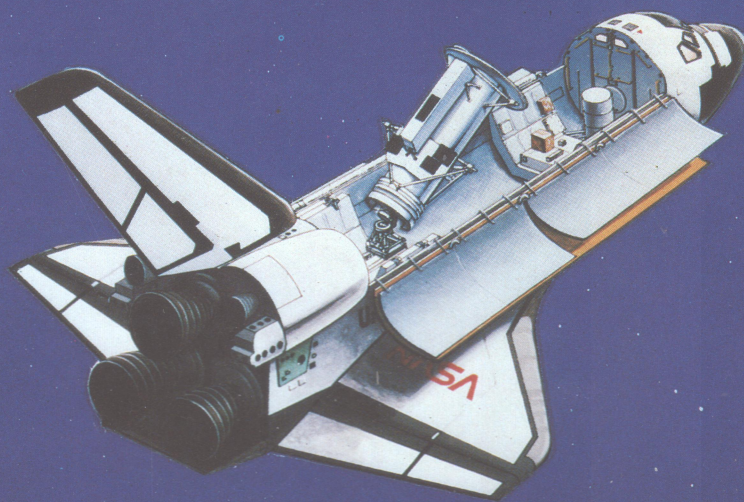


The Solar Optical Telescope

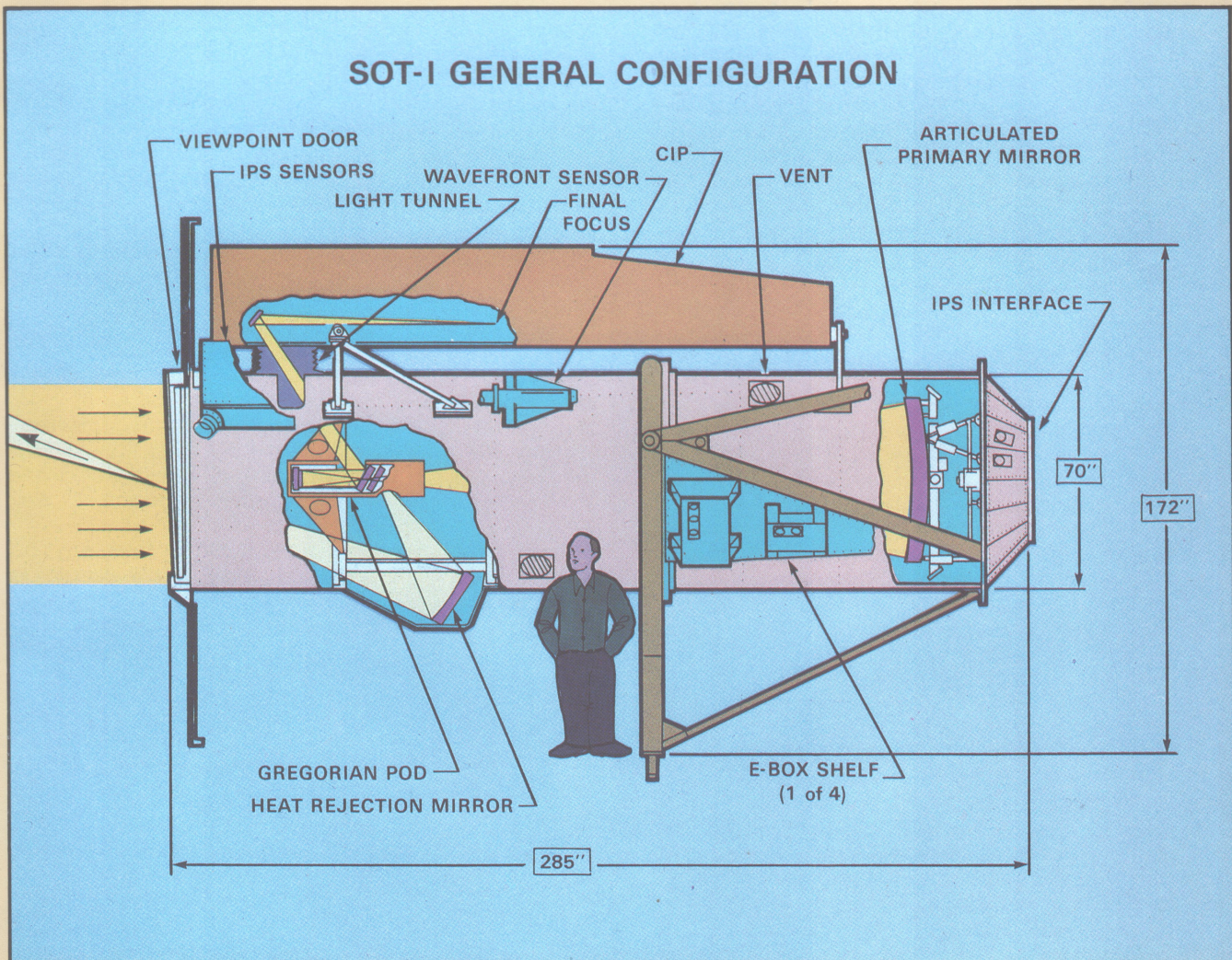


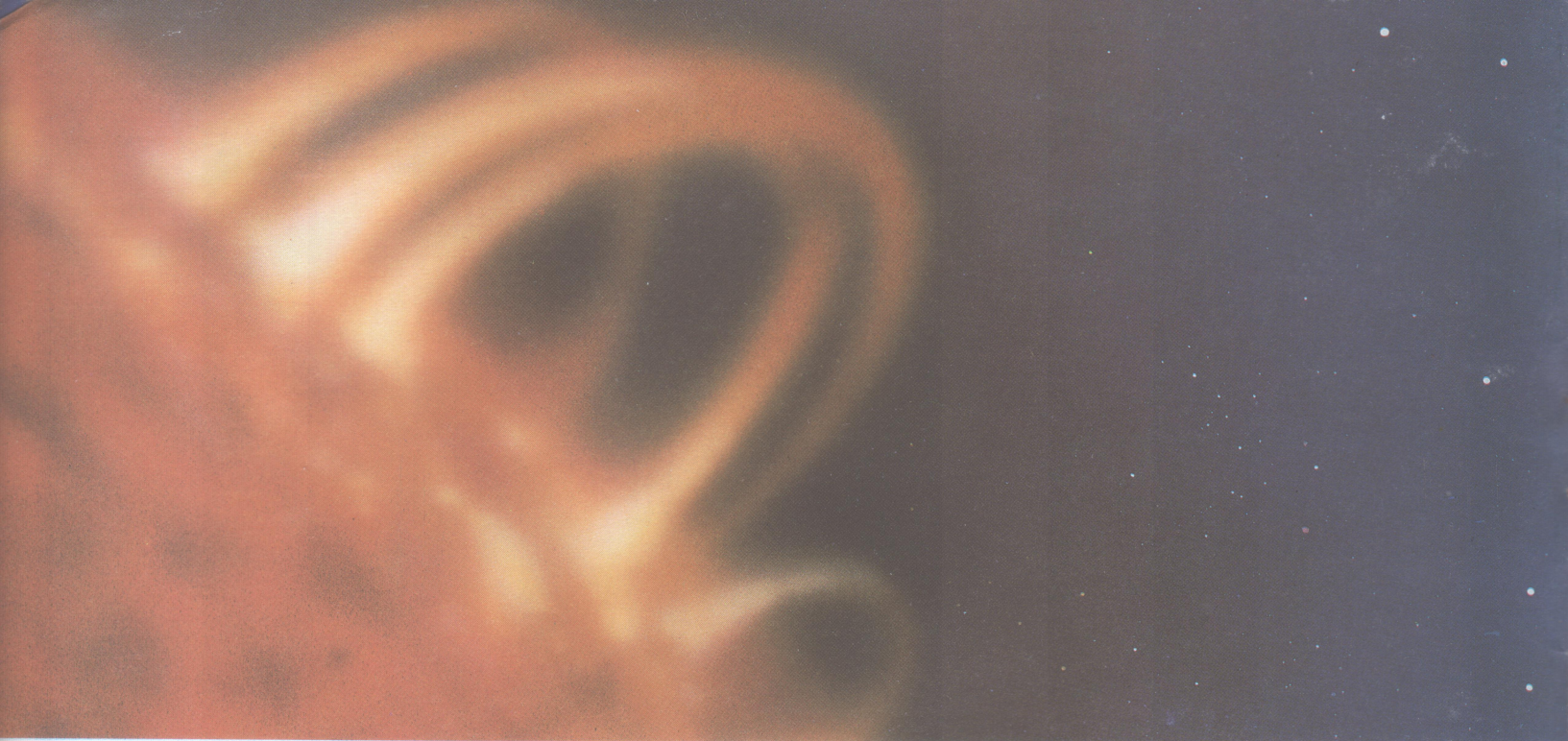
NASA

The Solar Optical Telescope is shown in the Sun-pointed configuration, mounted on an Instrument Pointing System which is attached to a Spacelab Pallet riding in the Shuttle Orbiter's Cargo Bay.

The Solar Optical Telescope

- will study the physics of the Sun on the scale at which many of the important physical processes occur
- will attain a resolution of 73km on the Sun or 0.1 arc seconds of angular resolution





Why is the Solar Optical Telescope Needed?

2

There may be no single object in nature that mankind is more dependent upon than the Sun, unless it is the Earth itself. Without the Sun's radiant energy, there would be no life on Earth as we know it. Even our primary source of energy today, fossil fuels, is available because of solar energy millions of years ago; and when mankind succeeds