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THE SOLAR MAXIMUM OBSERVATORY

In April 1984, the National Aeronautics and Space Administration attempted the first repair of a satellite in space. The Solar Maximum Repair Mission saved the nation's only orbiting solar observatory. This article is about the satellite observatory, why it is in space, what has been accomplished with its telescopes so far, and what solar physicists hope to achieve with it in the years to come.

INTRODUCTION

As Galileo showed in 1610, the sun is not a perfect sphere. It has spots. The number of spots has been noted daily for almost 300 years by astronomers hoping to find a clue to their cause. No one knows what causes sunspots, but it is known that their numbers peak every 11 years (Fig. 1). The number of powerful explosions, called flares, also increases. They usually occur in the solar atmosphere above sunspots and last for less than an hour. However, flares are poorly understood. A better understanding of them was the objective of the Solar Maximum Mission, launched just before the 1980 sunspot and flare maximum.

Life began for the Solar Maximum Mission in 1975 when the National Aeronautics and Space Administration (NASA) asked a group of solar physicists to meet at Snowmass, Colo., to outline the payload for a space observatory to study solar flares and other solar activity during the then approaching maximum of sunspot activity.[1] Since the next maximum was expected in 1979, NASA and the Congress put the Solar Maximum Mission immediately at the head of the "new start" list rather than delay the project for another 11 years. Work on the telescopes was started in 1976 at eight U.S. and five foreign institutions. All the instruments but one[2] were delivered on time, and the Solar Maximum Mission was launched on St. Valentine's Day, 1980.

A list of instruments on the Solar Maximum Mission appears in Table 1. The instruments can be divided between imaging and whole sun detectors. The difference in the number of flares recorded by the two types is a measure of our ability to forecast and point the telescopes to where the next solar flare will occur. The nonimaging instruments recorded all solar bursts during the allowed sun-viewing time in each orbit. In nine months the nonimaging Hard X-Ray Burst Spectrometer recorded 1750 events, but the Hard X-Ray Imaging Spectrometer observed only 600 of them.

Initially, good observations were obtained from all the instruments but, as the mission went on, some failures occurred. A position encoder bulb burned out in the Soft X-Ray Polychromator, a microprocessor failed in the Hard X-Ray Imaging Spectrometer, and the Coronagraph/Polarimeter electronics began to act erratically. Nine months into the mission, three fuses in the satellite guiding system failed and the cluster of telescopes (which had been able to track and hold the sun to better than 0.5 second of arc) tilted out of control. A standby pointing system, referenced to the earth's magnetic field gradient, could only keep the telescopes within 8° of the sun (which subtends 0.5°). For the imaging instruments, the mission was over. For the nonimaging instruments, flare data continued to accumulate, and over 7000 events have been recorded thus far.

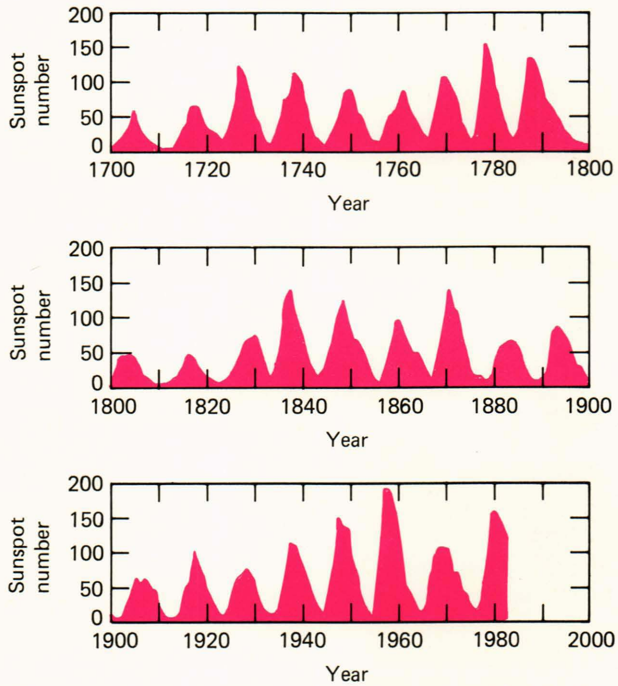

Figure 1 — Yearly mean sunspot numbers, 1700-1982. The mean number of sunspots varies with an 11-year period. The most recent sunspot maximum occurred in December 1980; it was the third highest peak ever recorded.

THE SOLAR MAXIMUM REPAIR MISSION

The platform on which the solar telescopes are mounted is called the Multiple Mission Satellite. It was built to be recovered someday (perhaps in 1986 or 1987) with a trunnion that an astronaut can grasp with a special tool (Fig. 2), and it appeared that the satel-

Table 1 — Instruments aboard the Solar Maximum Mission.

