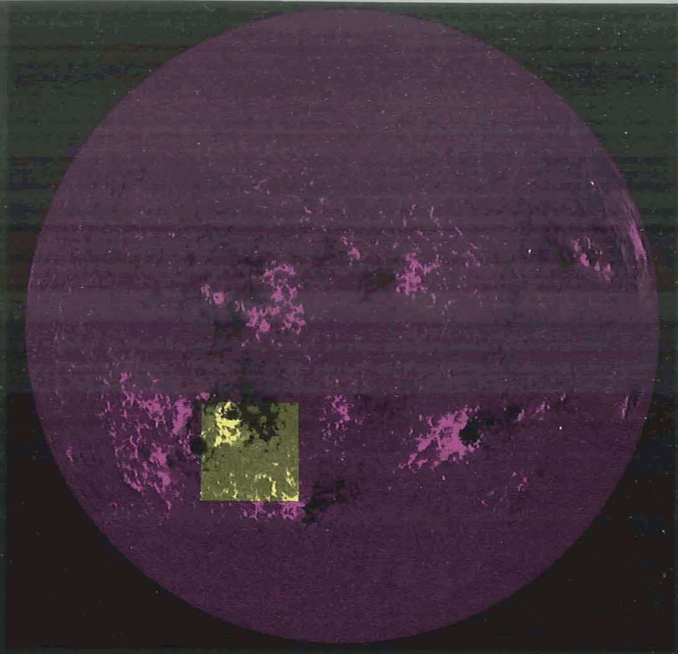
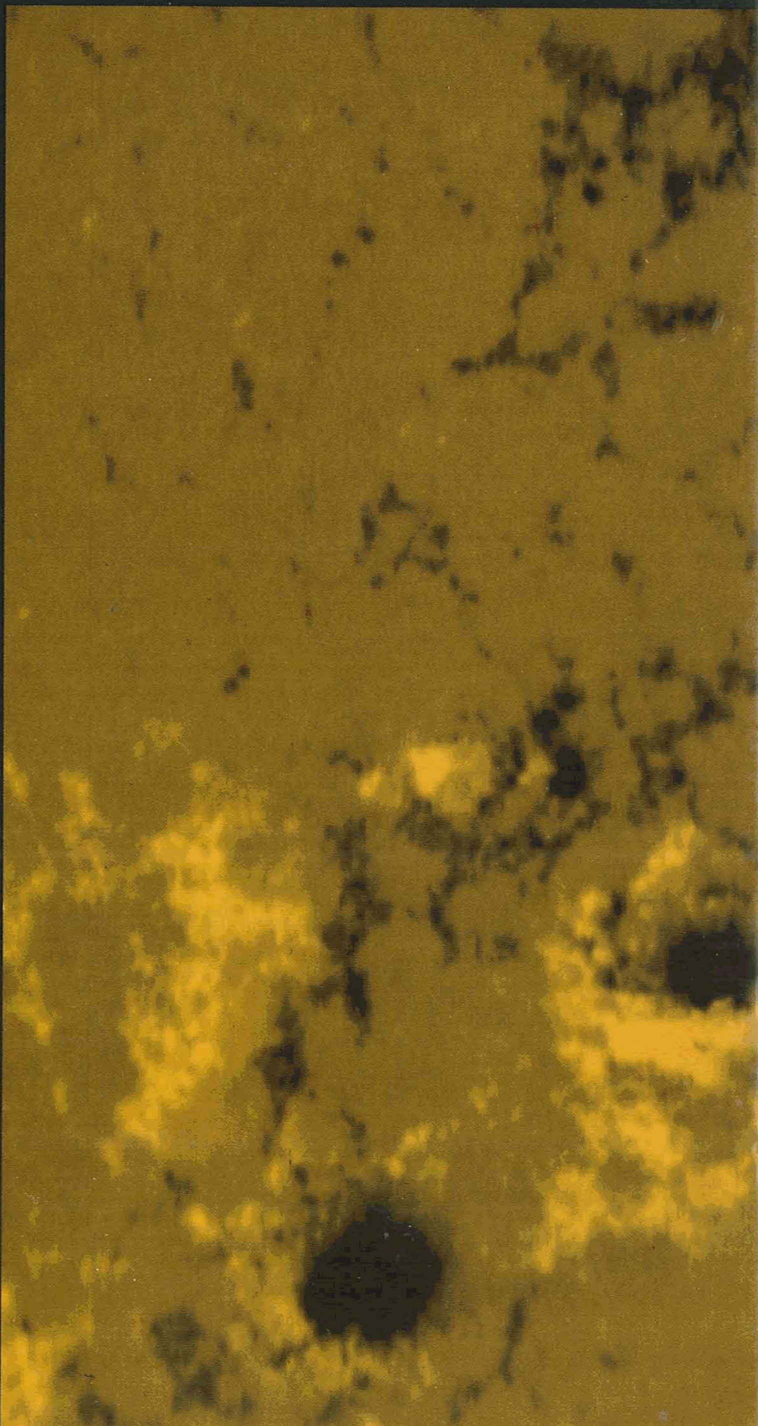
OSL

Orbiting
Solar
Laboratory

Our Window
On The Sun





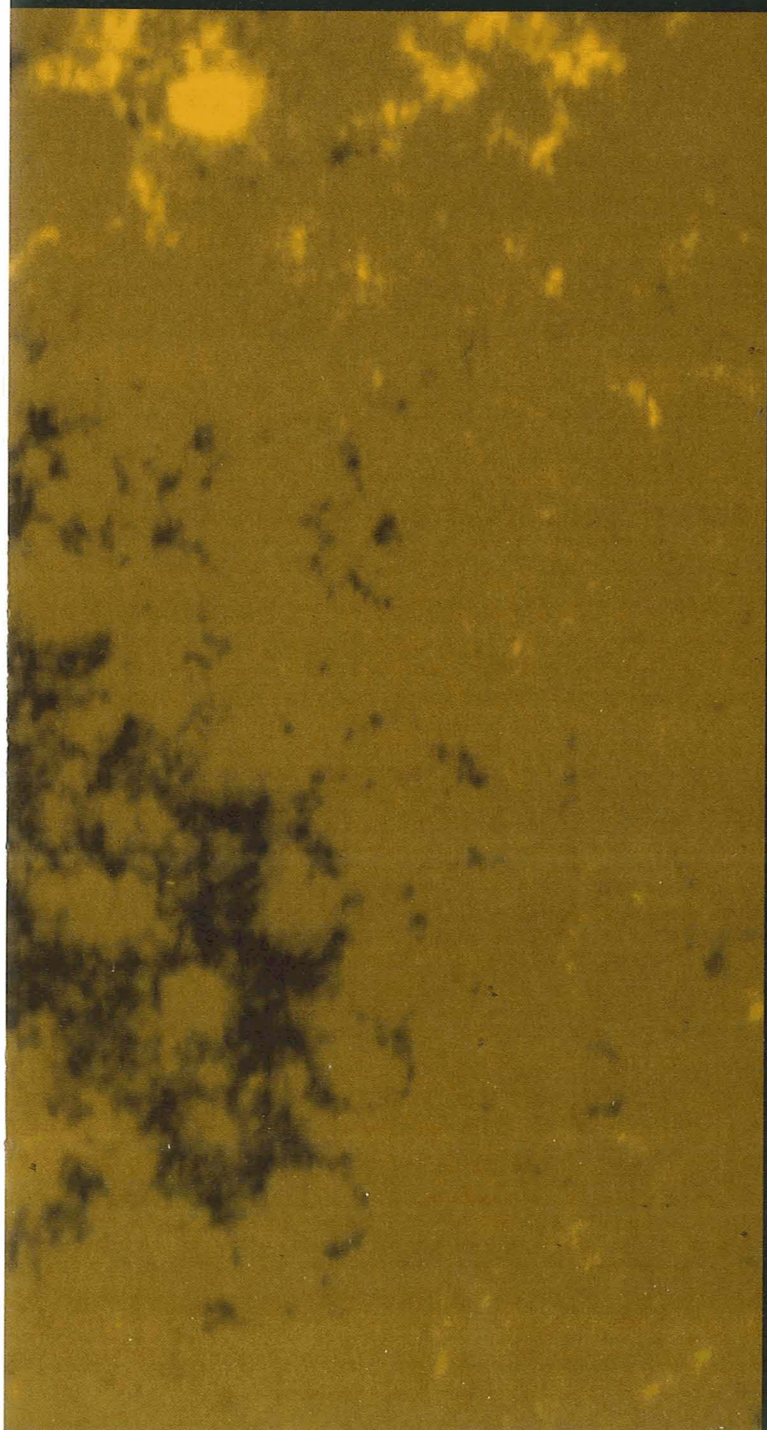
A Powerful Solar Observatory in Space

The Sun, the nearest star, is crucial for life on Earth and has always been an object of intense study. Indeed, many of the fundamental principles of astrophysics, which seeks to understand the physical nature of the universe, have been established through study of the Sun.

Magnetic activity within the Sun drives powerful events on its surface and in its atmosphere. From the Earth, these events can be seen as active regions with their sunspots and solar flares. But to observe such phenomena in detail requires more finely-tuned and powerful instruments, operating in space, across a broader range of the electromagnetic spectrum, than have ever been available in the past. Earth's atmosphere has always blurred the images received by visible-light telescopes on the ground. The atmosphere also acts as a barrier to the ultraviolet, extreme ultraviolet, and x rays that are similarly emitted from the Sun. All these wavelengths need to be captured, at the same moment in time, before the complex interrelationships of solar activity can be truly understood.

The Orbiting Solar Laboratory (OSL), the prime NASA solar mission for the 1990's, is uniquely designed to "see" across the wavelengths and so observe the fine evolving details of a wide range of phenomena on the surface of the Sun. By the turn of the century, OSL will enable scientists to solve mysteries that humankind has sought to unravel for thousands of years.

A magnetogram of the full disk of the Sun, in which white areas represent outward-pointing magnetic field, with close-up view of two sunspots. This ground-based image has a resolution of 2 arc seconds, which OSL will improve by a factor of 15.



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The Sun

Why Study the Sun?

Since prehistoric times, humankind has observed the Sun. Its rhythms intrigued our distant ancestors in locations as far apart as Stonehenge and the Big Horn Medicine Wheel of Wyoming. The Sun is the source of the heat and light that make possible life on Earth and it creates a spectrum of other significant effects on the Earth and in the interplanetary environment.

In addition, because the Sun is very much closer to Earth than any other star, it can provide detailed information about the nature of the stars and the universe that can be learned nowhere else. Since Galileo first studied sunspots in the seventeenth century, the Sun has fascinated scientists.

The Sun is also a unique laboratory for physics. Because of its huge scale, processes can be studied on the Sun that cannot be duplicated on Earth in any physics or engineering laboratory. Study of the Sun expands our knowledge of the way in which the physical world works, both on Earth and throughout the universe.

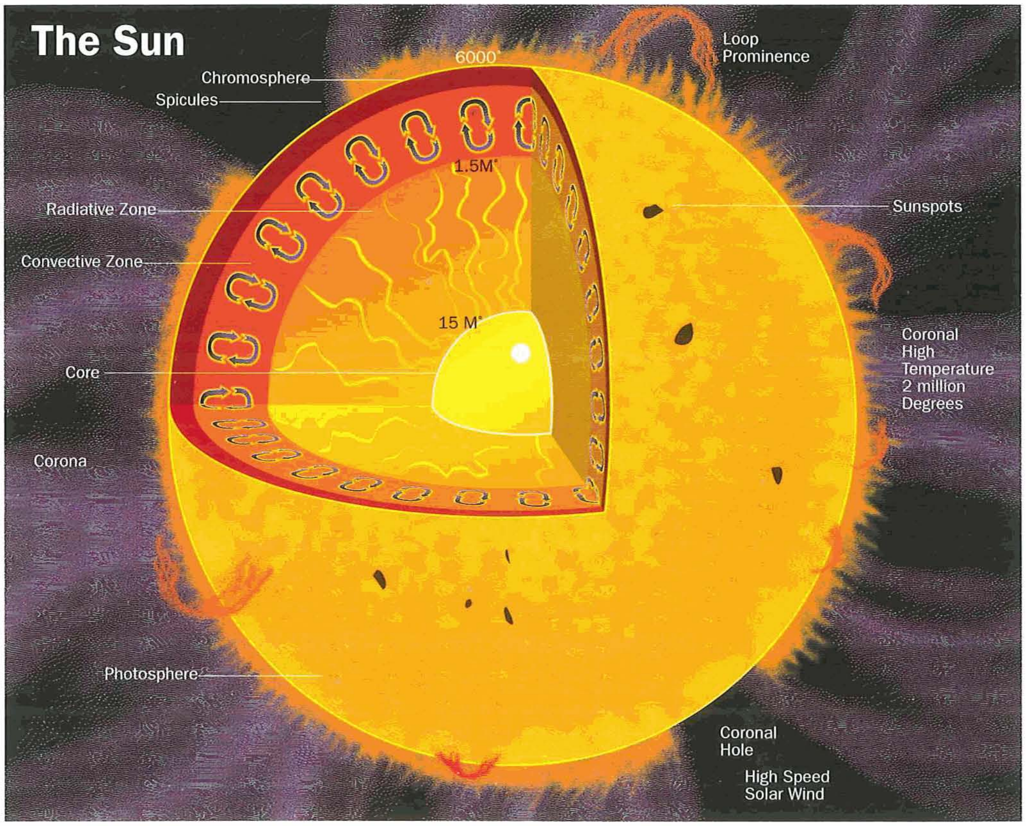
The Sun has been, and will continue to be, a compelling and important object of study.

What is the Sun?

What has all this study taught scientists—and what do they now need still to learn? It is known that the Sun is a sphere of hot, seething gases, of sudden outbursts and surges of radiation. The solar engine is driven by countless nuclear fusion reactions in its core, where the temperature reaches fifteen million degrees kelvin (K). Its energy encompasses the Earth, interacting in complex ways with the Earth's magnetic field and reaching out beyond the solar system into interstellar space.

It is known that very slowly, over millennia, the Sun is changing. About four and a half billion years ago, it is believed, the Sun was born out of a cloud of dust and gas. Approximately five billion years from now it will be transformed into a red giant star. It will consume the inner planets of the solar system and spew half of its mass into space in a series of gigantic expansions and contractions before subsiding into old age as a white dwarf.

Fortunately for life on Earth, the Sun in its present phase provides relatively constant radiation of heat and light. Although the Sun's brightness has increased by some 40 percent since its creation, the amount of solar energy retained by the Earth and its atmosphere has remained roughly the



The main features of the Sun.

same during its lifetime. That continuity has made possible life as it is known on Earth today. A small reduction in the average surface temperature of the Sun would initiate a major advance of the Earth's glaciers; a small rise would melt the icecaps, flood the continental coasts, and eventually turn the land masses to Saharan deserts.

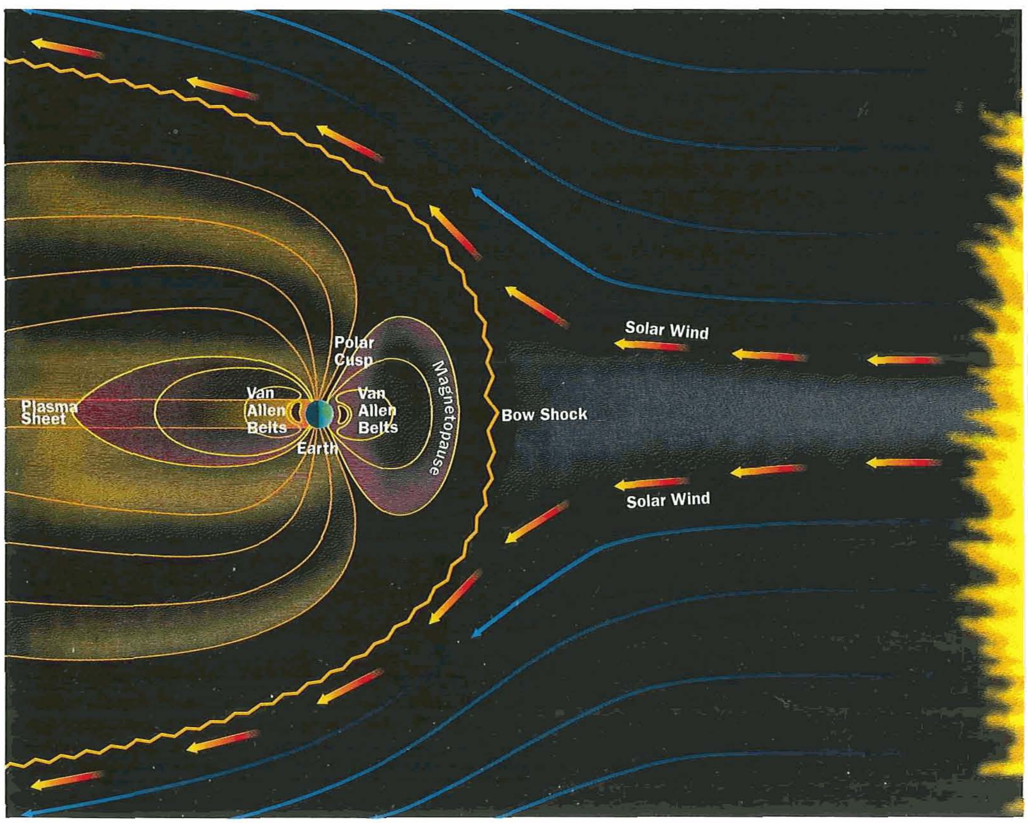
However, on much shorter timescales—every 11 years—magnetic activity deep within the Sun reaches a climax, causing outbreaks of dark sunspots, solar flares, and other forms of increased activity. The energy reaching the Earth during this period of maximum solar activity, known as the solar maximum, then rises some tenths of a percent compared with solar minimum. We do not yet understand the mechanisms that drive this cycle.