in taming the nuclear reaction that converts hydrogen into helium for our future energy needs, it will be the reaction first discovered, and still being studied, in the Sun's core that will provide that energy. Meanwhile, the Sun's radiation will continue to drive the circulation of our terrestrial atmosphere and will contribute to changes in our climate through subtle variations in the quantity and the spectrum of that radiation. Thus, the Sun remains, in some sense, as important today as it was to the ancients who worshiped it as a god and who sensed, even if they did not fully understand, how fundamental the Sun's role is in determining the character and viability of our home, the Earth.

Beyond its importance to life on Earth, the Sun is also of fundamental importance to stellar astronomy. The Sun is a very typical star, and it is the only star that we can study with high angular resolution, thanks to its proximity to us. This means that we can study physical processes that are of fundamental significance in understanding stars in general, on the scale on which these processes are actually occurring! The history of astronomy demonstrates convincingly that much of our understanding of the physics of stars comes from understanding these physical processes on the Sun first. It is for this reason that the Sun is often called the Rosetta stone of astronomy.

The Solar Optical Telescope will be the world's first facility that is capable of observing the Sun on the angular resolution of a typical photospheric (lower atmospheric) mean-free path for radiation and also on the scale known to characterize major changes in the gas-dynamic behavior of the atmospheric medium. In simple language, these are the scales on which energy is transferred in the solar atmosphere; hence, they are the scales on which the major physical processes that ultimately determine the dramatic large-scale behavior of the atmosphere take place.