Experiment	*Principal Institutions*	*Spectral Range*	*Spectral Resolution*	*Spatial Resolution*
Gamma-Ray/Neutron Spectrometer	Univ. of New Hampshire; Max-Planck Inst., Garching; Naval Research Lab.	Gamma rays: 0.3—9 MeV Neutrons: >20 MeV	476 channels (7% at 662 keV)	Full sun
Hard X-Ray Burst Spectrometer	Goddard Space Flight Center	20-255 keV	15 channels (30% at 122 keV)	Full sun
Hard X-Ray Imaging Spectrometer	Astron. Inst., Utrecht; Univ. of Birmingham	3.5-30 keV	6 channels (typically 16% at 14 keV)	8 × 8 min or 32 × 32 min
Soft X-Ray Polychromator	Lockheed Palo Alto Res. Lab.; Mullard Space Science Lab.; Appleton Lab.	1.4-22.4Å	Typically 0.20 mÅ	Typically 14 × 14 min for imaging; 6 × 6 min for spectra
Ultraviolet Spectrometer and Polarimeter	Marshall Space Flight Center; Goddard Space Flight Center	1100-3000 Å	0.02Å	Variable: 1 × 1 min to 15 × 286 min
Coronagraph/ Polarimeter	High Altitude Observatory	4465-6885 Å	4 broad bands; Fe XIV; H-Alpha	6.4 × 6.4 min or 12.8 × 12.8 min
Active Cavity Radiometer	Jet Propulsion Laboratory	Integrated sunlight	0.001% accuracy	Full sun

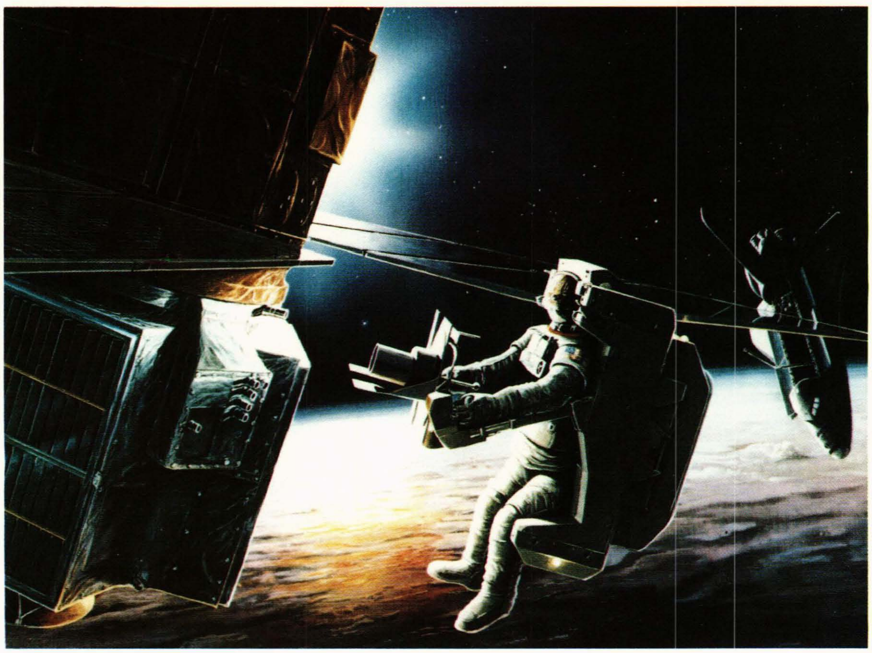

Figure 2 — Pre-mission painting of an untethered astronaut approaching the Solar Maximum Mission satellite. The special tool he holds for capturing the satellite did not lock onto the trunnion as planned. Subsequent efforts to stop the satellite's spin by grasping the solar panels by hand also failed because the arms of the solar panels do not pass through the satellite's center of gravity.

lite could be readily repaired by installing a new guidance unit. The team at NASA Goddard was enthusiastic, since a successful repair mission would vindicate the Multiple Mission Satellite design philosophy: to build a standard satellite that can be retrieved, altered, and repaired for many missions. The Solar Mission Maximum experimenters were equally enthusiastic because during nine months of full operation they had been able to carry out only a small part of the programs originally planned. Finally, in the space transportation world, a demonstration of after-launch service would give the space shuttle a decided edge over its competitors (such as the Ariane booster). The only problem was money. Congress at first turned down NASA's request to reprogram $50 million for the repair mission, but after some intense lobbying (particularly by scientists), funds were approved and NASA had 18 months to get ready for April's shuttle flight.

Two methods of capturing the satellite were developed and then rehearsed hundreds of times. During the flight, however, the primary approach, i.e., a zero-gravity bulldogging act by an untethered astronaut (illustrated in Fig. 2) failed and almost sent the solar observatory tumbling out of control forever. Attempts both to force the tool (shown) to clamp onto the trunnion and to stop the spinning by grasping the solar panels only worsened the satellite's wobble. The solar panels rotated out of the sunlight, so the satellite had to run on batteries that have a lifetime of only six hours.

The mission was saved by flight controllers at the Goddard Space Flight Center who were able to regain enough control with a magnetic torque system to reorient the solar panels and slow the spin rate to almost zero. Finally, using a mechanical arm and working from inside the shuttle, the astronauts were able to grasp the satellite and pull it safely into the shuttle bay (Fig. 3a).

The rest of the mission went extraordinarily well. Replacement of the attitude control module and of defective electronics in the Coronagraph/Polarimeter (Fig. 3b) was accomplished in less than half the programmed time.

The repair mission attracted great attention from the press, but relatively little was told about the accomplishments of the Solar Maximum Mission itself. In the four years since launch, solar physicists have been able to examine the data thoroughly. The results represent a substantial advance over the previous major solar mission (Skylab), whose Apollo telescopes recorded solar activity in 1973 during the decline from the 1969 sunspot maximum. The Solar Maximum Mission instruments generally have a much faster response time than the Skylab instruments, and they can record the bursts of hard X rays (energy greater than 10 kiloelectronvolts) and gamma rays (energy greater than 1 megaelectronvolt) that many believe are the key to understanding solar flares. Let us review some of the highlights of the scientific results so far. Data analysis is continuing at the institutions listed in Table 1, at APL, and elsewhere.