The Sun's bright surface is known as the photosphere (from Greek words meaning "sphere of light"). Above the photosphere lies the chromosphere, or "sphere of color," so called because of its bright red emission from hot hydrogen. Still higher above the solar surface lies the corona, or "crown," visible to the naked eye only when the Sun's bright disk is eclipsed. Beyond, flowing out into interplanetary space, is a stream of positively and negatively charged particles—a plasma—known as the solar wind.

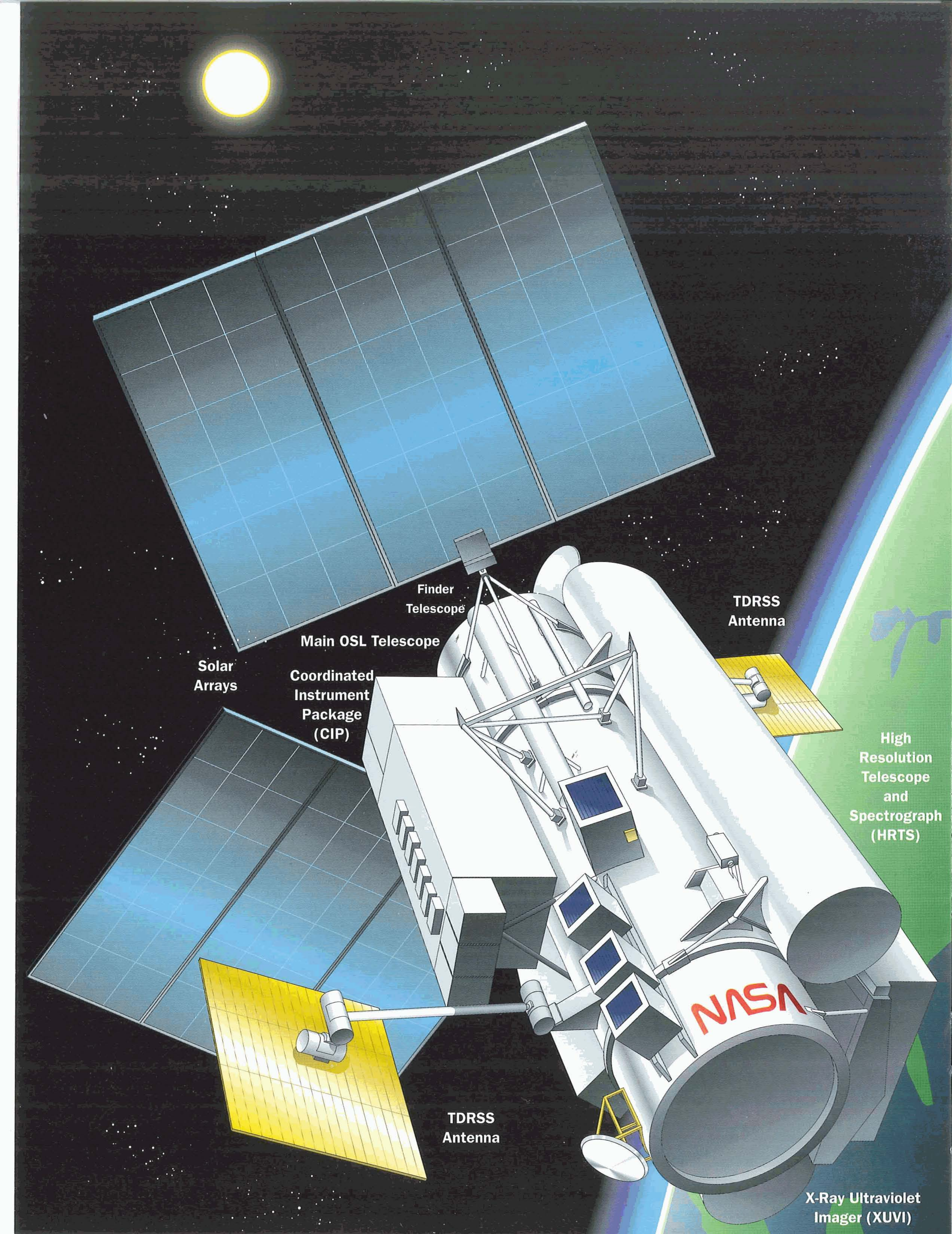
The solar wind catches the Earth in its flow and sweeps the lines of the terrestrial magnetic field—which forms a cavity in the solar wind known as the magnetosphere—out into the shape of a long tail.

As mighty forces contend within the Sun's million-mile sphere, their effects are manifested on the photosphere and spread outward in waves throughout the layers of the solar atmosphere. The effect of this process can be seen in visible light in the photosphere. Effects in the chromosphere can be detected by ultraviolet light, and those in the corona by extreme ultraviolet and x rays. The solar wind itself changes as these events unfold, carrying the direct effects into Earth's own space.

The Orbiting Solar Laboratory (OSL) will be designed specifically to read the messages in the three outer layers of the Sun—the photosphere, the chromosphere, and the corona—thereby giving us solutions to some of the deepest solar mysteries: the solar cycle, sunspots, flares, and many other phenomena.



A representation of the Earth's magnetosphere: the solar wind from the Sun on the right envelopes the Earth, flowing around the terrestrial magnetic field.


Finder Telescope
TDRSS Antenna
Main OSL Telescope
Solar Arrays
Coordinated Instrument Package (CIP)
High Resolution Telescope and Spectrograph (HRTS)
NASA
TDRSS Antenna
X-Ray Ultraviolet Imager (XUVI)

The Orbiting Solar Laboratory: A New Era in Solar Observations from Space

The key feature of the Orbiting Solar Laboratory mission is that it will place in space, in an almost continually sunlit orbit around the Earth's poles, the most powerful solar telescope ever flown. This telescope will be able to focus on a small area on the solar surface and observe the Sun in unprecedented detail almost continuously for most of the year.

Why Is This So Critical?

Study of the Sun from the ground is hampered by the Earth's overlying atmosphere in two fundamental ways. First, the atmosphere causes blurring of images from even the best ground-based telescopes, and this seriously degrades observations of key solar phenomena. Second, some of the most meaningful and informative emissions from the Sun occur at ultraviolet and x-ray wavelengths, which are not able to penetrate the Earth's atmosphere to ground level. Additionally, the day-night cycle experienced on Earth limits the time during which important events can be continuously observed. The solution to these problems is to make solar observations from space, where instruments can sharply capture the entire range of electromagnetic energy from visible light through x rays, and where the observing platform can orbit independently of the Earth's own rotation, and hence independently of the day-night cycle.

The United States has a long history of solar observations from space. They began with early rocket experiments in 1946, extended to the large solar telescopes on Skylab in 1973, and continued with the unmanned Orbiting Solar Observatories (1962–1978), the Solar Maximum Mission (1980–1989), and solar experiments on the Shuttle Spacelab 2 mission in 1985. These missions achieved major advances in solar research and hinted at the rich rewards to be gained from a mission that could provide a unique close-up view of the fine details of solar activity.

OSL builds directly on these important foundations and is eagerly awaited by solar researchers all over the world. OSL advances the concept of solar observation from space to a new level and offers, for the first time, coordinated, finely tuned, high-resolution space observations of the Sun at visible, ultraviolet, extreme ultraviolet, and x-ray wavelengths.

In addition, OSL has been designed as a major international solar facility for use by large numbers of scientists. Guest Observers and Guest Investigators will be selected. A theory program and OSL Graduate Student and Postdoctoral Programs will be set up.

Coordinated Observations of the Sun

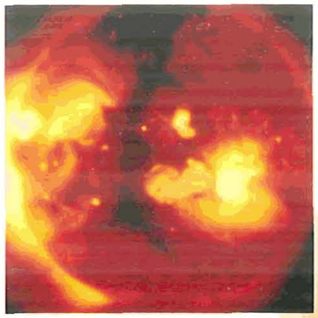
Strangely, the dense gases of the photosphere and chromosphere are relatively cool compared to the much less dense, but very hot, gases of the corona. Somehow, the low-energy, cooler gases at the solar surface are heated to become high-energy, hot gases in the corona. As a result, the Sun displays an enormous range of interrelated phenomena over an equally enormous temperature range. Observations in visible light show the interaction of turbulent motions and magnetic fields at the solar surface, and observations in ultraviolet and x-ray wavelengths show how the overlying hot chromosphere and corona respond to these interactions. But a complete picture of these processes requires simultaneous and coordinated observations at visible, ultraviolet, and x-ray wavelengths. Using such observations, scientists can correlate activity in the photosphere with that in the upper layers of the Sun's atmosphere, the chromosphere and the corona.

In the late 1990's, OSL will, for the first time, be able to obtain these unique measurements, with unmatched resolution and sensitivity simultaneously in a range of wavelengths and with precisely the required coordination.

OSL and its Instruments

The Orbiting Solar Laboratory will be a free-flying satellite, in a near-polar orbit. The spacecraft will fly in a Sun-synchronous orbit along the line separating the Earth's day side from its night side with its instruments pointing sunward. OSL will carry five major instruments that will observe the Sun in visible light, and at ultraviolet, extreme ultraviolet, and x-ray wavelengths. In addition, OSL will carry an instrument to measure solar irradiance.

The Coordinated Instrument Package (CIP) contains three visible-light instruments that will use the main OSL telescope, with its highly polished, one-meter diameter mirror. The size of this mirror, the largest solar telescope ever flown in space, will



A 1973 soft x-ray image of the corona, the hottest region of the Sun, (about 2,000,000 degrees kelvin [K])

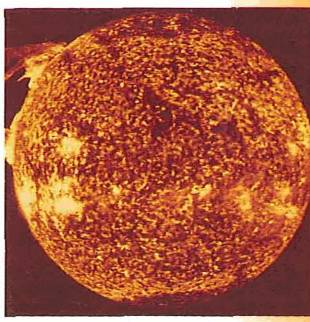
permit the CIP instruments to observe very small features, just a hundred kilometers across, to provide the most detailed data ever collected.

The first of the three powerful imaging and spectroscopic instruments in the CIP is the Photometric Filtergraph from the California Institute of Technology. This instrument, operating between the near infrared and the near ultraviolet wavelengths, will be particularly useful in studying the heating of the upper photosphere. The second CIP instrument, the Tunable Filtergraph from the Lockheed Palo Alto Research Laboratory, will map motions and magnetic fields in the photosphere to help study the interactions between velocities and magnetic fields—a key goal of OSL. The third instrument, the Kiepenheuer Institute Solar Spectrograph provided by the German Space Agency (DARA), will precisely measure magnetic fields, velocity, and turbulence in the photosphere and chromosphere.

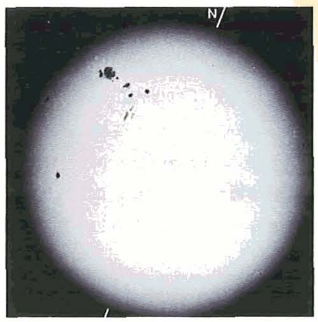
Each of the two additional major instruments uses its own optics, rather than the main OSL telescope. The High Resolution Telescope and Spectrograph, developed by the U.S. Naval Research Laboratory, will obtain images and spectra (lines showing the presence of various chemical elements) in ultraviolet wavelengths of the hotter chromosphere and the transition region into the corona. The X-ray Ultraviolet Imager, a joint effort of the Italian Space Agency and the U.S. Air Force Geophysics Laboratory, will probe the hottest region of the atmosphere—the corona—where temperatures reach millions of degrees kelvin.

All five major instruments will work together to measure the evolution of solar activity at the surface and beyond, and to help researchers attain an even greater level of understanding of the way in which the Sun works.

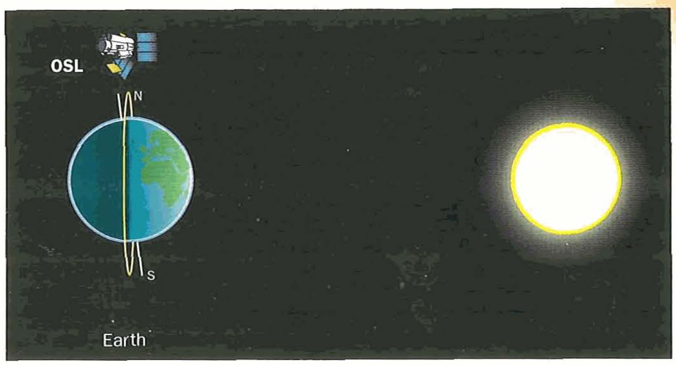
The Active Cavity Radiometer Irradiance Monitor (ACRIM), developed at NASA's Jet Propulsion Laboratory, is being flown as part of a long-term program to measure changes in the Sun's radiant energy (total solar irradiance or TSI). The instrument will further explore TSI variability discovered by previous ACRIM instruments to extend the long-term high-precision database of measurements.



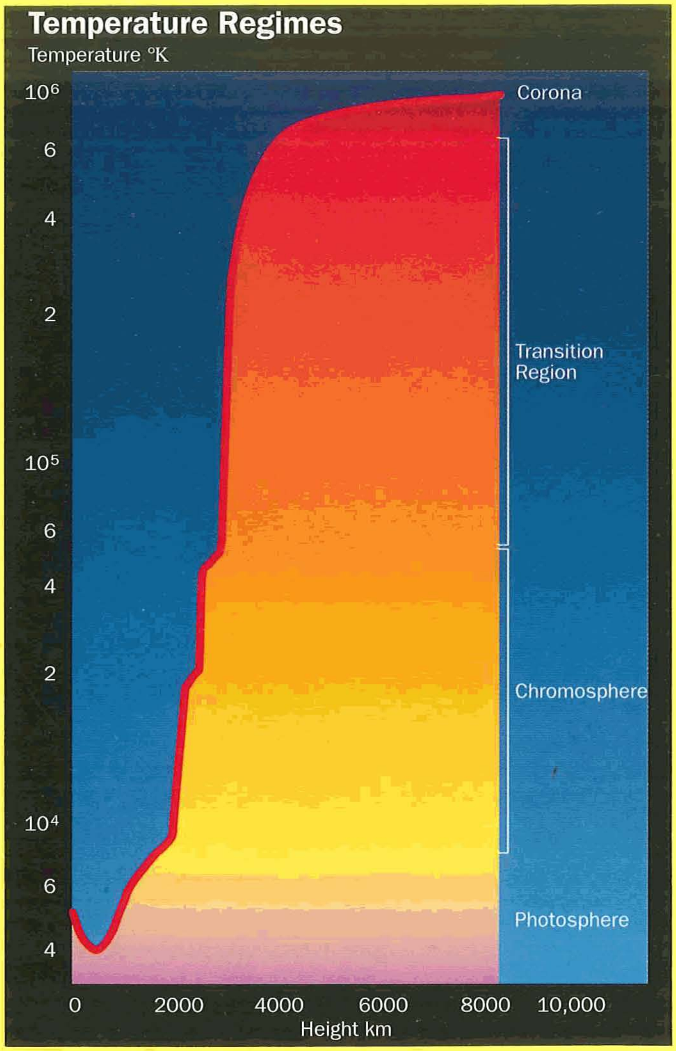
An extreme ultraviolet image of the Sun shows the chromosphere (up to 10,000 K).



A visible-light image of the Sun shows the photosphere (around 6,000 K).



OSL will operate primarily in a continually sunlit orbit for most of the year.



It is not yet understood why temperature rises dramatically with increased distance from the visibile surface (zero kilometers on the scale).

The Solar Cycle and Solar Magnetism

The Sunspot Cycle and Magnetic Activity

Viewed closely, the Sun is by no means constant. Solar activity is driven by changing magnetic fields in the photosphere with a crude rhythm of about 11 years. Numerous dark spots develop on the photosphere—some many times the size of the Earth—and magnetic activity on the solar surface increases considerably. Sunspots are created when concentrations of very strong magnetic fields appear in the photosphere and choke off most of the energy (and thus the visible light) flowing outward from the solar interior. The deficiency in the radiation from the dark spots is compensated for by the enhanced brightness of the active regions. As a result, the solar energy reaching the Earth is a few tenths of a percent greater at sunspot maximum than at its minimum.

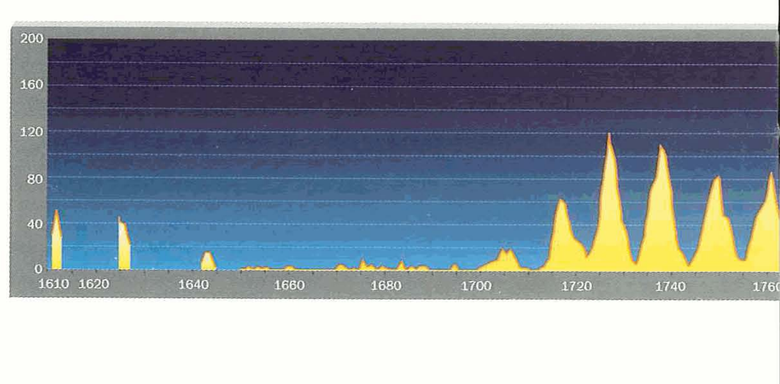
The Sun's radiation is also harder at sunspot maximum—that is, it contains a larger fraction of high-energy ultraviolet and x-ray emission. In addition, associated with sunspots are solar flares, enormous magnetically-driven explosions in and above the active regions, which produce vast quantities of high-energy electrons, protons, and atomic nucleii. These blasts create shock waves and ejections of solar gases into interplanetary space. Similar magnetic processes occur throughout the universe, but the Sun is the place where they can best be studied in detail. OSL's high-resolution observations of solar flares at visible, ultraviolet, and x-ray wavelengths will greatly increase our understanding of explosive magnetic events, both in the Sun and elsewhere in the universe.

Terrestrial Effects of Solar Magnetic Activity

As solar activity rises and falls, the solar wind fluctuates and produces small changes in the topology of the Earth's magnetic field. Solar flares and the charged particles they emit can create intense disturbances called geomagnetic storms.

