysis of large numbers of molecular constituents in various body fluids. The quantities of the constituents of all physiologic fluids represent potentially useful diagnostic information; however, the analysis of urine presents the greatest challenge. In a bibliography on urinary constituents, the literature for a 3-year period has more than 3000 citations to more than 700 molecular constituents, many of which could have pathologic significance (*1*). In this article I describe some of the new high-resolution analytical systems that are based on the use of high-pressure liquid chromatography, and that are at least potentially useful for the analysis of urine and other less complex body fluids. Such systems are used primarily for the identification and quantification of the low molecular weight (less than 1000) components of physiologic fluid.

The term "high-resolution analysis" is used to describe a procedure in which a large number of the constituents of a sample mixture are separated and quantified. Thus, high-resolution analytical techniques provide (i) a means of separating the individual components and (ii) a means of detecting and quantifying the separated components. Several high-resolution liquid chromatography (LC) systems have been developed for these applications, and now a whole family of instruments is available for separating and quantifying various types of biochemical constituents. These include analyzers for ultraviolet absorbing constituents (*2–4*), amino acids and related compounds (*5, 6*), carbohydrates (*3, 7*), and organic acids (*8, 9*); other, more highly specialized analyzers have also been developed. Much of the early work on high-pressure LC was directed toward the development of separation systems for physiologic fluids (*2–4, 10*). Liquid chromatography, as a method for separating complex biochemical mixtures, represents a useful complement to gas chromatography. Although a more rapid separation can be achieved with gas chromatography, sample preparation and volatilization of biochemicals naturally occurring in an aqueous medium can be complicated and time-consuming, and the results are likely to be difficult to quantitate. Conversely, sample preparation for LC systems (many of which use aqueous eluents) is frequently very simple, in

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