RESEARCH HIGHLIGHTS

Gamma Rays

The Gamma-Ray Spectrometer made an important discovery[3] when it recorded neutrons emitted by a flare on June 21, 1980 (Fig. 4). The neutrons were nuclear reaction products produced when beams of protons struck the solar photosphere. The existence of proton beams in flares has been known for a long time, and flare protons have been detected on earth. The neutron spectrum, however, provides a sensitive measure of the energy spectrum of the protons and of the depth to which they penetrate the sun's atmosphere.

Another important result is that the protons must have been accelerated in the flare at the very outset. The simultaneous arrival at earth of gamma rays (top of Fig. 4) from proton-induced reactions and X rays from electron-induced reactions proved it. Prior to these results, it was thought that as long as 20 minutes might be required to accelerate protons. Now it is clear that electric potentials equivalent to at least 25 million volts can develop within 2 seconds of flare onset. The simple time-of-flight calculations suggested by Fig. 5 can be made with confidence for neutrons, which follow straight line paths to the Gamma-Ray Spectrometer on the satellite. Protons and other charged particles, on the other hand, must spiral about the magnetic fields between the sun and the earth, and their travel time (and hence their instant of release at the sun) can be estimated only after a guess about the structure of the interplanetary magnetic fields.

The results show that neutrons and gamma rays are emitted from layers of the solar atmosphere where the density is between 10^{12} and 10^{16} particles per cubic centimeter, that is, from the chromosphere (see Fig. 6). The neutrons and gamma rays are nuclear reaction products from collisions of protons with atomic nuclei. Their spectra depend on the relative abundances of oxygen, carbon, nitrogen, neon, magnesium, silicon, and iron in the solar atmosphere. The relative abundances of these elements have long been a subject of debate because of deep disagreements between results from optical and from ultraviolet spectrum analyses. Although it is too early to say that the old disputes can now be settled, we can say that gamma-ray spectra will be very helpful in measuring elemental abundances on the sun. The results could be of fundamental importance because of the key role these elements play in theories of stellar evolution.

X Rays

Impressive progress was also made with the Hard X-Ray Imaging Spectrometer, which was capable of taking a photograph of solar flare X-ray emission each 1.5 seconds. The photographs, in which features down to 8 seconds of arc are resolved, showed that flares are like two uninsulated high voltage electric cables that have been brought too close together. The Hard X-Ray Imaging Spectrometer and the Hard X-Ray Burst Spectrometer showed that the flash phase of flares is characterized by temperatures of 100 million degrees at the point where two magnetic-field loops collide.[4] Such collisions happen when magnetic fields emerge from beneath the photosphere and expand into the tenuous atmosphere of the corona (Fig. 7). The point of collision heats to 100 million degrees in less than a minute, and it is there also that high voltages probably develop to accelerate protons. However, we cannot be absolutely sure of that until we have a telescope that will form images from the gamma rays. The existing Gamma-Ray Spectrometer has no spatial resolving power.

The Hard X-Ray Imaging Spectrometer's images show that virtually all flares consist of a low-lying, compressed magnetic loop colliding with one or more expanded loops. Both circuits are grounded in the photosphere, and, when the density of matter in the loops is not too high, electrons accelerate at the collision