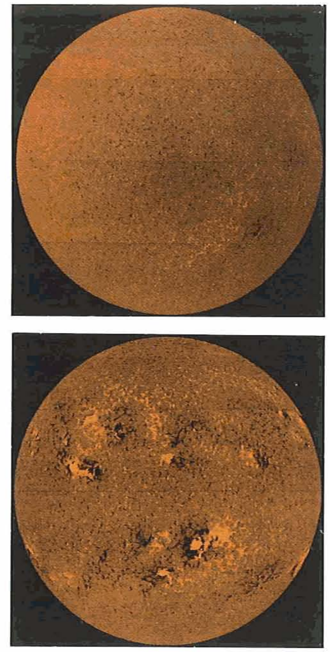
Erupting solar flare taken in H-alpha.

These storms cause large changes in the Earth's magnetic field, which in turn produce particle acceleration in the magnetosphere, aurorae, and the disruption of radio communication. Strong increases in ultraviolet and x-ray radiation heat the Earth's upper atmosphere, thus creating additional drag on satellites and shortening orbital lifetimes. The stream of high-energy particles created during large solar flares reaches levels dangerous to human beings in interplanetary space, and even causes concern for crews and passengers in high-altitude aircraft. On the ground, magnetic field changes can damage expensive equipment in long-distance power transmission systems, interfere with long-distance communications, confuse navigational equipment, and



A representation of solar activity since the year 1610, showing changes in sunspot numbers.

produce other effects that become more important as technology—and hence reliance on these facilities—advances. OSL will improve our ability to understand and predict these solar events and their important societal consequences on Earth.

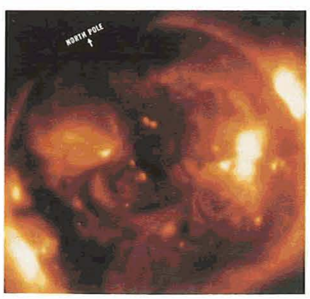


Ground-based images of magnetic fields show solar activity near solar minimum (top) and solar maximum (bottom).

Understanding the Solar Cycle

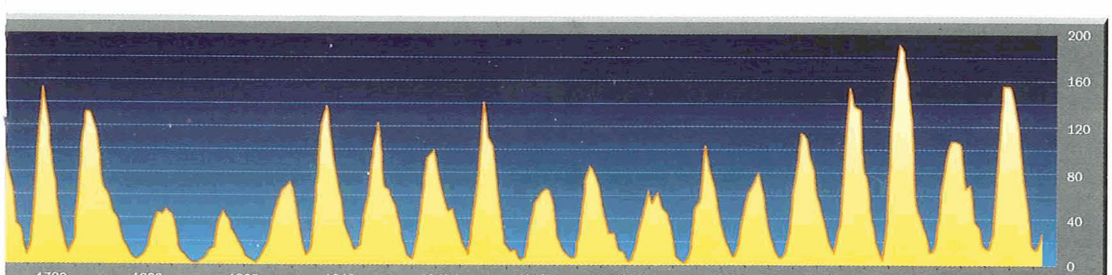
Despite centuries of observations, there is still no truly quantitative theory—no model that can be expressed in precise mathematical terms—for the cycle of magnetic activity. Two key processes in particular require new observations from space. First the birth of new active regions—the emergence of new magnetic fields, over a period of days, from the solar interior into the photosphere—must be studied. Second, the breakup of magnetic active regions by turbulent motions beneath the surface and the way in which the resulting magnetic debris is carried towards the solar poles needs to be investigated further. It is this movement towards the poles that appears to introduce new solar cycles. Long, uninterrupted observing periods are needed to track such sequences.

These processes can be studied in sufficient detail only with very high-resolution images that cannot be obtained from the ground. OSL's one-meter optical telescope, with essentially perfect image quality and operating above the turbulence of the Earth's atmosphere, should lead to epoch-making advances in our understanding of the solar activity cycle.



The high contrast in this x-ray image of the corona, taken from Skylab, shows the range of temparature and densities in the corona.

Previous observations from space have provided considerable data on x-ray and ultraviolet emissions from active regions and flares. Ground-based observations at visible wavelengths have provided information on the photospheric magnetic fields which are ultimately responsible for these emissions. With OSL it will be possible, for the first time, to obtain simultaneous high-resolution data on x-ray emission from the corona coordinated with high-resolution data on magnetic processes in visible light from the photosphere and with ultraviolet emissions from the chromosphere. The ability to observe all three together from space is a powerful new tool, and a key factor in the rationale for OSL.



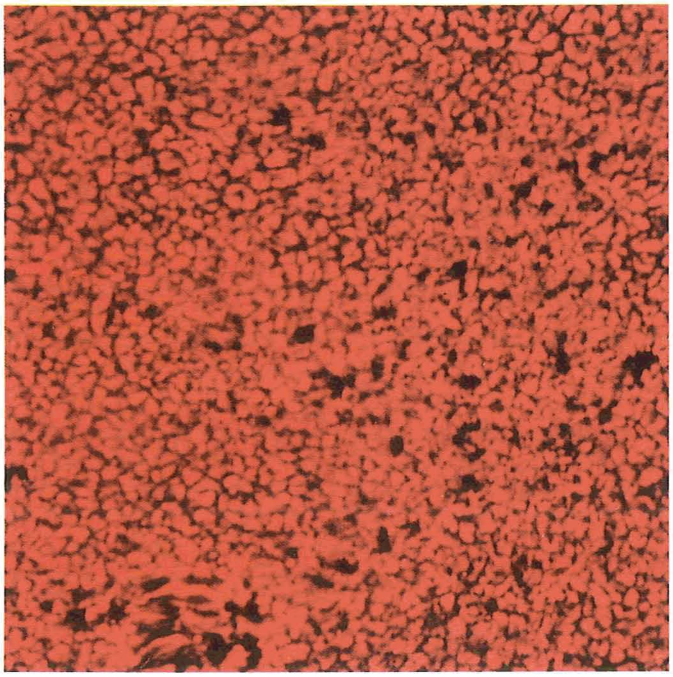
The Surface and Interior of the Sun

The surface, or photosphere, of the Sun, is actually the topmost layer of a seething ocean of hot and turbulent gases. Its temperature reaches some 6,000 degrees kelvin (K). Rising convective flows, which bring heat from the deep interior, bubble up to the surface, resulting in a pattern of constantly overturning cells called granules. This granulation pattern, which can just be seen with ground-based telescopes, characterizes the photosphere. The interplay between the convecting gases and magnetic fields is the root cause of all the phenomena of solar magnetic activity. Unfortunately, the convective flows and the magnetic field concentrations that accompany them occur on so small a scale that they cannot be studied by observers using ground-based telescopes—the blurring caused by the Earth's atmosphere is just too severe.

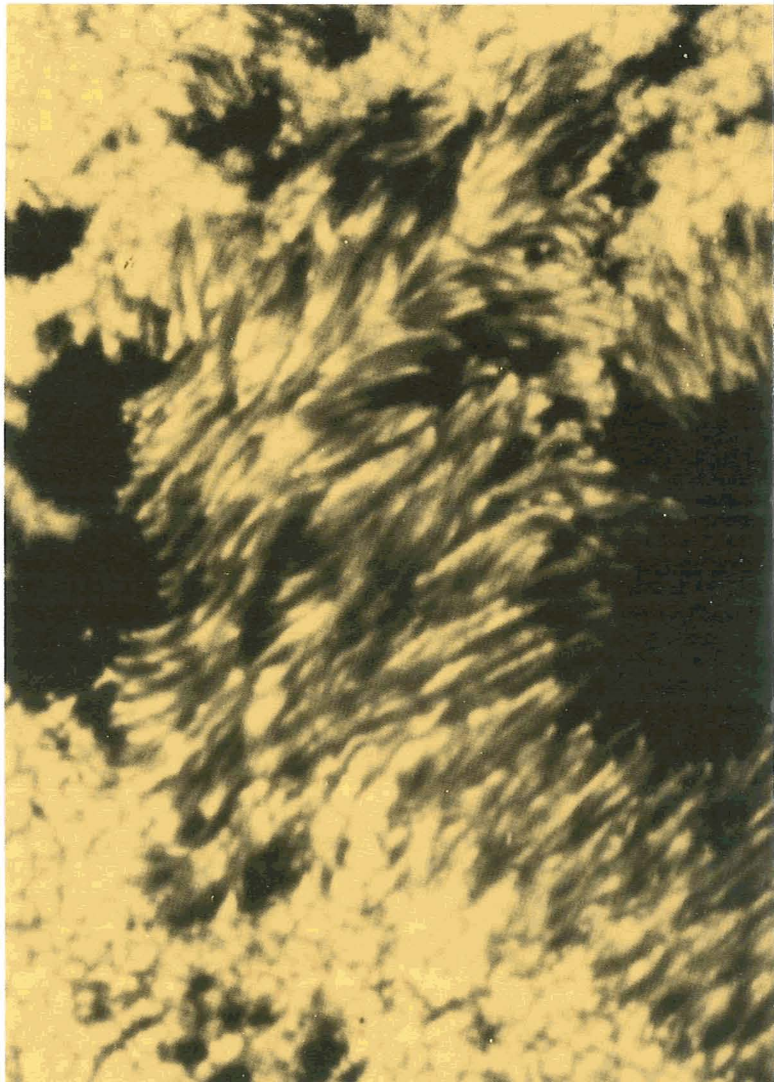
Sunspots—Gigantic Magnetic-Field Concentrations

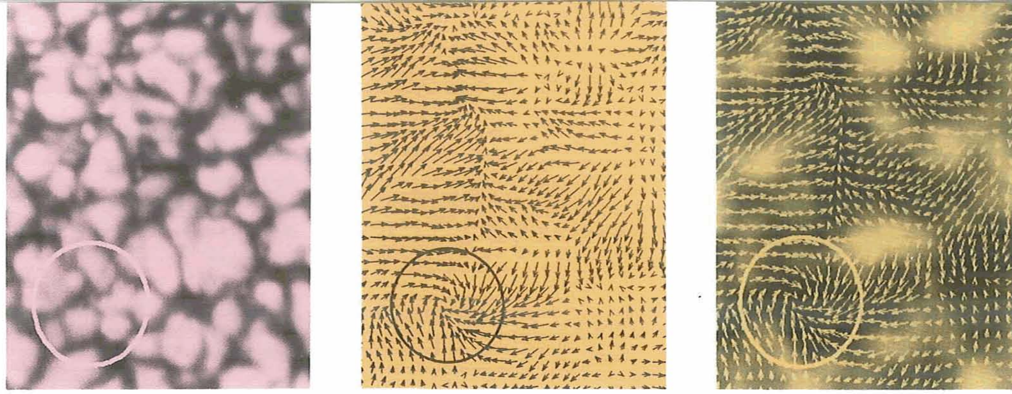
Theory suggests that far below the regions accessible to direct observation, the Sun's convective motions interact with weak magnetic fields, stretching and concentrating them and creating rope-like strands of strong magnetic field. These strong magnetic fields eventually rise to the surface to produce magnetic active regions. As the active regions age, surface convection gradually spreads and disperses them. Their fragments are the seeds from which a new 11-year episode of magnetic activity grows. This roughly cyclical process, part of the so-called solar dynamo, is extremely complex and as yet is not understood.

Sunspots display an intricate fine-scale structure and an ever-changing pattern of waves and bright flashes caused by the interplay among magnetic fields and convecting gases.



Granules on the high-resolution photospheric image show heat flows from the deep interior. This image was taken with a prototype of the Tunable Filtergraph to be flown in the Coordinated Instrument Package on OSL.



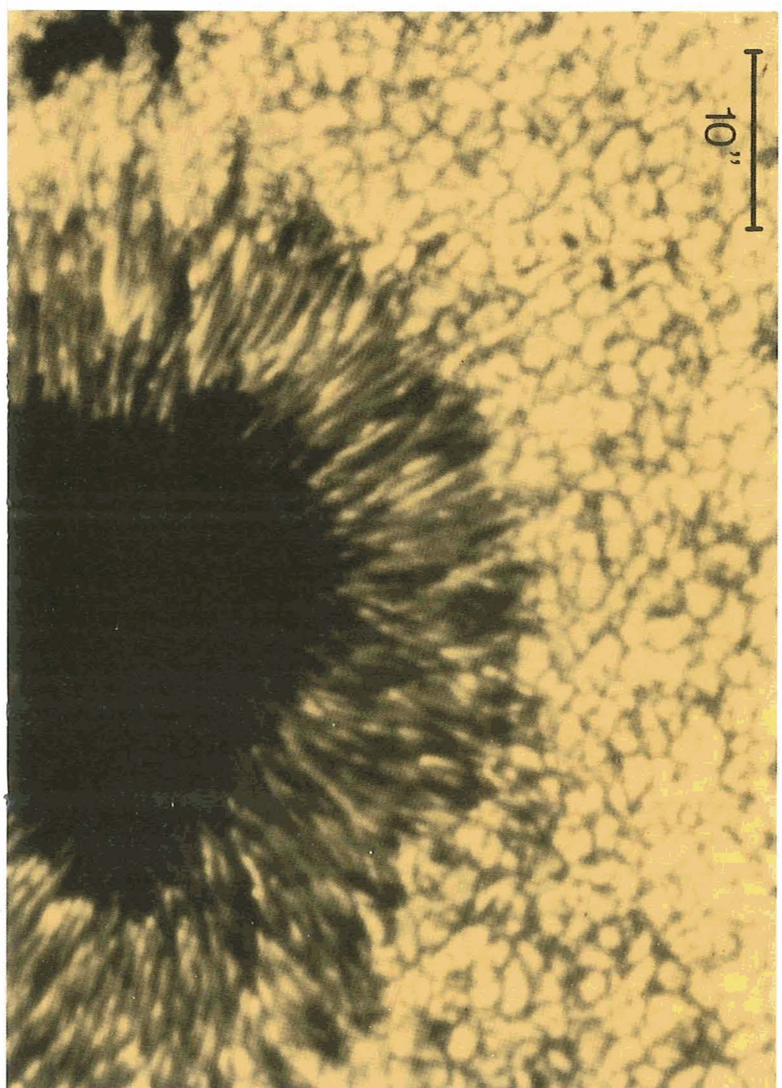


An example of high-resolution velocity maps, showing photospheric granules with upwelling and flow fields. Superimposed on magnetic field maps, these images can be used to model the interaction of material flow and magnetic fields.

OSL will make it possible to observe sunspots in close detail, and this in turn should make it possible to understand their subsurface structure and examine the way in which they form and decay. This is expected to shed light on the characteristics of the stretched magnetic fields deep below the surface, and the way in which these fields are concentrated to become sunspots.

Fine-scale Magnetic Structures in the Photosphere

The magnetic fields outside sunspots are compressed into tiny regions at most a few hundred kilometers across. OSL's solar telescope, viewing from space, will bring our picture of these small magnetic fields into sharp focus for the first time. With its extraordinary resolution and image stability, this telescope will finally reveal the small-scale action of magnetic fields under convection, and the details of the way in which convection is altered where the fields are strong. At the same time, with OSL's companion telescopes tuned to ultraviolet and x-ray wavelengths, scientists will see precisely the effect these interactions have on the overlying atmosphere—the seat of the hot corona, solar flares, and the solar wind.



Surface Magnetic Fields as a Clue to Interior Magnetism

While it is not possible to see directly into the Sun's interior to study the details of the solar dynamo, theoretical techniques can be used to make best-guess numerical descriptions, or models, of the process. The models can then help predict in detail the behavior of the photosphere. OSL will be able to observe with high resolution both within sunspots and outside, and these measurements will enable models to be tested and improved.

OSL will enable scientists to follow the development of magnetic regions after they reach the surface, and see whether they are torn apart by the convective turbulence there, are annihilated in a burst of energy when opposite magnetic polarities merge, or sink below the surface again. Likewise, OSL will allow detailed study of the way in which magnetism modifies the outflow of convective energy, choking off the heat outflow inside sunspots, but enhancing outflow from the tiny, bright magnetic elements outside them.

This sunspot is 65,000 km across. OSL will see fine details as small as 100 km.

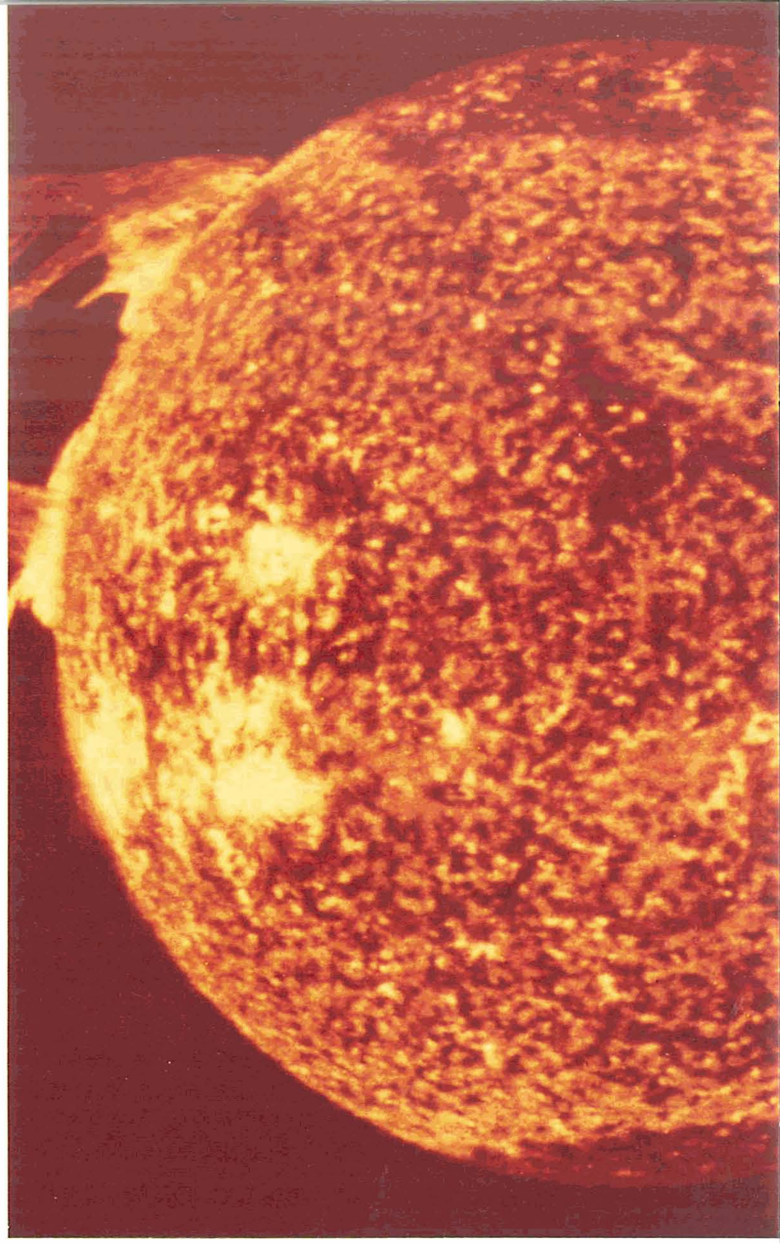
The Sun's Chromosphere and Corona

The Solar Chromosphere

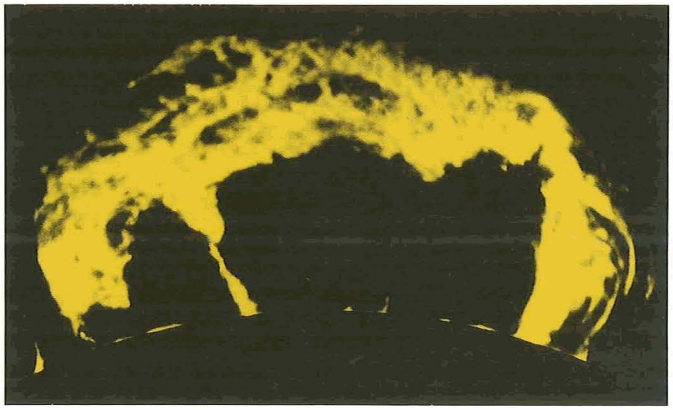
Above the photosphere is an extended hot and tenuous atmosphere. Its lower part is called the chromosphere—or sphere of color—after the brilliant red emission from its most abundant constituent, hydrogen. The chromosphere is the transition region between the photosphere and the corona. Radiation of excess energy from the chromosphere, less dense than the photosphere, helps keep its average temperature less than 10,000 degrees kelvin so that the chromosphere is a few thousand degrees hotter than the photosphere.