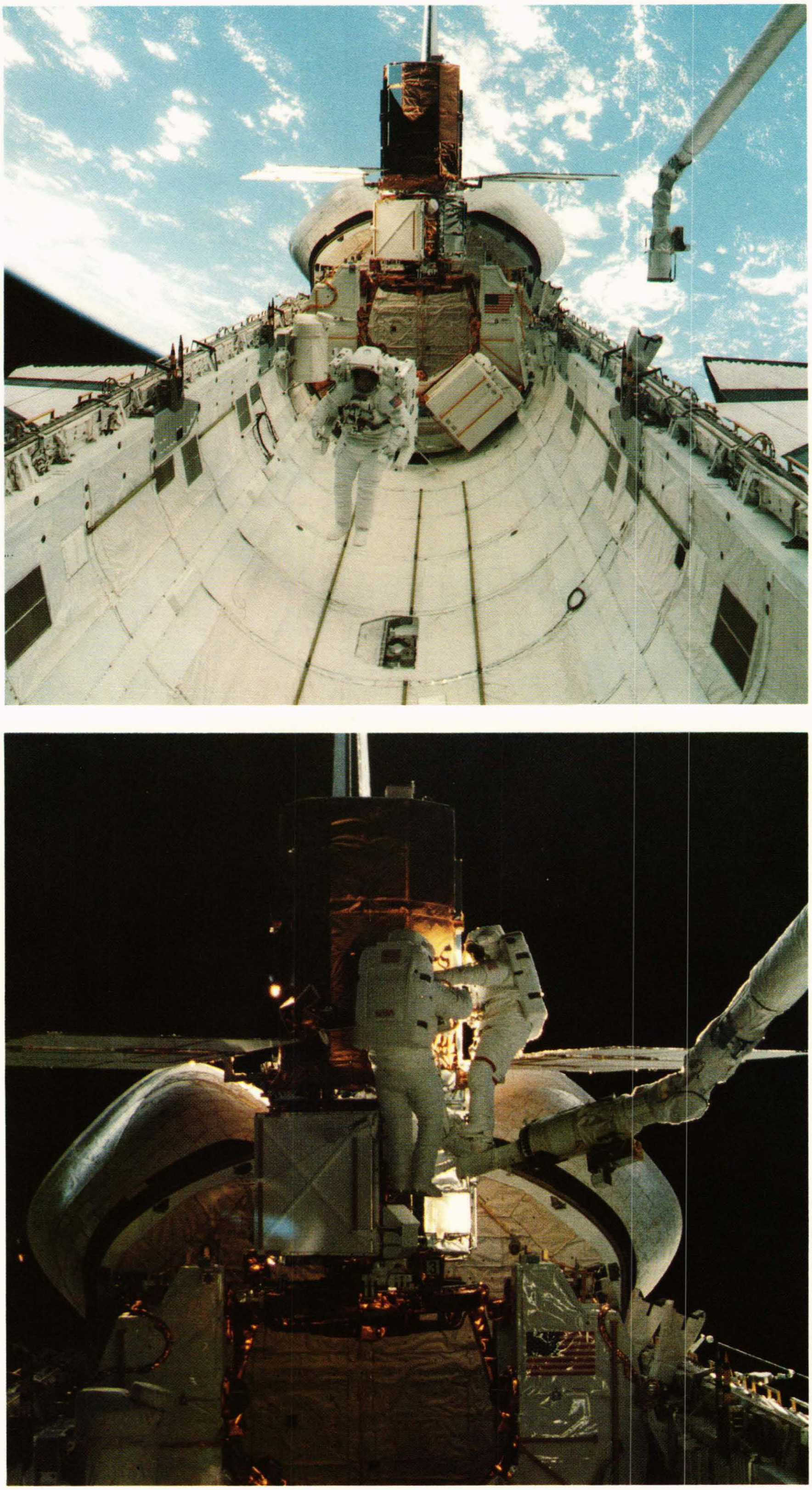

Figure 3 – (a) In-flight photograph of Astronaut James D. van Hoften after a busy day of work. The Solar Maximum Observatory is successfully berthed in the rear shuttle bay. (b) In-flight photograph of Astronauts George D. Nelson (right) and James D. van Hoften repairing the Coronagraph/Polarimeter. They have already installed a new attitude control module (the white box behind Nelson). They are using the "mobile foot restraint" of the shuttle's mechanical arm (upper right) to reach the telescope cluster of the Solar Maximum Observatory. The satellite was successfully plucked from orbit with a grappling device at the end of the arm.

point and spin away at nearly the speed of light until they strike the chromosphere. There, they emit braking radiation (bremsstrahlung), which is a continuous spectrum of X rays. The X-ray spectrometer was the first instrument able to form images of the bremsstrahlung radiation sites. The constellations of magnetic

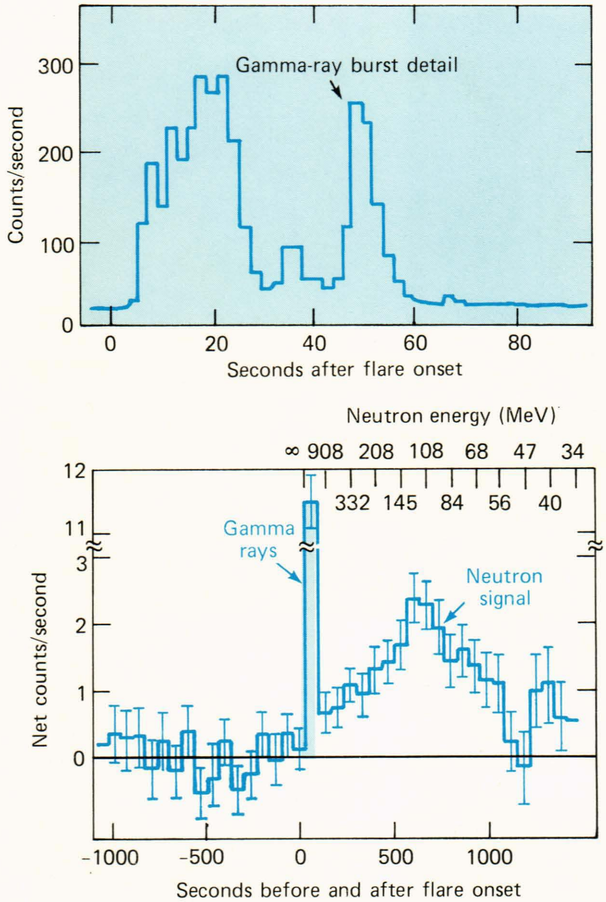

Figure 4 — Flare signals detected by the Gamma-Ray/Neutron Spectrometer. The sharp peak was due to gamma rays (high energy photons). The slower rising signal was caused by neutrons. Because the neutrons were released at the same time as the gamma rays, one can deduce their energies from the time of flight to the earth. Gamma rays arrive after 8 minutes, neutrons after 10 to 25 minutes.

loop intersections with the chromosphere thus pictured have helped us enormously in building the three-dimensional flare model in Fig. 7.

The structure of the high temperature region at the collision point is probably too small to be pictured by any of the satellite's telescopes. We can only speculate from theory that the 100 million degree flare core is a "raisin cookie" of magnetic field nodes, with each node a reservoir of invisible electric current energy that can accelerate electrons and ions (Fig. 7). The rate of electric energy dissipation in a hot plasma, or fully ionized gas, can be estimated from theory and experience in the plasma fusion program; it depends on temperature, density, and the magnetic field gradient. Current estimates, based on energy release in flare cores of approximately 100 ergs/cm^3/second, imply that the magnetic field gradients there must be much higher than the gradients we have resolved with telescopes.[5] That is, the spectrometer results showed the cookies, but could not resolve the raisins.

Less speculative conclusions can be drawn from movies made of successive X-ray imaging spectrometer photographs. They show that, from the instant

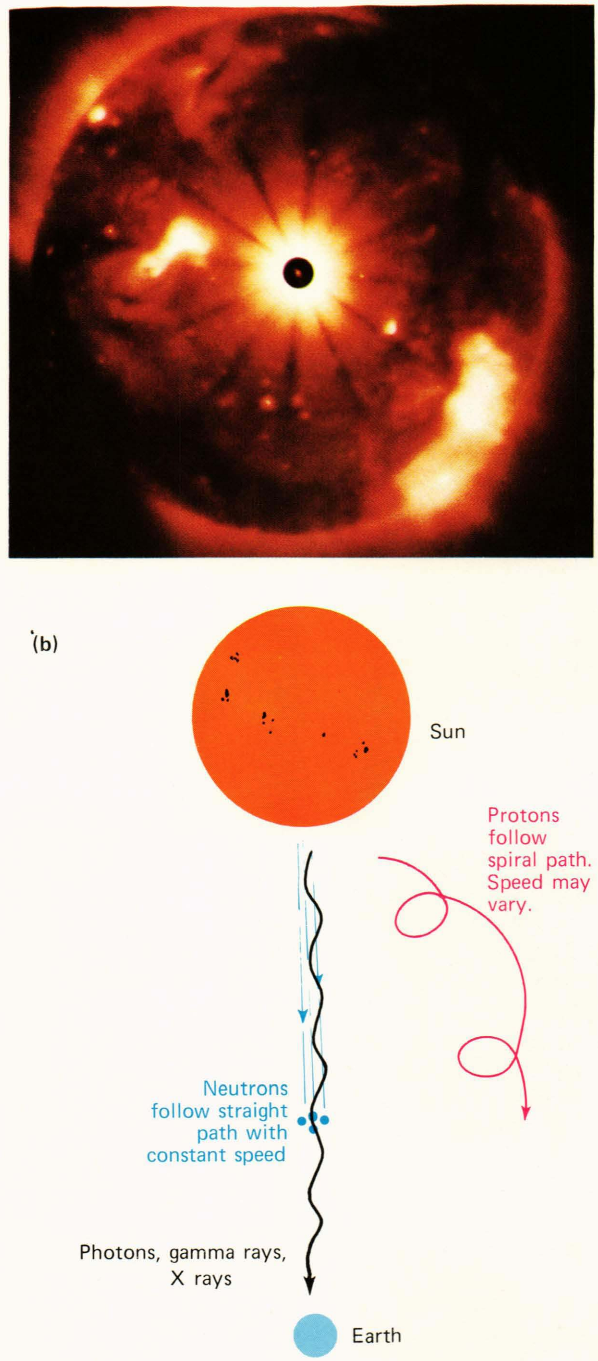

Figure 5 — The photograph shows a 1 second exposure of the X-ray emitting core of a solar flare overlaid on a 64 second exposure, which shows the stable and feathery solar corona plus flare X rays scattered by the telescope mirrors. The drawing illustrates the paths followed by X and gamma rays and by neutrons and protons from the flare to the earth.

when a flare core first brightens, the plasma in the colliding loops starts emitting X rays. An X-ray emitting front sets out along the loops, starting at the collision site. It stops only when it intersects the chromosphere. The soft X-ray front propagates at about 1000 km/second. Preliminary results, obtained at APL, indicate that these fronts carry away most of the energy devel-

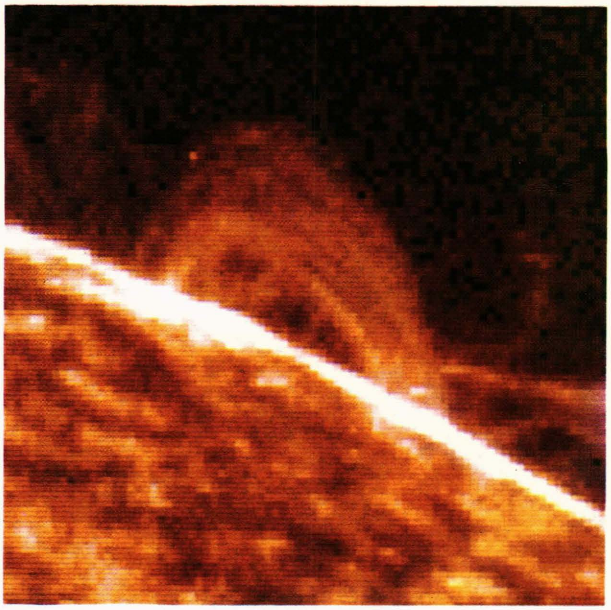

Figure 6 — Flare loops in the corona seen on March 27, 1980, by the Ultraviolet Spectrometer and Polarimeter. Flares are composed of several loop-shaped circuits carrying electric currents in the solar corona. The chromosphere (bright strip) is a 2000 km layer of gas at a density intermediate between those of the corona and of the photosphere.