But why should temperature rise at all with increasing distance from the core of the Sun—the source of all its energy? Scientists suspect that this heating is caused by the interaction of turbulent convection and magnetic fields at the surface, but the details of the mechanism remain unclear. The chromosphere is permeated by fine tongues of hot gas, concentrated over local patches of magnetic field in the photosphere, which give an appearance when viewed from the side (that is, at the solar edge, or limb), that has been likened to that of a prairie fire. However, the motions are much more violent than in any prairie fire and can become supersonic, producing shock waves and localized regions of very high temperature.

The chromosphere produces strong ultraviolet radiation similar to that detected at visible wavelengths in the red-shifted spectra of many other stars. Observations from some of the more distant and interesting stars are, of course, very crude compared with solar observations, but nevertheless show that chromospheres are common to stars with convection and rotation. Instruments on OSL will capture ultraviolet light to reveal a wealth of detail on the Sun's chromosphere, thereby yielding a rich harvest of information that can be applied to the sparser data on other stars.



The chromosphere seen in extreme ultraviolet.



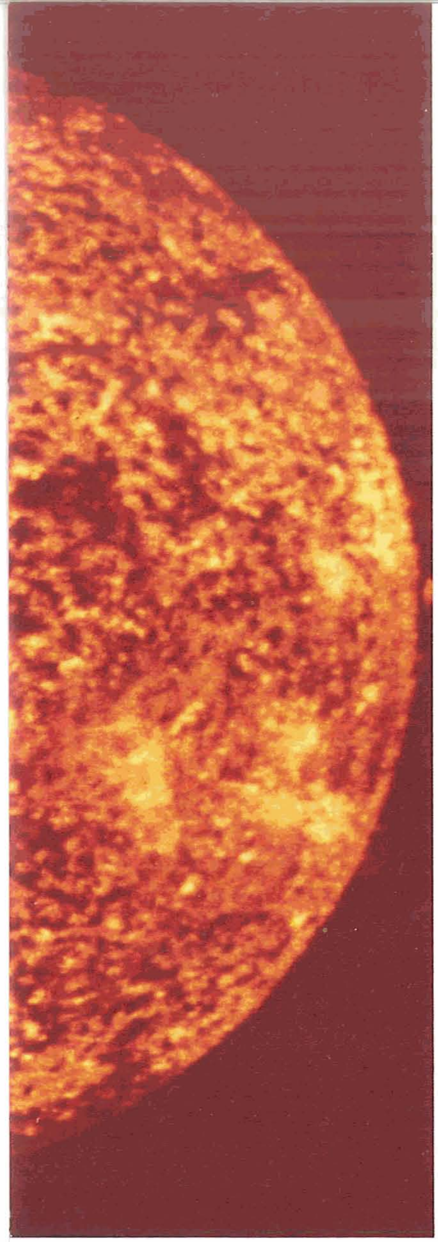
A large prominence erupting from the chromosphere at the limb of the Sun.

The Solar Corona

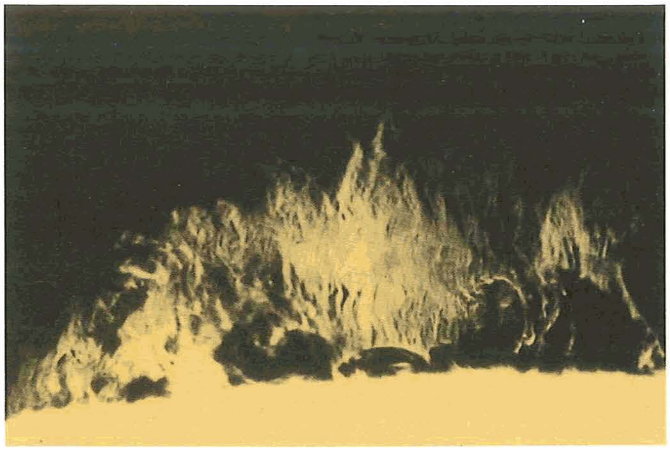
At higher altitudes the density of the solar atmosphere is much lower than in the chromosphere and the temperature is much higher, well above one million degrees kelvin. This hot, rarified outer atmosphere of the Sun is the corona, and may be seen in eclipse as a crown of light encircling the Sun and extending far out into space. In fact, the outer traces of the corona extend to the orbit of the Earth and beyond. A disturbance in the solar atmosphere, such as a solar flare, may spread its influence throughout the corona, and thus create an impact on the Earth.

The Problem of Heating of the Corona

Despite many years of study—the high temperature of the corona was discovered more than 50 years ago—it is still not known how the chromosphere and corona are heated. It was thought that the heating was caused by acoustic shock waves from the turbulent convection in the interior.

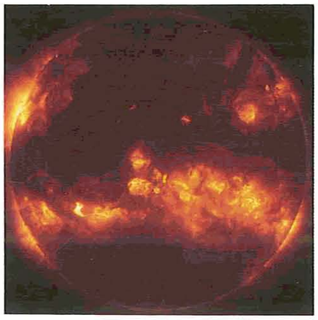


Spaceborne ultraviolet observations in the late 1970's, however, showed that this cannot account for all the heating of the upper chromosphere and the corona. Some scientists are now searching for different kinds of waves, including waves that involve the magnetic field. An alternative hypothesis is the suggestion that the heating results from continuous dissipation of magnetic energy as magnetic fields are twisted by convective motions in the interior. A third possibility is that the atmosphere, when studied closely over an extended period of time, will be found to undergo continuous tiny flares— that is, explosive releases of magnetic energy so small and frequent that they seem to be essentially continuous in time and space.



An H-alpha filtergram of a quiescent prominence, again at the limb, shows fine-scale structure.

OSL will, for the first time, allow physicists to view the solar chromosphere and corona with a resolution comparable to some of the fundamental physical scales of the processes which shape it. With its sharpness of observation at visible, ultraviolet, and x-ray wavelengths, OSL also can help investigators trace the causal connections between coronal heating and events in the photosphere.



Coronal image in soft x rays, taken with a 63.5Å x-ray telescope.

Prominences: Chromospheric Clouds in the Corona

The Sun's magnetic fields, arched from the photosphere, interact with the ionized gases, or plasma, of the chromosphere and corona. In many cases the geometry of the field causes the plasma to outline the magnetic field structure, forming extensive cloudlike concentrations known as prominences. These are strikingly visible above the limb, or edge, of the Sun, and are often seen extending more than a hundred thousand kilometers into the near-vacuum of the surrounding hot corona. Prominences are apparently thermally insulated from their much hotter surroundings by the magnetic fields, which drastically decrease thermal conduction.

OSL will allow particularly important observations of prominences to be made. With OSL's superb angular resolution, scientists will for the first time obtain clear images of the very fine threads of prominence structures. Using the mission's multi-wavelength capability, they will discover the details of their temperature and density structures. This will tell them a great deal about the way in which the magnetic field insulates ionized gases from their hotter surroundings.

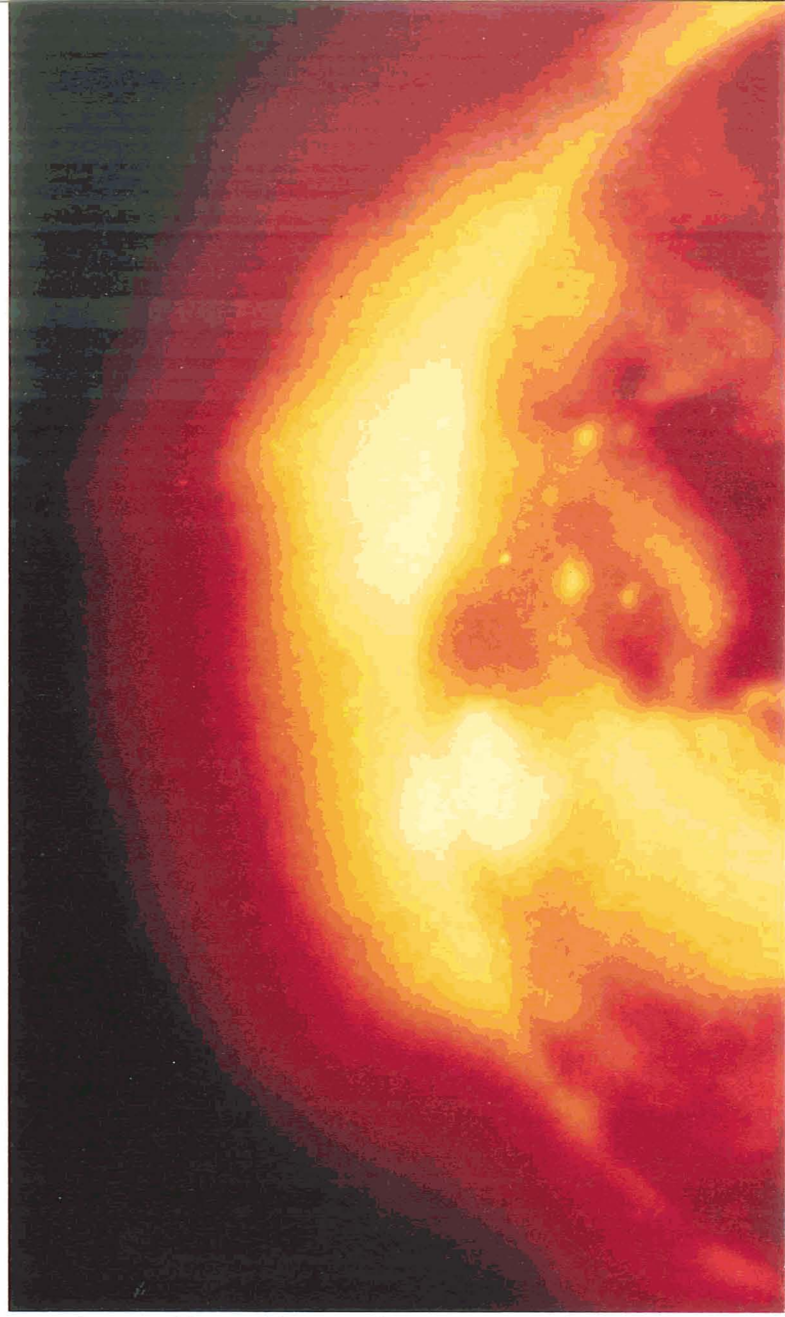
The Magnetic Structure of the Corona

Magnetic Loops

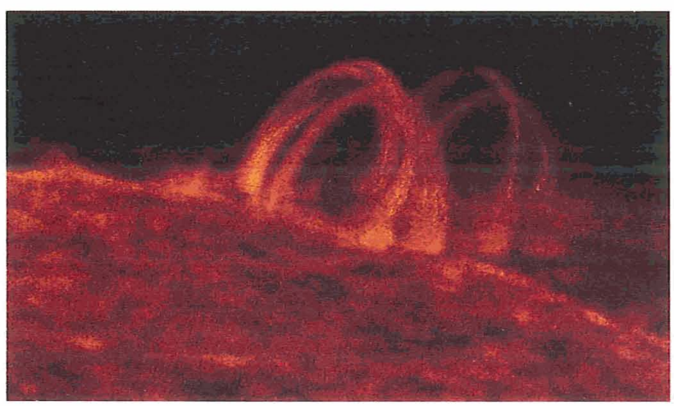
The fact that the extended solar corona is highly structured is evident from brief eclipse observations. But its real structure became clear only after the Skylab mission in 1973, when ultraviolet, extreme ultraviolet, and x-ray observations showed the appearance of the corona in front of the solar disk. At these wavelengths the photosphere is extremely faint, and so its light does not swamp the emission from the overlying corona as it does in the visible. It was found that parts of the corona that emit ultraviolet, extreme ultraviolet, and x rays consist almost entirely of those glowing magnetic loops, each of which remains arched between two magnetic feet of opposite polarity, anchored in the photosphere. For reasons still not quite understood, some of the magnetic loops are filled with relatively dense and confined hot gas, and so glow particularly brightly at ultraviolet and x-ray wavelengths. Neighboring magnetic loops are much less densely filled and emit less energy.

Coronal Holes and the Solar Wind

In some extended regions of the corona there is almost no extreme ultraviolet or x-ray emission, because the density of material there is very low. These regions, called coronal holes, have a magnetic geometry quite different from the loop structures that characterize active regions, or indeed the large-scale

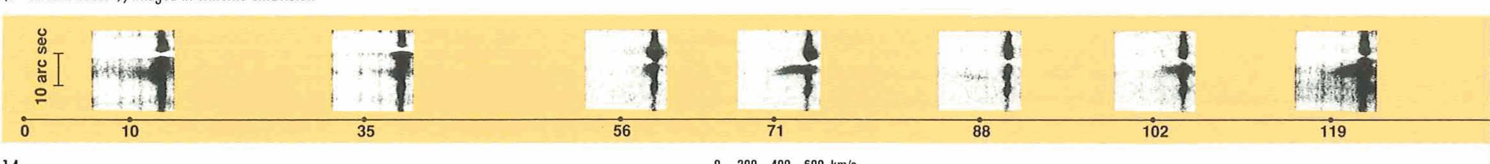


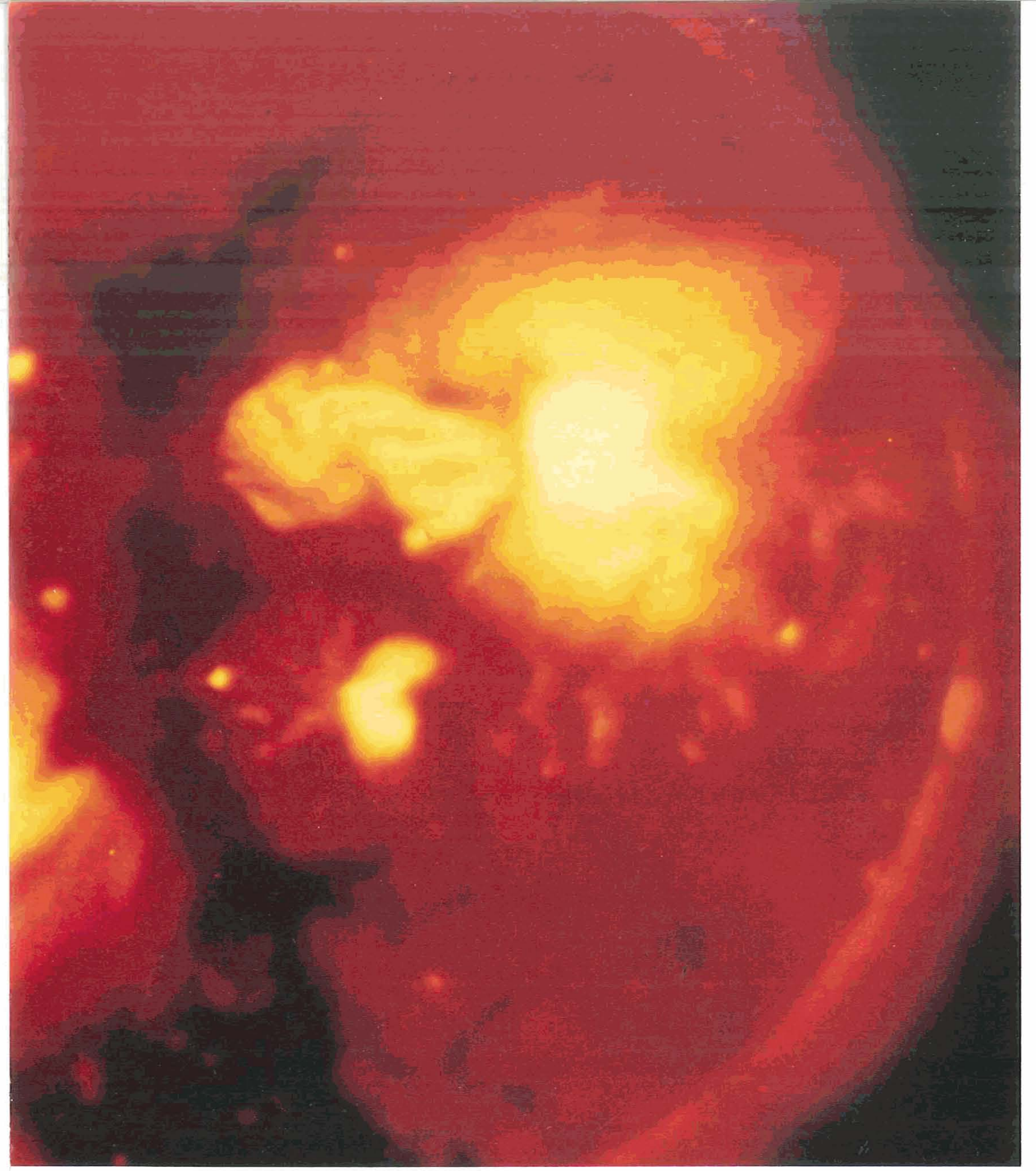
A 1973 soft x-ray image of the corona, the hottest region of the Sun, (about 2,000,000 degrees kelvin).



The arches of a high-definition coronal loop. Seen in ultraviolet and x-ray light, the Sun's disk is mostly dark, except for solar magnetic activity.

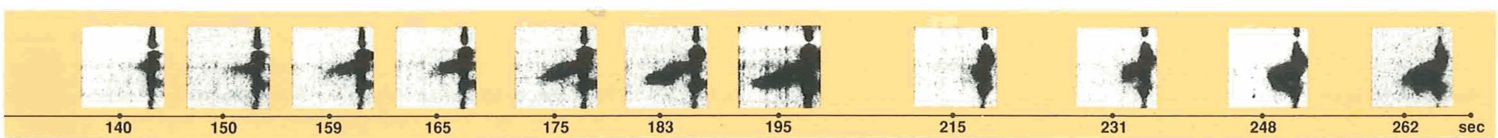
An evolving spectral image of a small energetic spurt of coronal material (a "coronal bullet"), imaged in extreme ultraviolet.





structure of the so-called quiet corona. In coronal holes the field arching out from a foot in the photosphere does not return to another foot of opposite polarity, but rather lies open out into interplanetary space. While a magnetic loop confines the hot gases, in a coronal hole the magnetic field opens outward, allowing the solar wind to flow out into space and past the Earth.

The processes that produce the solar wind are still not understood. It is critical to determine what powers it and how material is fed into the solar wind at the base of coronal holes, where the high-speed solar-wind streams originate. The ultraviolet spectrograph on OSL can attack this problem by making detailed measurements, for example, of sporadic small-scale spurts of material ("coronal bullets"). Such material was discovered by previous sounding rocket flights, but these flights are of short duration and their instrumentation is not powerful enough to make detailed studies. Similar but more frequent and prolonged observations by OSL—with its superlative instrument quality—may provide major clues to the process of solar-wind acceleration and the source of its material.



Solar Flares

Solar Flares—The Most Energetic Phenomena in the Solar System

A solar flare is an explosive outburst of energy from the Sun. Stored energy, equivalent to more than one hundred million 25-megaton nuclear bombs, can be released in only a few seconds when the right conditions are present. Such releases occur mostly in the form of x rays, ultraviolet radiation, energetic particles, shock waves, and mass ejection from the Sun.

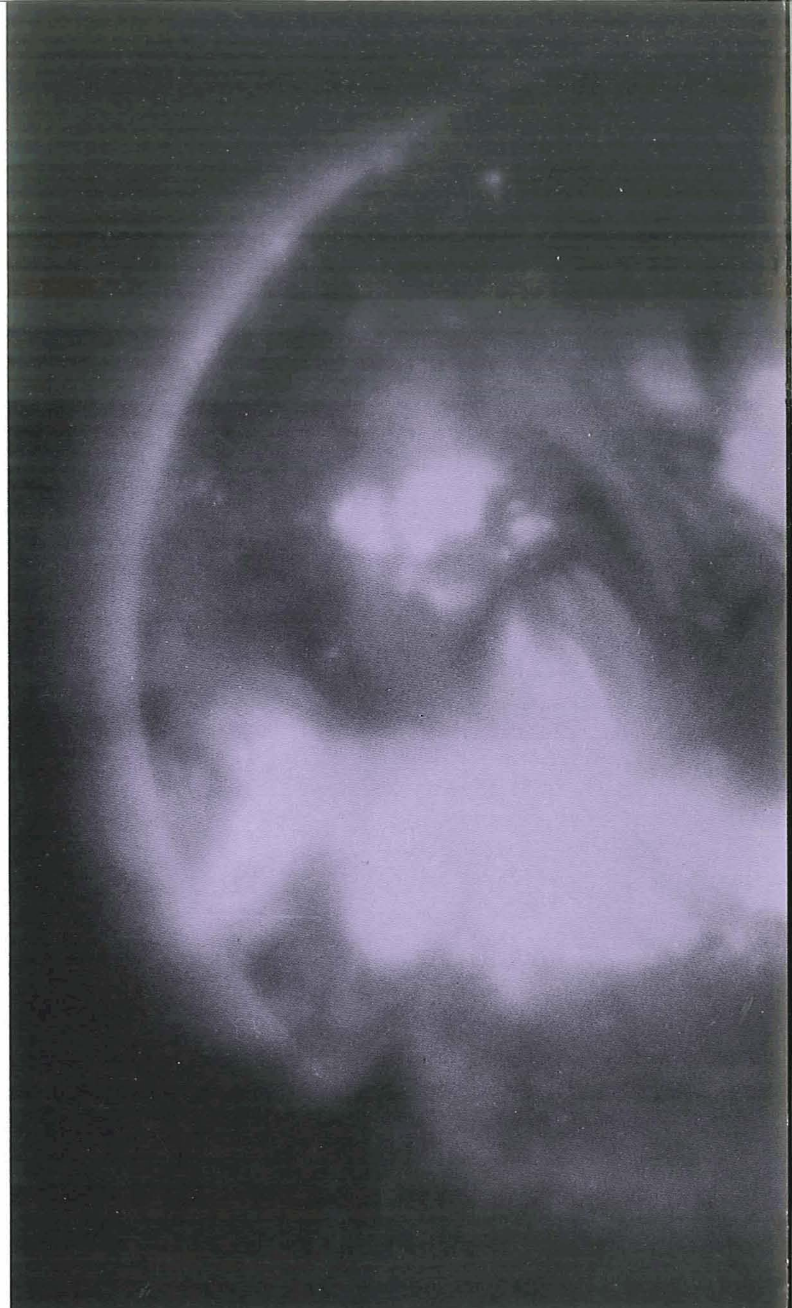
Solar flares provide splendid opportunities for physicists to study the interactions of magnetic fields and hot gases over a range of energies. A deeper understanding of these dramatic events will surely lead to advances in many areas of astrophysics and plasma physics.

Effects of Solar Flares on the Earth and its Environment

Flares produce a wide variety of effects that sometimes have a severe impact on Earth. In March 1989, for example, flare-related events included high-frequency communication outages and disruption of navigation, anomalous radar echoes, at high latitudes, and electric-power outages including a 9-gigawatt failure in Quebec that affected six million people for half a day and caused damage costing millions of dollars. Heating of the Earth's upper atmosphere caused by large flares around this time produced increased satellite drag, leading to uncontrolled tumbling of several satellites and more rapid orbital decay of others. Flare-associated particle events caused failures in microelectronic circuits, buildup of electric charge on spacecraft, and radiation doses to crews of high-altitude aircraft. In the future, particle events such as these could create serious radiation hazards to manned space missions at high inclination or outside the Earth's magnetosphere. Obviously, it is important to learn all we can about flares, if only because of the practical need to predict their likely occurrence and magnitude.

The Scientific Study of Solar Flares

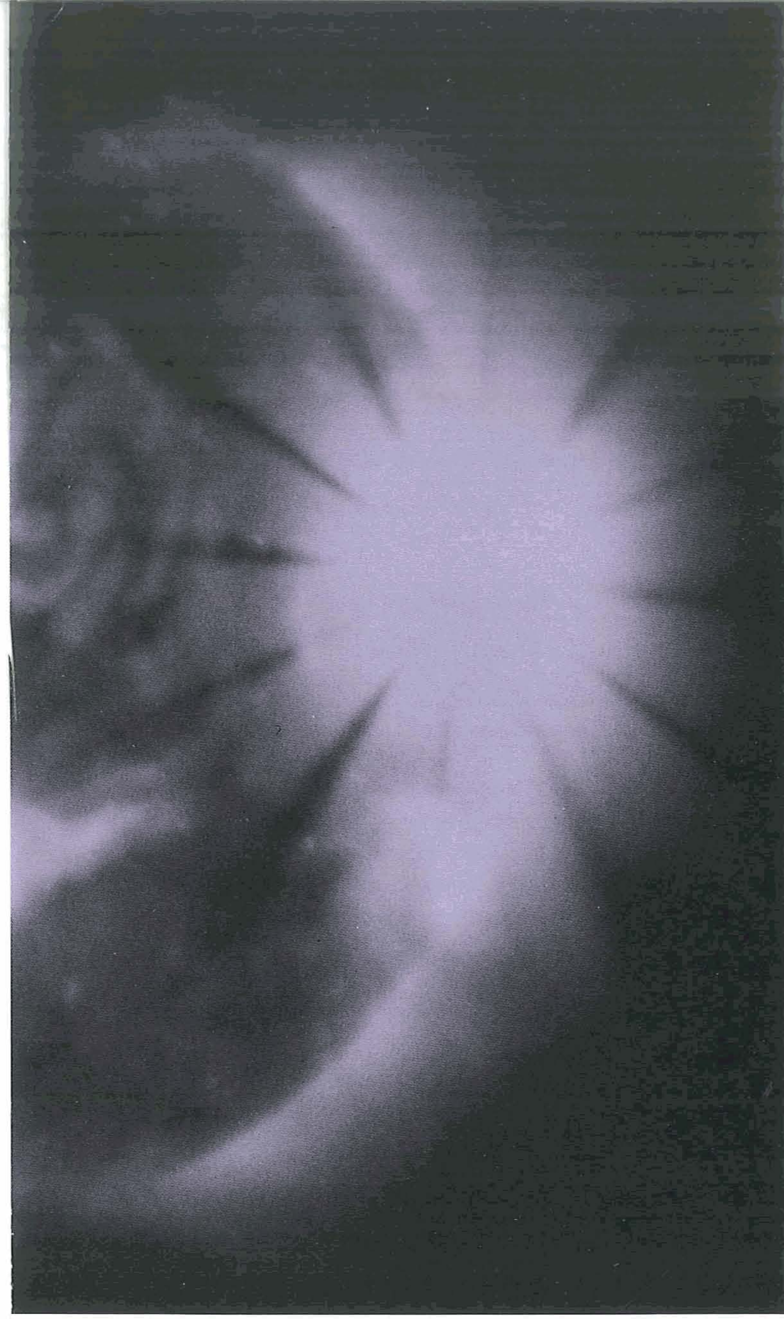
While solar flares are readily observable at various levels in the solar atmosphere, detailed examination requires both a multi-wavelength observational capability and extremely high spatial resolution. The flare energy release sites are known to be very small in size, and the important emissions from these include both ultraviolet and x-ray wavelengths. OSL, with its ability to acquire coordinated images at high spatial and temporal resolution in many wavelength regimes—in effect, to observe the interactions of plasmas and magnetic fields simultaneously at many levels in the solar atmosphere—represents the most powerful mission yet planned for the study of solar flares. OSL can observe features as small as 100 km across. As a result of this superior resolution, it may prove possible to get a detailed picture of the regions where the flares are triggered. In any case, the data will tell us where within the flare volume the triggering actually occurs and will help greatly in identifying the various mechanisms that may cause flares.

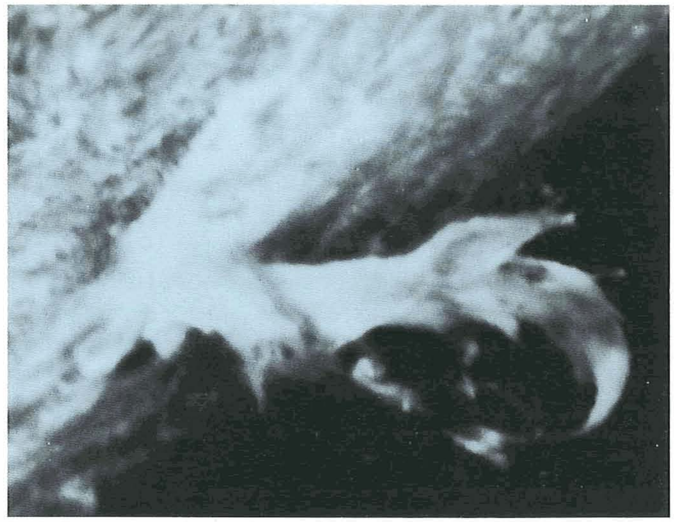


An overexposed image of a flare near the west limb (right) taken in soft x rays on October 1, 1973 from Skylab.

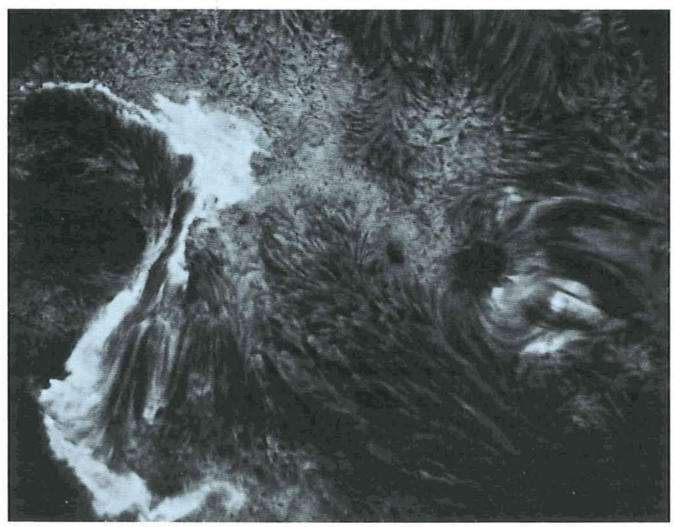
Predicting Solar Flares

OSL will help scientists predict flares in two important ways. First, OSL will map the changing magnetic geometry in active regions. This will allow estimates to be made of the rate at which stored magnetic energy is building up at different places in the active region and help in the calculation of three-dimensional models of temperature, density, and other important factors. Second, OSL will probably allow scientists to see the triggering process itself for the first time. These two advances, in combination, should reveal the characteristics that make certain active regions particularly ripe for major flares.



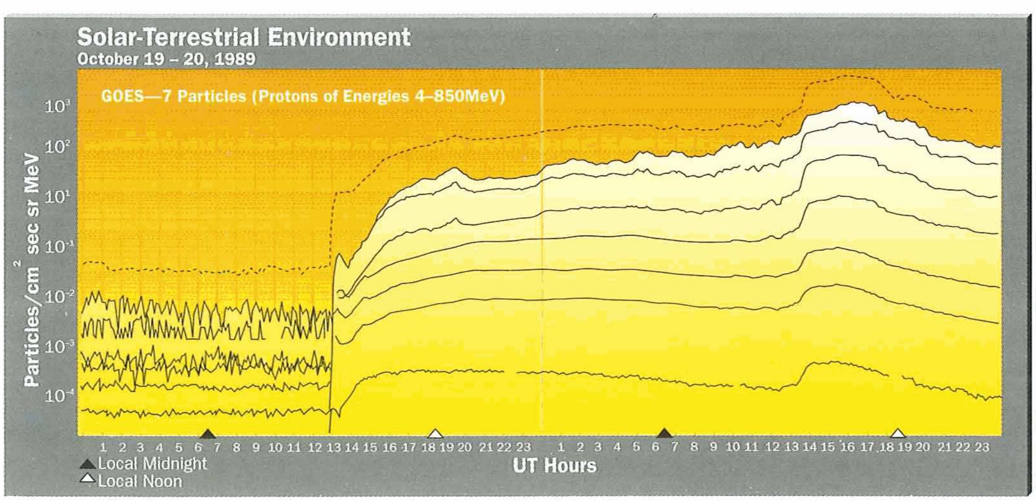


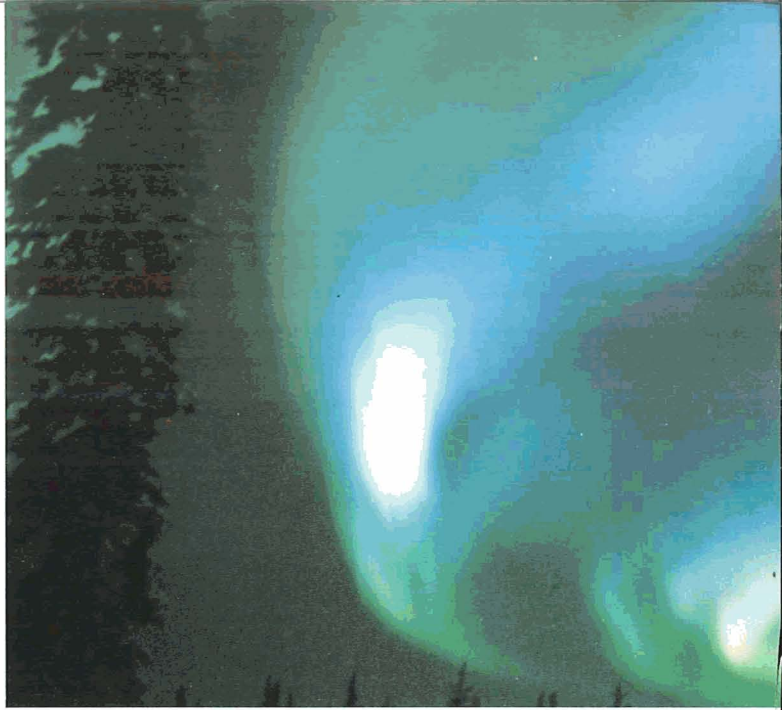
H-alpha filtergram of a complex, twisted energetic loop associated with a flare near the limb.