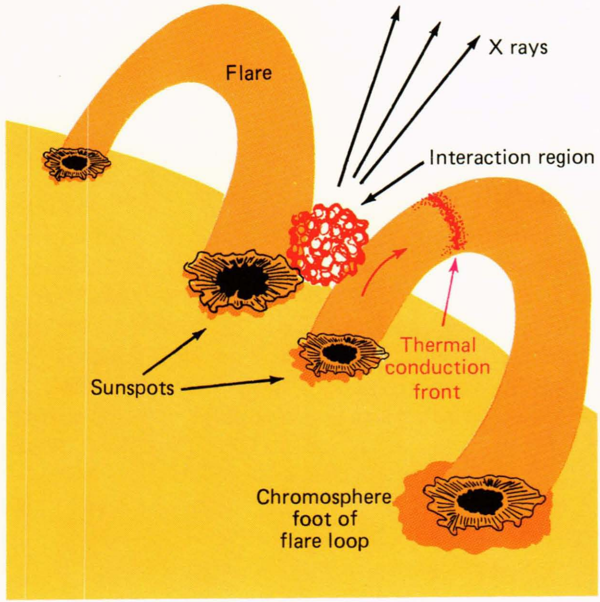

Figure 7 — Flare loops are rooted in sunspots in the photosphere. Their energy is probably released at many nodes (blue) too small to be seen with any telescope. The temperature around the nodes is close to 100 million degrees. Because of the intense heating, thermal conduction fronts can race through the loops, raising the temperature to 20 to 30 million degrees.

oped in flare cores.[6] The recorded spectrum of emissions from the fronts can be used to infer the plasma density and a temperature at each point on the magnetic loops for each instant during a flare. The spectral analyses performed so far indicate that the moving fronts are caused by a temperature increase instead of a density increase in the magnetic loops. We have interpreted these results as evidence for electron thermal conduction. If this interpretation is correct, then the conduction fronts would be the first to have been detected in an astrophysical context, although the importance of conduction has long been recognized in solar flare and supernova cloud theories.[7]

Ultraviolet Rays

When electron beams and conduction fronts reach the chromosphere, flashes of ultraviolet and visible light appear. The Ultraviolet Spectrometer and Polarimeter had the highest spatial resolution of any of the instruments and showed the impact points clearly (Fig. 8). The energy suddenly injected into the cool surface raises the temperature there from 10^4 K to over 10^7 K. The Ultraviolet Spectrometer and the Soft X-Ray Polychromator showed that hot, upward-moving plasma appeared in the corona just as energy was being deposited in the chromosphere. Simultaneous observations from ground-based telescopes showed optical emissions.[8] Analysis of the optical emission showed that material was being stripped off the top of the chromosphere, i.e., "evaporated" (sudden heating with a density decrease), at the same time as the hot material was arriving in the corona. Doppler shifts of the atomic X-ray lines recorded by the Soft X-Ray Polychromator indicated that most

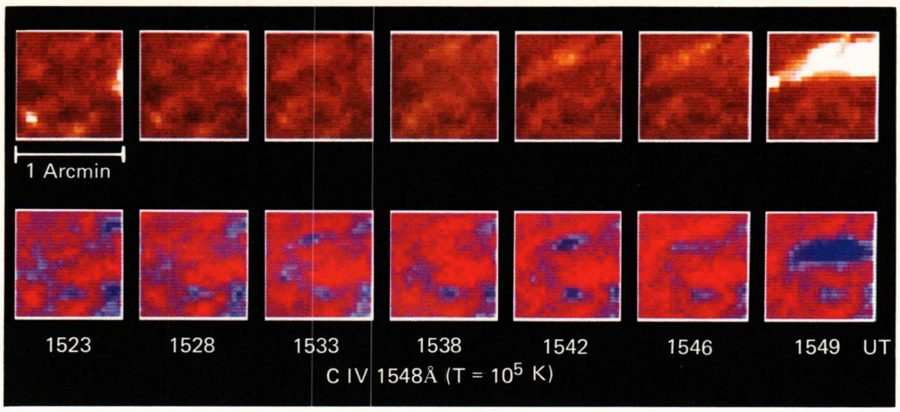

Figure 8 — The chromosphere brightens when struck by either atomic particles accelerated in the flare or by the thermal flare waves. This series of images from the Ultraviolet Spectrometer and Polarimeter shows the brightening (images from ultraviolet emission of carbon, top series) and the upward rush of material (blue patch, bottom series) associated with many flares. The top series of images is derived from the sum of two spectral channels, while the bottom series is based on the difference signal from the spectral channels.

flares cause such chromospheric evaporation and that the evaporated material expands into the corona at about 200 km/second.[9]

About 10^{15} grams (or 1 billion metric tons) of chromospheric matter are heated to 10^7 K in each major flare. A tremendous flux of X rays results and the material cools rapidly by radiation and conduction.[10] It therefore becomes dense and falls back into the chromosphere. Some of the most spectacular images of solar phenomena are of the so-called coronal rain of infalling material (Fig. 9) that follows flares.

During large flares, the X-ray flux reaching the top of the earth's atmosphere rises to 10,000 times the background level. X-ray and ultraviolet radiation heat our atmosphere and make it expand. This increases the drag on satellites, sometimes bringing them down sooner than anticipated. (Skylab fell to earth because the level of solar flare activity became higher than predicted when the Skylab orbit was selected.)

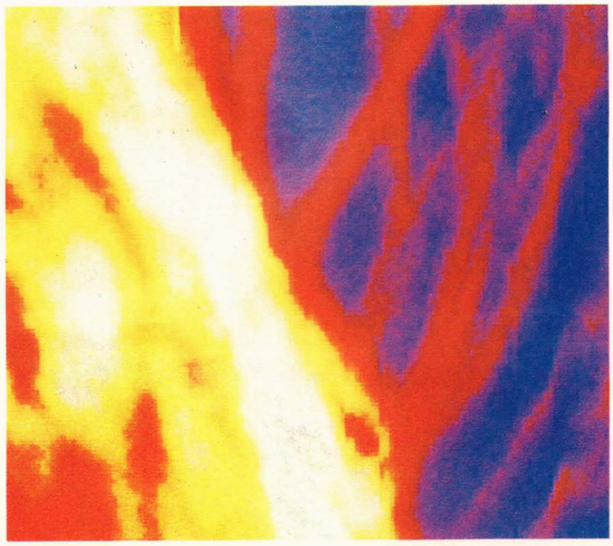

Figure 9 — Coronal rain follows major flares. Material that was evaporated from the chromosphere cools, becomes denser, and then falls at about 50 km/second back into the sun.

Mass Ejection

Another consequence of flares is ejection of coronal plasma into interplanetary space. Figure 10 shows the expansion of a giant loop or bubble (we are not sure which) following a major flare. The pictures were made with the Coronagraph/Polarimeter. By analyzing successive coronal pictures obtained through various polarizers, solar physicists can deduce the number and three-dimensional distribution of the electrons in the bubble.[11] The electrons themselves do not emit light but reflect it through a process called Thompson scattering in which each electron acts like a tiny antenna to relay the visible spectrum from the sun's photosphere to the earth. The more electrons there are in the ejected plasma cloud, the brighter it appears. The

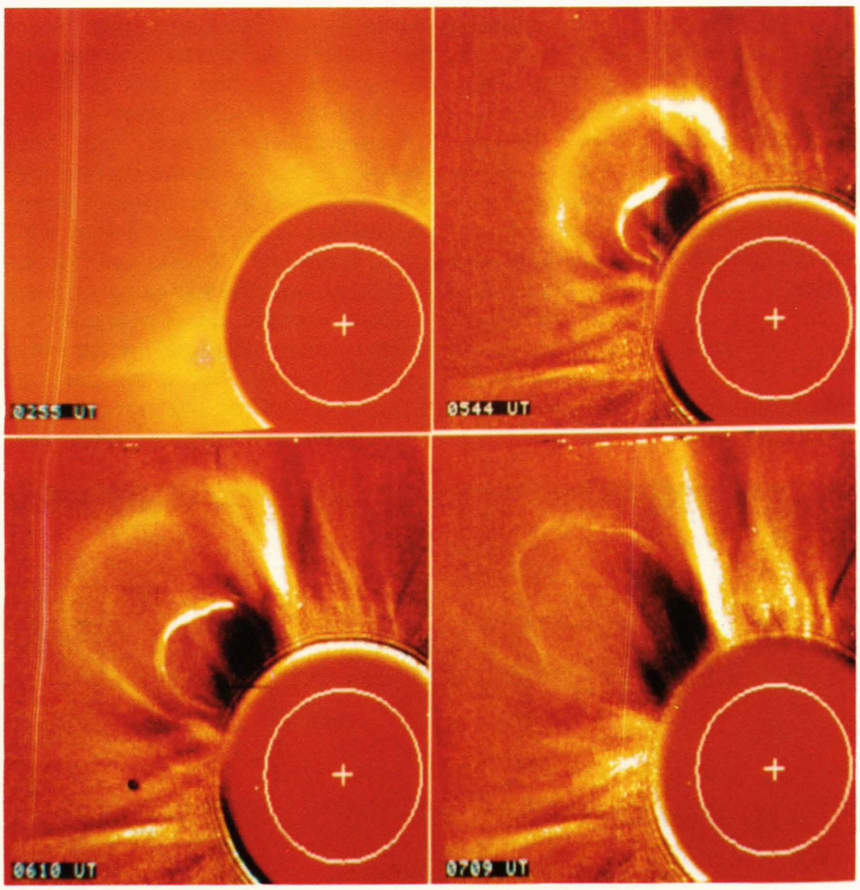

Figure 10 — During many flares some material is permanently ejected from the sun. These pictures show the passage through the corona of a mass ejection photographed by the Coronagraph/Polarimeter.

ejected clouds move through space at about 1000 kilometers per second. Some of them drift straight to the earth and cause magnetospheric disturbances. Unfortunately, the relationship between coronal ejections and magnetospheric disturbances is not yet clear because there are many other solar and interplanetary phenomena that perturb our magnetosphere.

THE SOLAR CONSTANT

Flares account for all solar radiation at energies greater than 10 kiloelectronvolts (hard X rays and gamma rays). Large flares exceed the background solar radiation in soft X rays and in the ultraviolet by about 10,000 times; in a few narrow spectral bands they exceed the stable visible emission by a ratio of about 3. But, as the Active Cavity Radiometer results showed, they have no discernible effect on the total radiant energy from the sun. The "solar constant" does not change by even 0.001% during flares. However, as Fig. 11 shows, it does change. The radiometer revealed the nonconstancy of the solar constant. The variations are caused principally by sunspot comings and goings.[12] The sharp dip in the solar irradiance shown in Fig. 11 was caused by the emergence of a giant spot group. Solar irradiance returned to near-normal when the spot group rotated out of sight about 10 days later. But the most important result of the radiometer experiment is hidden in the words "near-normal." After accounting for all the variations expected from sunspots and bright regions (called faculae), the experimenters were left with irregular variations at a level of 0.02%. These unexplained variations may be important clues to the origin of the solar cycle itself (Fig. 12).