(Above) Another flare in H-alpha seen on the solar disk with a sunspot at its right and elongated structure thought to trace the orientation of the magnetic field in the chromosphere.

(Below) The flux of protons (radiation) in near-Earth space at the onset of an energetic solar particle event on on October 13, 1989.





The aurora—often called the Southern or Northern Lights.

The Sun and the Earth's Magnetosphere and Atmosphere

The Magnetosphere

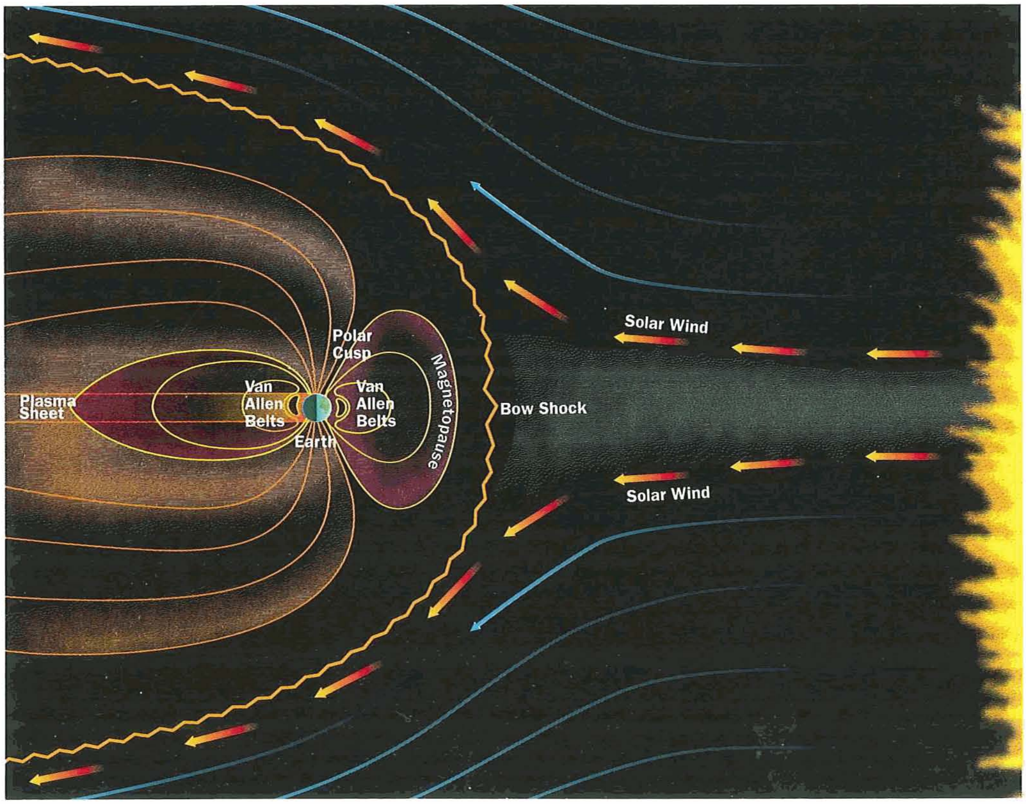
The Sun and the Earth are both magnetized bodies. The magnetic field of the Earth interacts with the solar magnetic field and the ionized solar wind, and causes a cavity to form in the solar wind flow around the Earth. This cavity is called the magnetosphere. Neither the physical characteristics of the magnetosphere nor the processes occurring in it is well understood.

Solar Influences on the Earth's Atmosphere

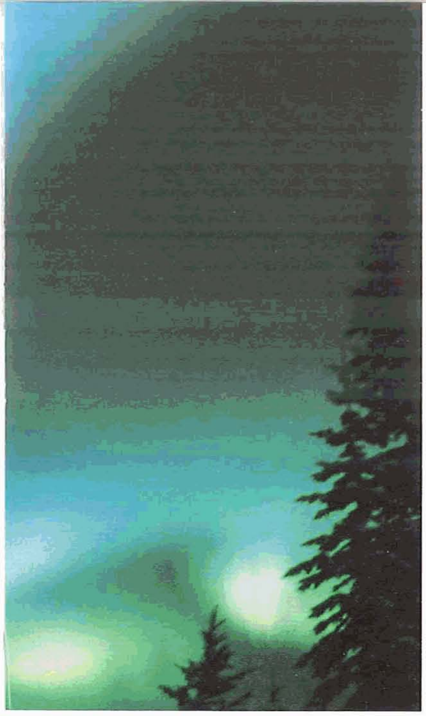
The aurora is but one dramatic manifestation of the effect of the solar wind on the Earth's magnetosphere and lower atmosphere. The heating of the Earth's upper atmosphere, or thermosphere, is governed by both particles and radiation flowing from the Sun. Electrically charged particles, shaken out of the tail of the magnetosphere by flares or other disturbances in the solar wind, travel back up the field lines of the magnetosphere and so excite the aurora. Changing ultraviolet radiation as a result of solar events also causes heating and outward expansion of the upper atmosphere, roughly in phase with the 11-year magnetic activity cycle.

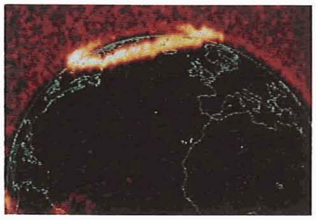
The Sun may also have significant influences on the lower atmosphere, or troposphere, the seat of the Earth's long-term climate and daily weather variations. If a true influence of the Sun on the troposphere can be confirmed, it will have far-reaching importance. There is some indirect evidence that the Sun does affect terrestrial weather and climate. Perhaps the best example is the "Maunder Minimum," a period between 1645 and 1715 when there was abnormally low solar activity and at the same time a prolonged period of unusually cold weather. Recent satellite measurements by the ACRIM instrument on the Solar Maximum Mission (SMM) show that the Sun is a few tenths of a percent fainter at times of low activity. This suggests a possible physical mechanism, but a solid cause-and-effect relation between Sun and climate has yet to be proved. The ACRIM instrument on OSL will continue our precise measurements of the total energy output of the Sun and provide correlated data with other OSL instruments.

OSL will be able to make important observational contributions to magnetospheric physics by providing better data on the phenomena of solar activity that start the chain of solar-terrestrial relations, and ultimately produce effects important to life on Earth.

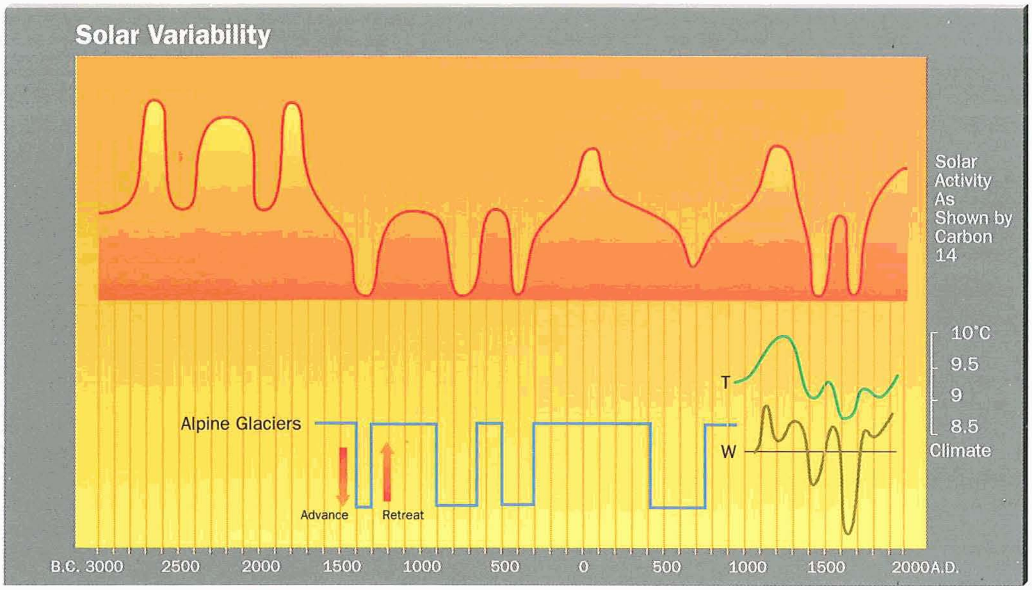


The solar wind interacts with the Earth's magnetosphere.





The auroral oval around the north pole seen from the Dynamics Explorer satellite.



A connection is often suggested between solar variability and climate, as shown by changes in carbon 14 deposits in tree rings (changes in strength of the solar wind), variations in mean annual (T) and extreme winter (W) temperature, and glacier growth.

(after Eddy)

Europe experienced a "Little Ice Age" in the seventeenth century, recorded by Brueghel as an unusual freezing of Dutch canals.

The Sun and Astrophysics

A Close-up View of a Star

The Sun is the star closest to Earth. Because of its proximity, the Sun provides astrophysicists a detailed view of the workings of stars in general. Studies of the Sun have already helped show what all stars are made of, what the pressure and temperature are in their deep interiors, what makes them luminous, and how their brightness and life history depend on their size. These relationships have subsequently been found to hold not only for nearby stars, but for stars throughout the Milky Way, and in distant galaxies throughout the universe.

The Sun and Cosmic Magnetic Fields

Compared with the Sun, all but the very largest nearby stars are only points of light in the best ground- or space-based telescopes. However, many other stars have spots and spot cycles, and are surrounded by high-temperature coronas producing x-ray emission very much like that of the Sun. In fact, on other stars these phenomena often exist on a much grander scale. For example, flares on some other stars might be a thousand times larger than those on the Sun. It is known roughly what is happening in these extraordinary outbursts only because relatively tame solar flares can be studied in great detail.

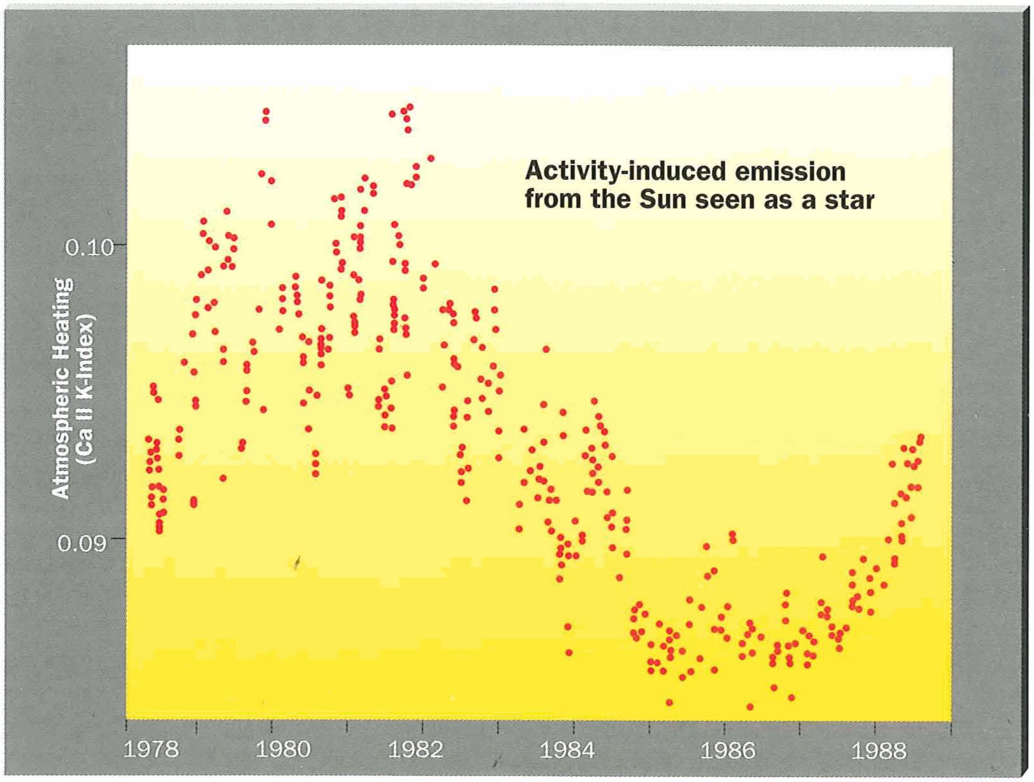
Within the Sun, a huge magnetic dynamo creates the 11-year cycle of solar magnetism, sunspots, and flares. Similar engines probably exist in other stars, in the Earth and some other planets, and in other more exotic high-energy objects in the universe. These objects include the nucleii of active galaxies and accretion disks around compact stars, such as white dwarfs, neutron stars, and black holes. But the Sun provides the most revealing place to view cosmic magnetic fields and their interaction with the ionized gases, or plasmas, that make up most of the matter of the universe.

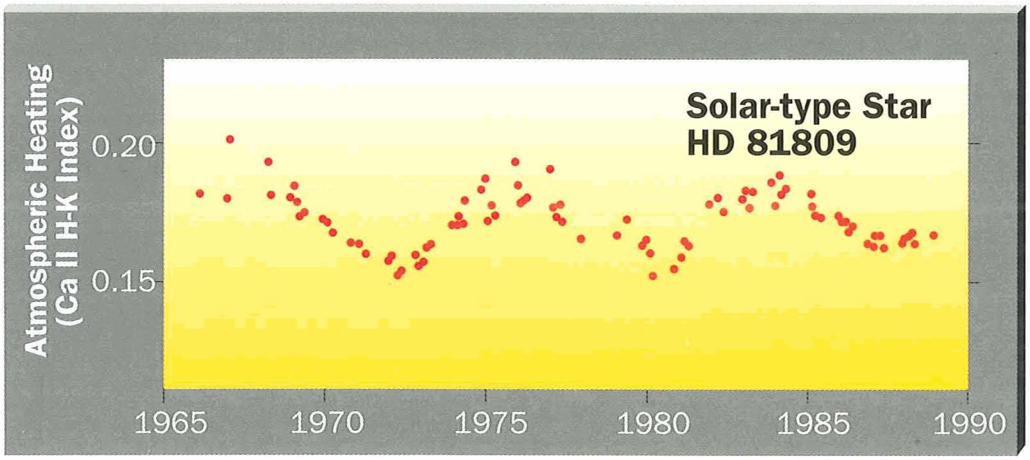
Other planets are known to possess magnetospheres, as do pulsars, which primarily emit radio waves. New observations of the ways in which magnetic fields and ionized plasmas interact will find application in the wider context of astrophysical magnetospheres and will lead to the development of more detailed theories.

A Rosetta Stone for Astronomy

For these reasons, the Sun is sometimes called "the Rosetta Stone of Astronomy." Each solar layer studied by OSL is like a text in one particular language, offering a version of what the others are saying. These meanings can then be applied to the varied, but fragmentary, messages read in other stars and galaxies. The instruments on OSL, because of their unprecedented angular resolution and because of the closeness of their target, will reveal the Sun in microscopic detail. And, because of OSL's multi-wavelength coverage, from visible light to x rays, it will be possible to probe the behavior of magnetized astrophysical plasma at temperatures up to tens of millions of degrees kelvin, a level of detail far beyond the capabilities of any other astronomical instrument foreseen today. In this way, OSL will contribute very significantly to humankind's understanding of basic astrophysical processes.

Activity cycles over the years on stars that resemble the Sun.





(Left) The solar corona, where temperatures reach some two million degrees K, imaged in x-ray emissions.

The Orbiting Solar Laboratory: The Mission

The Orbiting Solar Laboratory is being developed at NASA's Goddard Space Flight Center (GSFC). GSFC is the focus of mission design and implementation and will be the center of operational control and science operations after launch. All science data will be transferred to the GSFC National Space Science Data Center (NSSDC) at the end of the mission.

OSL will be launched some 330 miles (500 kilometers) into space on a Delta II expendable launch vehicle into a Sun-synchronous circular orbit around the Earth's poles. The spacecraft will weigh 7400 lbs (3364 kg) and be 15 ft (4.5 m) long and 9.2 ft (2.75 m) across. Two 200 square-foot (18 sq. m) solar panels, deployed after launch, will provide 1800 watts of power during sunlit operations. Two standard NASA nickel cadmium 20 amp-hour batteries provide power at other periods. A pair of high-gain communications antennae will also be deployed after launch.

The spacecraft's orbit will allow it to remain on the dayside of the Earth, almost constantly in sight of the Sun, thus enabling it to observe the Sun for many hours daily except during those seasons when the tilting of the Earth's axis brings lasting night to one or the other of the poles.

The mission will use NASA's Tracking and Data Relay Satellite System (TDRSS) both to communicate science data and to receive and transmit information related to the operational control of the spacecraft. TDRSS will allow the spacecraft to remain in direct ground contact for several orbits at a time, and will enable scientists to follow many events on the Sun from start to finish.

The mission is planned to last at least three years, beginning in the late 1990's, with the goal of lasting eight years. If the expected goal is achieved, OSL will be able to observe a substantial portion of the Sun's ascent toward a new solar maximum, predicted to occur in the year 2001, and to provide observations through the maximum and into the subsequent minimum.

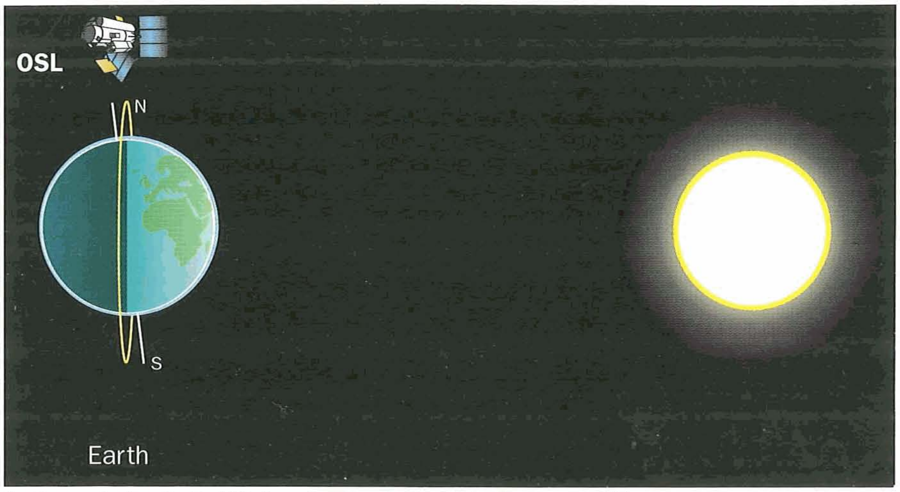
Instruments on OSL

A key feature of the mission is that simultaneous and coordinated data will be taken by instruments studying different parts of the Sun's surface and upper atmosphere. In this way, scientists can trace the relationships between the interaction of magnetic fields and gas motions in the photosphere, and the response of the overlying atmosphere in terms of heating, motions, shock waves, flares, and the solar wind.

OSL Will Carry Six Separate Scientific Instruments:

- the Coordinated Instrument Package (or CIP), comprising three instruments fed from the visible light collected by the main telescope
- the High Resolution Telescope and Spectrograph (HRTS) to observe in the ultraviolet
- the X-ray Ultraviolet Imager (XUVI) to observe in the extreme ultraviolet and in x rays
- the Active Cavity Radiometer Irradiance Monitor (ACRIM) to measure total solar irradiance.

On-orbit field-of-view coalignment and image stabilization will be possible for the CIP, HRTS, and XUVI instruments. While these instruments will focus on small surface areas of the Sun, OSL will also carry a finder telescope, with a larger field of view, to provide an image of the full solar disk. This will allow scientists to identify rapidly evolving solar targets, such as emerging magnetic regions, whose locations cannot be predicted.

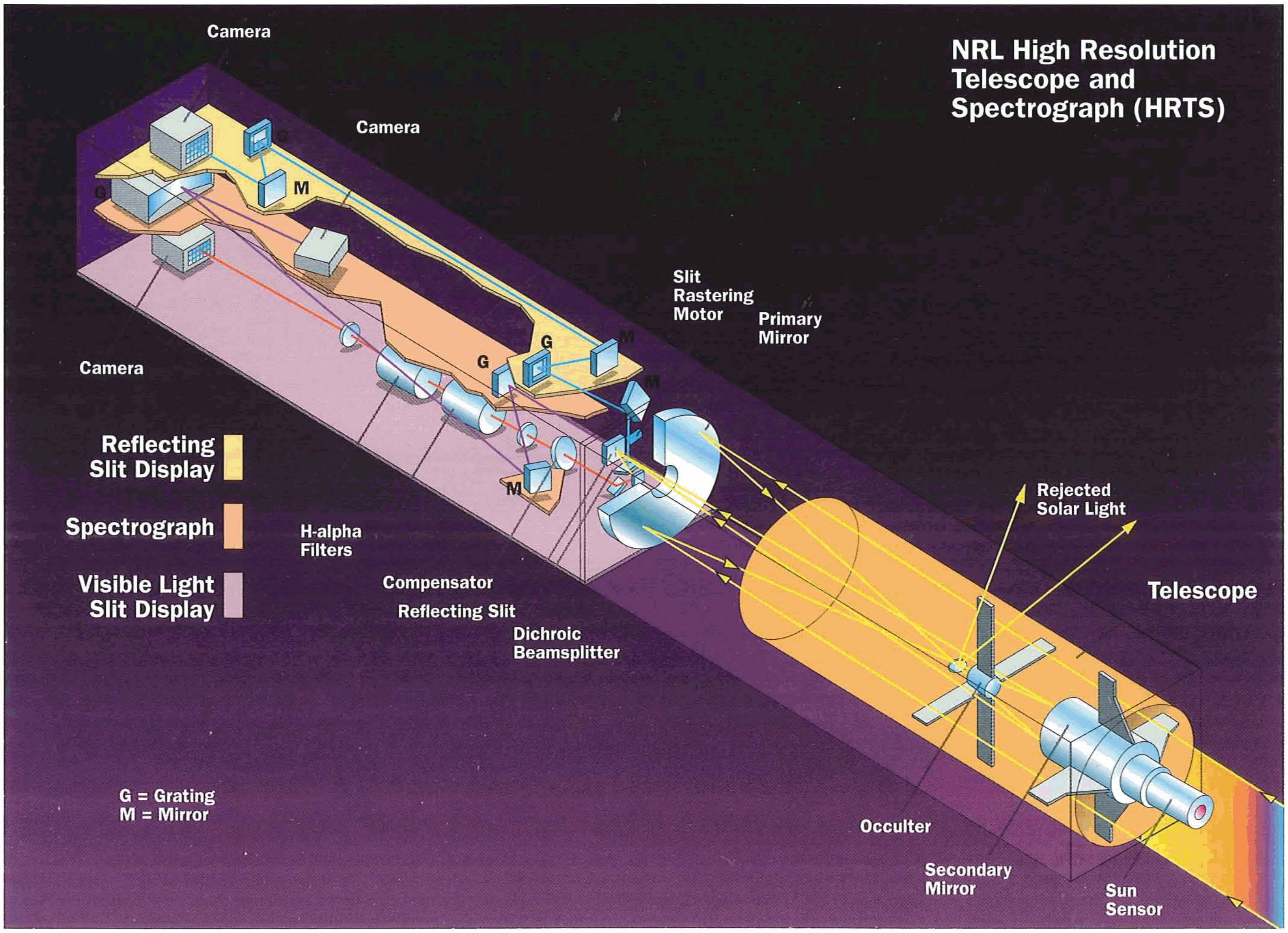


The almost-continually-sunlit orbit of OSL allows science operations to take place throughout most of the year.

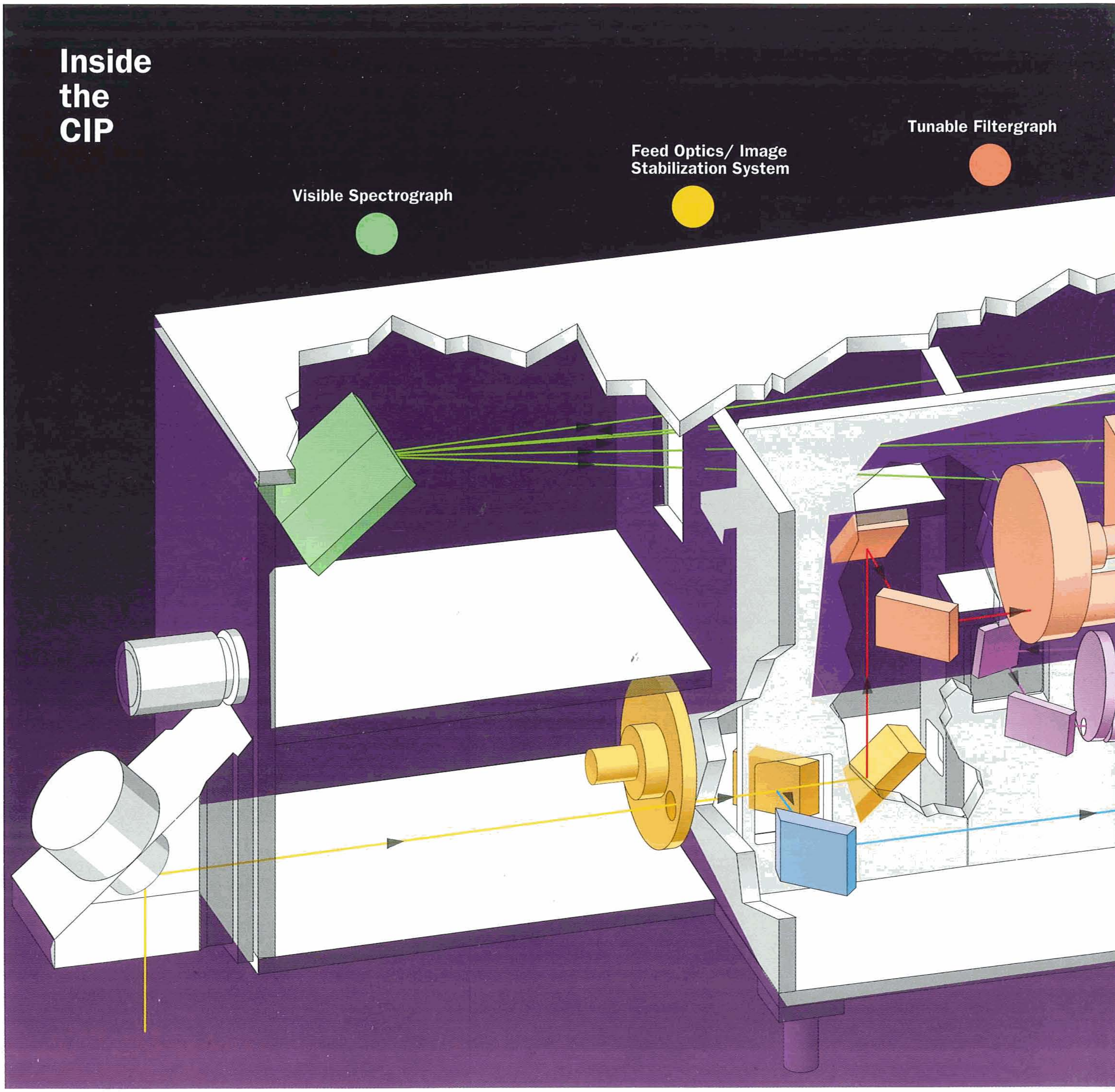
The Optical Telescope and Coordinated Instrument Package

The main telescope on the OSL— the largest and most powerful solar telescope ever flown—will be an optical telescope with a mirror one meter in diameter. This instrument will be able to produce images and spectra at the diffraction limit of the telescope with a resolution of about 100 km (0.13 arc second) on the solar photosphere. No telescope has yet observed such small areas on the surface of the Sun. This main telescope will feed a Coordinated Instrument Package (CIP), which will share its focal plane among the CIP instruments, making it possible to coordinate the exact time and location on the Sun of their observations.

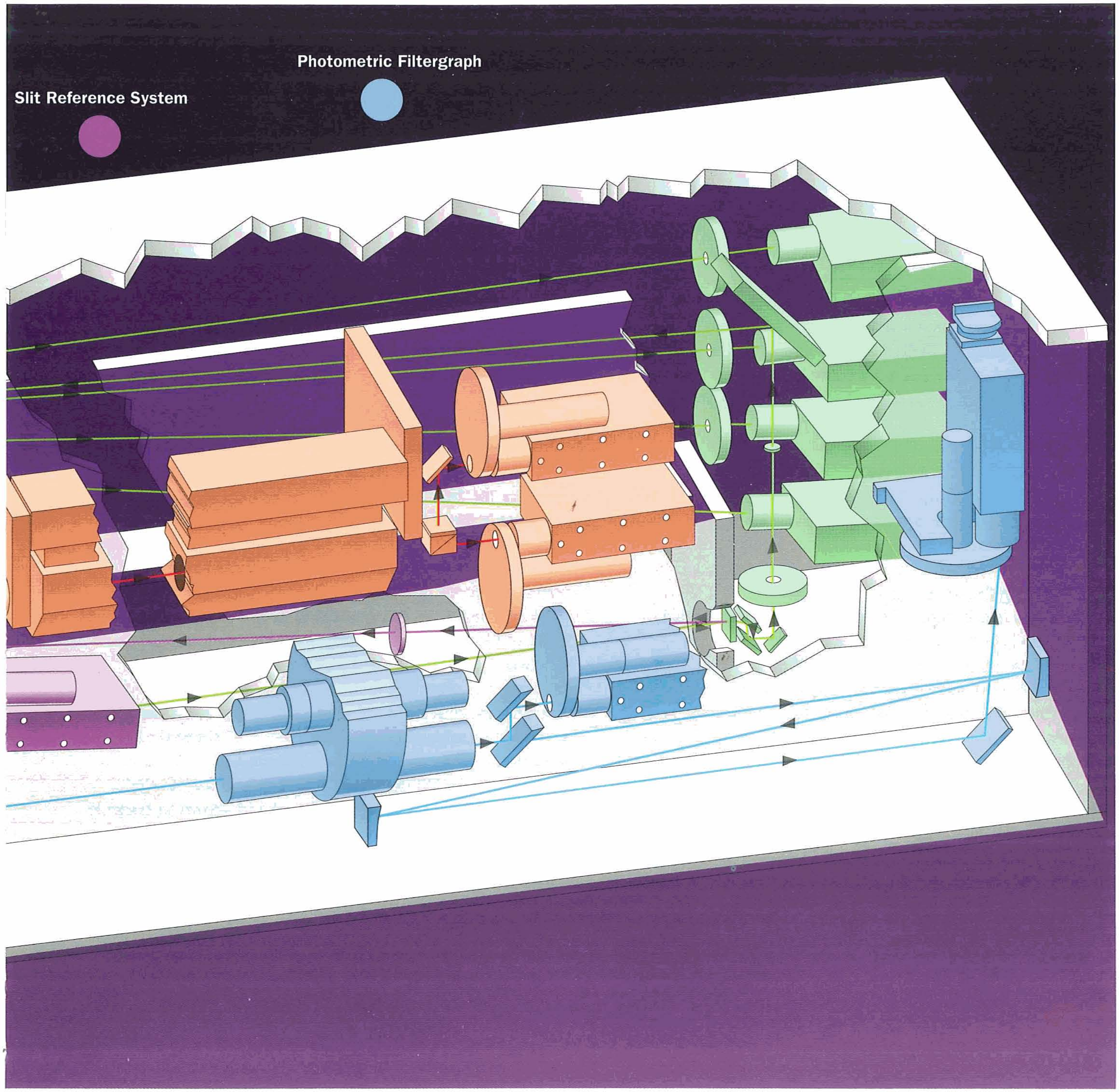
There are three instruments in the CIP. The Photometric Filtergraph, from the California Institute of Technology, is designed to image the Sun in broad wavelength bands across the visible spectrum. It will record data on two charge-coupled device detectors. Light will fall on these detectors through a series of interchangeable filters, selecting wavelengths from the near-ultraviolet (near-UV) at 2300 angstrom units (Å) to a red wavelength of 6687 Å in the visible. At the near-UV wavelengths, the Photometric Filtergraph can achieve spatial resolution twice that possible in the visible. This will be particularly useful in studying the heating of the upper photosphere where near-UV radiation originates.



The High Resolution Telescope and Spectrograph (HRTS) from the Naval Research Laboratory.



The Coordinated Instrument Package (CIP).


Photometric Filtergraph
Slit Reference System

A second CIP instrument, the Tunable Filtergraph/ Magnetograph, from the Lockheed Palo Alto Research Laboratory, obtains narrowband images over a wavelength range of 4600 to 6563 Å, with a spectral bandpass isolating only part of a spectral line. Various observing modes allow it to record the pattern of line-of-sight motions in the photosphere (using the Doppler effect) and the magnetic field (using the Zeeman effect), both with unprecedented spatial resolution and image stability. This will permit study of the physical interaction between velocities and magnetic fields—a key goal of OSL.

The third CIP instrument, the Kiepenheuer Institute Solar Spectrograph, a very high-resolution imaging spectrograph provided by the German Space Agency (DARA), will record the spectral profile of a number of important solar spectral lines over a wavelength range of 2800 to 8540 Å. It will provide information on physical parameters like density, velocity, and turbulence in the solar photosphere and the chromosphere—again with spatial resolution as good as 100 km.

The High Resolution Telescope and Spectrograph

The High Resolution Telescope and Spectrograph (HRTS) instrument will comprise a telescope with an aperture of 30 cm and a spatial resolution of 350 km (0.5 arc second), and three focal-plane instruments. One is a tandem Wadsworth spectrograph covering the wavelength region from 1200 to 1700 Å, which allows simultaneous recording of the spectral profile of six emission lines formed in the high chromosphere and chromosphere-corona transition zone. Lower-resolution sounding rocket data have already shown that these lines can clearly indicate the violent motions associated with atmospheric heating. A second ultraviolet spectrograph—the UV slit image display—will obtain spectral images at 1550 Å to study the thermal structure of the base of the chromosphere, where magnetic and dynamic heating first cause the temperature of the atmosphere to increase on moving outward from the Sun. The third HRTS instrument—the visible-light slit image display—records images in the visible H-alpha line at 6563 Å. This is provided to ensure precise co-registration with the CIP data from the optical telescope.