The puzzling radiometer results have spawned several symposia and workshops, and recently, an organized campaign to obtain better photometric observations from the ground. Our purpose is to discover the solar disk positions of the unrecognized bright and dark features that appear in the irradiance records but cannot be found on the poorly calibrated images available up to now. The program has been extended to include all Active Region Time Scale phenomena since the success of the Solar Maximum Repair Mission has rekindled our hopes of understanding the internal workings of the sunspot cycle. From an analysis of the time series irradiance data, it has been inferred that the solar interior rotates no more than twice as fast as the surface.[13] This is an important result for efforts to discriminate among solar dynamo theories, some of which call for an interior rotation rate 10 times faster than the surface rate.

With the prospect for extending the solar irradiance series for a somewhat greater proportion of the 11-year solar cycle than 9 months, solar physicists are understandably excited about the Solar Maximum Repair Mission. While the instruments are still best suited to studying flares, much more of the observing time will now be devoted to slowly evolving phenomena. It is a natural redefinition of the observatory's purpose.

At APL, we continue with analysis of the X-ray data, but we shall also be active in the Active Region Time Scale program. We are currently working on models of large-scale solar magnetic fields in order to see how they influence long-lived structures in the co-

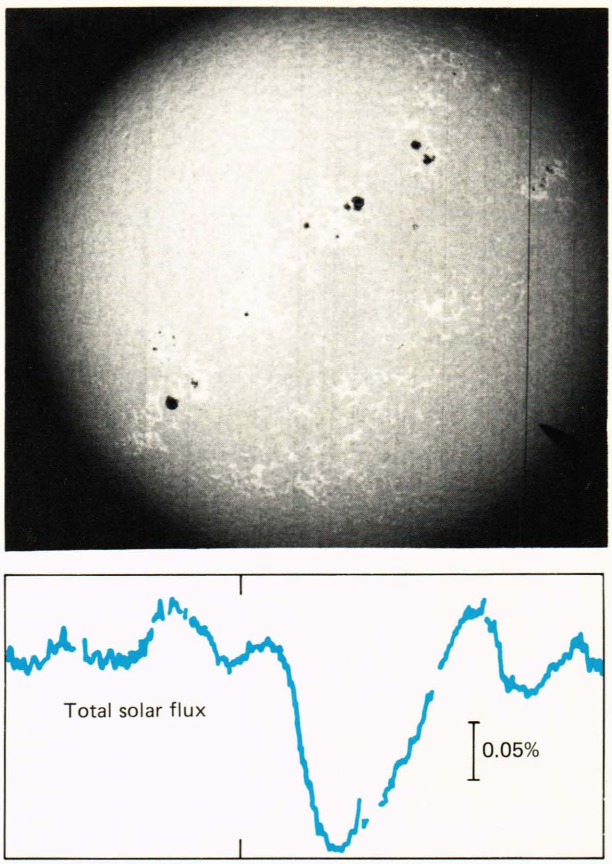

Figure 11 — The appearance of large groups of sunspots causes large dips in the sun's radiant flux. The graph is based on data obtained with the Active Cavity Radiometer.

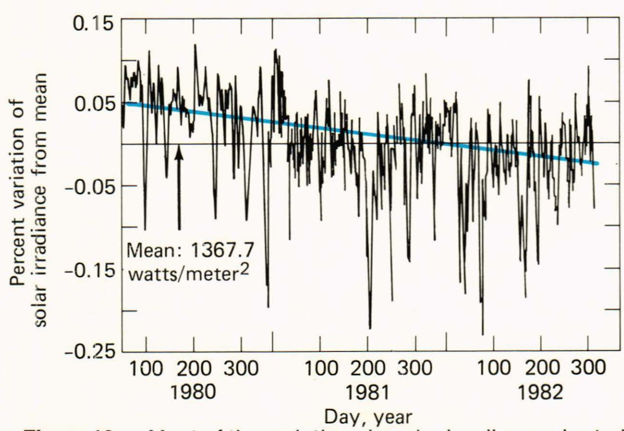

Figure 12 — Most of the variations in solar irradiance charted here were caused by the appearance and disappearance of sunspots. The long-term trend (colored line) suggests that the sun grew 0.09% dimmer in 1010 days of the Solar Maximum Mission, but we must wait a few more years before this trend can be confirmed.

rona. We are also building a compact telescope that will monitor solar magnetism from a satellite observatory. We expect that such an observatory will be launched during the next solar maximum. If the Solar Maximum Mission is kept operating until the new observatory is launched, it will surely make major contributions to solar physics, from the study of flare cores to the study of the solar core itself.

Note added in proof. Just two weeks after the repaired satellite observatory was released, the sun produced the largest flare of the current cycle. The flare was recorded in detail by the rejuvenated telescopes, which worked well. However, at least another month will be required before all engineering tests are completed. Some problems acquired during the long years of inactivity have appeared, but the scientists in charge believe that most problems can be resolved and that the Solar Maximum Observatory will operate until 1990.

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