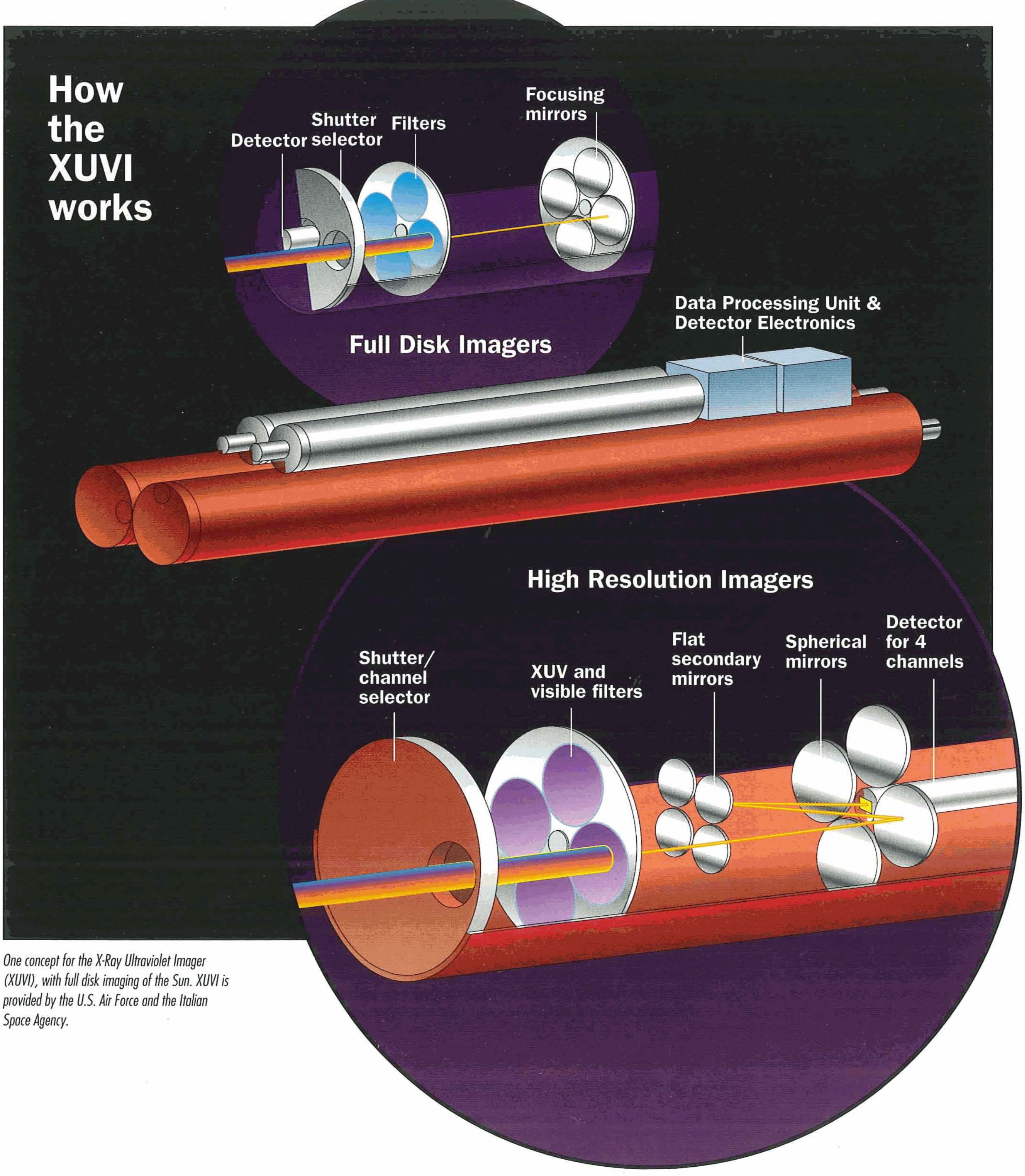
The X-Ray Ultraviolet Imager

The third major telescope on the OSL is the X-ray Ultraviolet Imager (XUVI). This telescope, provided jointly by the Italian Space Agency and the U.S. Air Force Geophysics Laboratory incorporates a new technology for x-ray astronomical telescopes. Multiple layers of coatings on a standard normal-incidence mirror create the high reflectivity required for x-ray observations, which previously required complex and less accurately figured grazing-incidence mirrors. The result is that for the first time the solar corona will be imaged with a spatial resolution approaching 350 km. The eight wavelength bands—from 45 to 335 Å—are determined by the characteristics of multilayer coatings, and separate imaging systems, with individualized coatings, are provided for each wavelength. Again, provisions are made for precise co-alignment of the XUVI images with data from the other instruments on OSL.

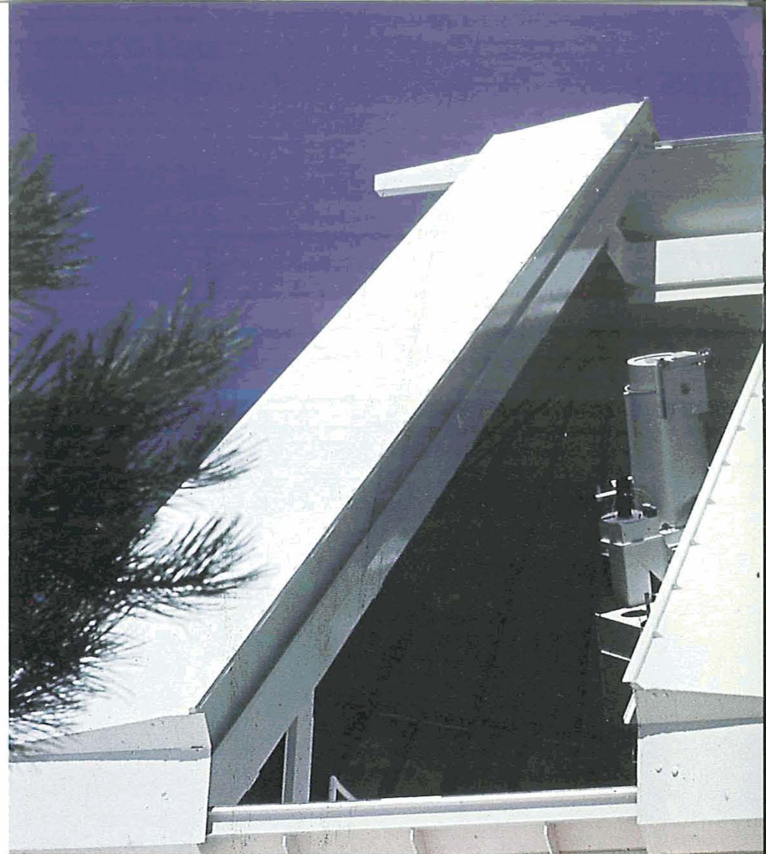
The Active Cavity Radiometer Irradiance Monitor (ACRIM)

The Active Cavity Radiometer Irradiance Monitor (ACRIM), developed by NASA's Jet Propulsion Laboratory, represents the latest in pyrheliometric technology, a specialized form of radiometry and the most accurate and precise for measuring total solar irradiance (TSI). The ACRIM experiment on the Solar Maximum Mission (SMM) provided an almost continuous record of changes in TSI since 1980, detecting variations ranging from timescales of only minutes to the 9-year period of SMM's lifetime. During declining years of solar cycle 21 between 1980 and 1985, a systematic decrease in total irradiance was observed, with a net drop in average value of 0.1%. The TSI stayed almost constant between 1985 and 1987, the solar minimum, while results in 1988–1989 showed an increase exceeding the original decline.

Temporary TSI decreases of as much as 0.25% over periods of a few days have been found and shown to coincide with periods of increased sunspot activity. A direct relationship has also been established between peaks in irradiance (or at least decreases in the net irradiance deficit produced by sunspots) and active faculae (large bright spots on the Sun's photosphere). In order to develop a high-precision database on solar irradiance over the long term, the ACRIM instrument will be flown on a number of missions over the next ten years or so, in addition to the flight of opportunity on OSL.



One concept for the X-Ray Ultraviolet Imager (XUVI), with full disk imaging of the Sun. XUVI is provided by the U.S. Air Force and the Italian Space Agency.



The Evans Facility at the National Solar Observatory, Sunspot, NM.

OSL: A Solar Research Facility

The international solar research community eagerly awaits the launch of OSL. A vital aspect of the mission is the early and active involvement of scientists representing all the disciplines concerned in the project. By design, a large number of researchers will participate in the definition of coordinated research programs and in data analysis, interpretation, and publication. A total of some 100 Principal Investigators (PI's), Co-Investigators, and Facility Scientists are presently involved in the mission. Many are already developing data-analysis techniques and working to refine the theoretical models necessary to simulate the dynamic processes that OSL will uncover. To prepare for full operations, a theory program will be initiated some three years in advance of launch, and an OSL Graduate Student and Postdoctorate program will be set up.

Following an initial three-month period of observation reserved for the PI's and their teams, Guest Observers and Guest Investigators, selected competitively on a worldwide basis, will be invited to participate in the program, opening up OSL as a major international solar research facility. A program of simultaneous, correlated ground-based solar observations from around the world is also being planned.

Data-Gathering and Communication

Among the innovative data-analysis techniques available to OSL investigators will be co-alignment of data sets representing the output of the different OSL instruments, the creation of digital-data "film strips" for visual analysis, and advanced techniques for correlating OSL data with data from ground observatories and other space missions. Through the capacity, sophistication, and coordination of its ground data-handling systems, OSL will make real the scientific promise of its advanced instrumentation.

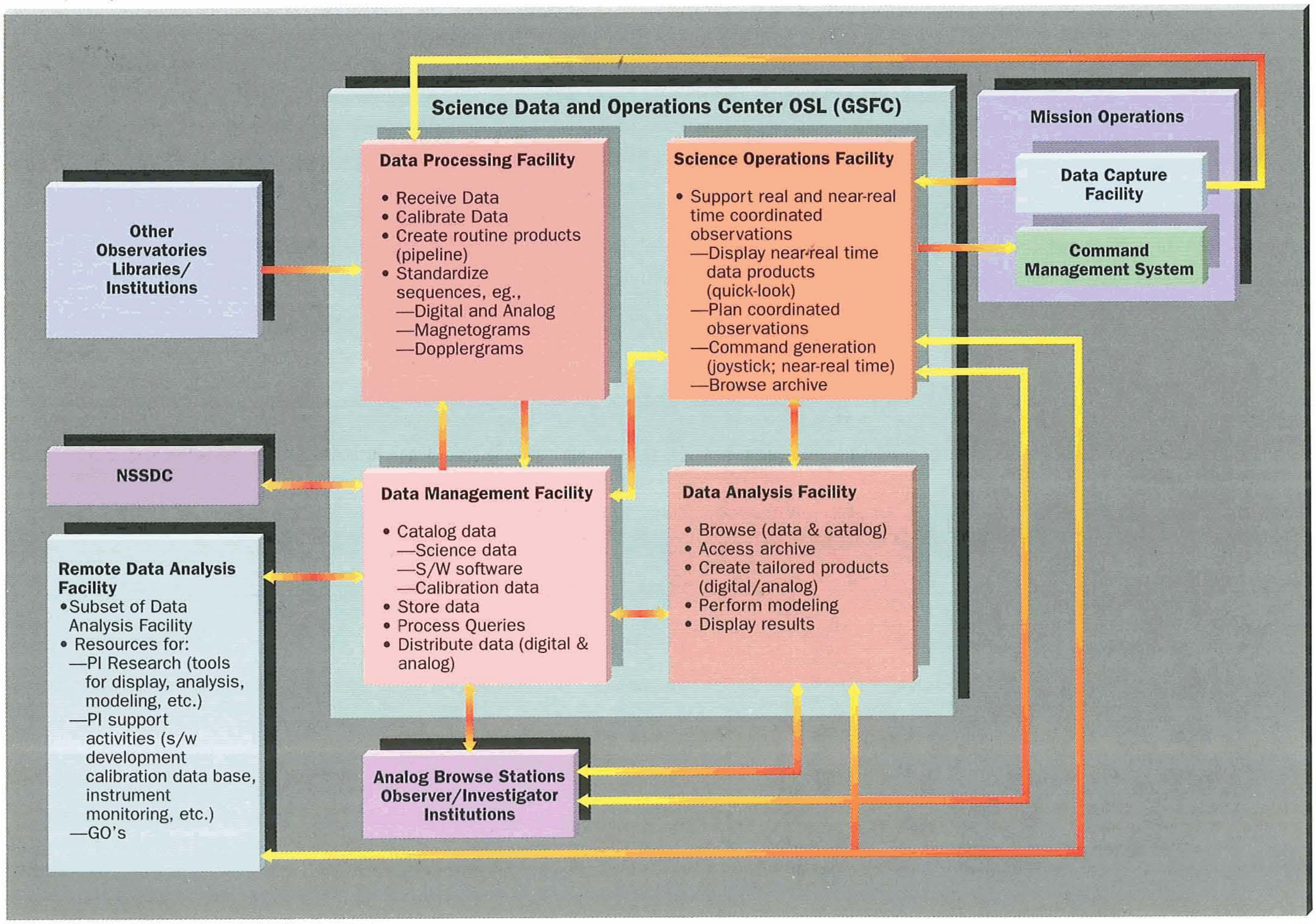
Unlike previous missions, such as Skylab, OSL will not collect images on film for later retrieval, or transmit analog signals to ground stations, but will use high-resolution Charge-Coupled Device (CCD) cameras that translate visual data into digitized form. Data will be transmitted at an information rate of at least 20 million bits per second (Mbps), over an 8-hour period of operations each day, for most of the year. Science data will be collected at 2 Mbps for the remaining hours of the day. The resulting data stream will be relayed to NASA's TDRSS, and thence to Earth. OSL will remain in direct ground contact via TDRSS for several complete orbits at a time, permitting the observation of many solar events from start to finish. Data from TDRSS will in turn be relayed to the center of mission operations and science planning at NASA's Goddard Space Flight Center.

Ground Systems and Data Facilities

The Science Data and Operations Center (SDOC) at Goddard will plan and schedule observations. At the scientific and operational heart of the SDOC, the Science Operations Facility (SOF) will provide displays of OSL's data products—digital and analog sequences, magnetograms, and dopplergrams—directly to the scientist on a quick-look basis and in near real time. It will also permit observers almost to "fly" OSL during their scheduled observation time slots by means of command sequences generated at state-of-the-art computer workstations. At the end of allocated observing time, all data will be centrally bulk-processed for full scientific analysis, using investigators' calibration and reduction algorithms.

To increase OSL's benefit as a solar facility to the scientific community, remote data analysis facilities will be established throughout the country. Each will provide resources for PI research, including tools for display, analysis, and some modeling, software development, database work, and instrument monitoring. Additionally, analog browse stations will be provided at a number of Observer and Guest Investigator institutions.

(Below) OSL science data handling at the Goddard Space Flight Center.



Summary

By the late 1990's, the Orbiting Solar Laboratory will offer long-term, high-resolution measurements of the Sun for the first time simultaneously at visible, ultraviolet, and x-ray wavelengths. A multinational effort with Italian and German collaboration, OSL will use the largest solar telescope ever flown and a suite of five major science instruments to collect data of unprecedented clarity and sensitivity.

The coordinated operation of these instruments, each penetrating to different layers of the Sun's atmosphere, will build up a three-dimensional picture of key solar processes and their interactions, essential for the understanding and early prediction of many forms of solar activity.

Many interrelated phenomena occur on the Sun. Magnetic fields cause heating or induce motions, such as shock waves, solar flares, and the outward expansion of the solar wind. OSL will map these dynamic processes by collecting data from the solar surface, the hotter overlying chromosphere, and the extremely hot corona.

The data will thus provide a composite image of interrelated solar activity from the solar surface up through the layers of the solar atmosphere and beyond.

The energy output of the Sun is variable. Dark sunspots surface on an eleven-year cycle while, at the same time, surrounding magnetic active regions radiate even more brightly. Violent and as yet unpredictable solar flare events produce vast quantities of high-energy electrons, protons, and nuclear particles in seconds, and drive shock waves and ejections of solar gases into interplanetary space. While changes in solar output are tiny by some stellar standards, they can create significant effects on Earth. It is important to understand those changes, both in order to predict them and to distinguish solar-driven from human-induced effects on our terrestrial environment.

In addition, the Sun is a star—the closest star to the Earth—and the only one that can be studied in great detail. Investigations of the Sun have already helped show much of the physical nature of other, more distant stars. However, because phenomena on other stars cannot be imaged, it is essential to study the Sun, where physical processes can be seen in detail. Investigations of solar processes will also have significant benefits for other disciplines, such as the study of plasmas, in which Earth-bound laboratories cannot provide the experimental scale required.

Previous observations from space have provided data on UV and x-ray emissions from magnetic active regions and flares, and ground-based observations at visible wavelengths have provided coarse information on the photospheric magnetic fields that are ultimately responsible. The unique multi-wavelength observational capability of OSL is the key to the mission, offering a powerful new means of understanding how the Sun works, and a way forward in answering many fundamental questions about the behavior of the Sun and its effect on the Earth.

OSL Instruments and Mission Details

OSL Main Telescope :

- 1 m diameter Gregorian reflecting telescope
- 24 m effective focal length
- Commandable secondary mirror
- 0.13 arc sec spatial resolution
- 3.9 arc min unvignetted field of view

CIP: Photometric Filtergraph
(California Institute of Technology)

- 160 x 160 arc second field filter camera
- 2300-6687 Å, low spectral resolution

Tunable Filter/Magnetograph
(Lockheed Palo Alto Research Laboratory)

- 160 x 160 arc sec field
- 4600-6563 Å, medium spectral resolution

Kiepenheuer Institute Solar Spectrograph
(Kiepenheuer Institute, Germany)

- 0.1 x 80 arc sec field
- 2800–8540 Å, high spectral resolution

High-Resolution Telescope and Spectrograph
(Naval Research Laboratory)

- 30 cm diameter Gregorian reflecting telescope
- Spectrograph (1200–1700 Å)
- UV slit image display (1550 Å)
- Visible slit image display (6563 Å)

X-Ray Ultraviolet Imager
(Italian Space Agency, USAF Geophysics Laboratory)

- 45-335 Å, high resolution imaging (0.5 arc sec)
- Full sun & inner corona imaging (2-3 arc sec)
- Multilayer coatings to isolate 8 different solar emission lines

Active Cavity Radiometer Irradiance Monitor
(Jet Propulsion Laboratory)

- measures TSI variability
- absolute accuracy of 99.9%

OSL will be launched on a Delta-II expendable launch vehicle from the Western Test Range, California, into a sun-synchronous polar orbit at a height of 510 km and an inclination of 97.4° to the Equator. The Laboratory will weigh about 7,400 lbs and is 15 ft long and 9.2 ft in diameter.

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OSL Science Working Group

Ester Antonucci, University of Turin (XUVI)

R. G. Athay, High Altitude Observatory (member emeritus)

Guenter Brueckner, Naval Research Laboratory (HRTS)

George Doscheck, Naval Research Laboratory

Richard Fisher, High Altitude Observatory

John Harvey, National Solar Observatory

Bruce Lites, High Altitude Observatory

Donald Neidig, Air Force Geophysics Laboratory

Robert Noyes, Harvard Smithsonian Astrophysical Observatory

Egon Schroeter, Kiepenheuer Institute for Solar Physics (Solar Spectrograph)

Daniel Spicer, NASA/Goddard Space Flight Center, Project Scientist

Alan Title, Lockheed Palo Alto Research Laboratory (Tunable Filtergraph)

Richard Willson, Jet Propulsion Laboratory (ACRIM)

Harold Zirin, California Institute of Technology (Photometric Filtergraph)

Kees Zwaan, University of Utrecht

OSL Program Manager: Richard J. Howard, NASA Headquarters

OSL Program Scientist: William J. Wagner, NASA Headquarters

OSL Project Manager: Roger Mattson, NASA/Goddard Space Flight Center

National
Aeronautics and
Space
Administration

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