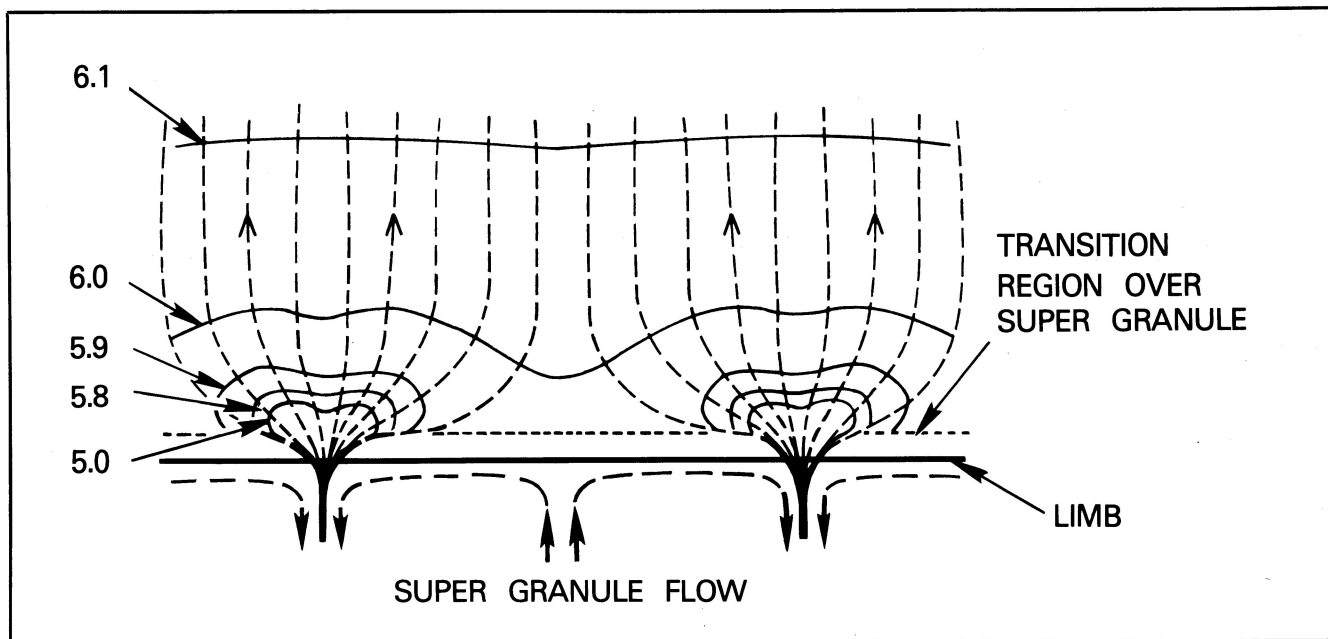
For example, the heating and expansion of the solar wind that bathes the Earth in solar plasma is ultimately attributable to small-scale processes that occur close to the solar surface. Only by observing the underlying processes on the small scale afforded by the Solar Optical Telescope can we hope to gain a profound understanding of how the Sun transfers its radiant and particle energy through the different atmospheric regions and ultimately to our Earth.

Perhaps the best analogy for the radical new perspective that the Solar Optical Telescope will give us on solar physics is that of the role of the microscope in clarifying the nature of blood. Before the invention of the microscope, there was a great deal of speculation on the nature of this vital fluid. Since the discovery of blood circulation by the physician Harvey, we have understood that blood somehow is involved both in "feeding" the body and in removing some of its locally generated waste products. But how? Only with observations of blood cells and the determination of their structure and function could our current understanding develop. For this, the microscope was needed. In a like manner, the Solar Optical Telescope will provide views of the solar surface that, for the first time, will permit its basic structure, "cellular" or otherwise, to be resolved.

The Sun has long been the focus of human attention and admiration. The arts attest nobly to this interest. In the closing phases of Mozart's famous opera "The Magic Flute," the Sun-priest utters the lines (loosely translated):

'The Sun's golden rays pierce through the night,
And scatter the powers of Darkness to flight.'

It is appropriate that we should approach the objects of nature both from the perspective of the arts as well as from that of the sciences. The Solar Optical Telescope gives us the opportunity of taking the next great step in scientifically understanding the Sun, as well as those other fascinating astronomical objects of which it is the closest member, the stars.



Schematic cross section of "quiet" solar atmosphere, with supergranulation flow below limb and inhomogeneous magnetic field above limb given as dashed lines. Numbers are Log₁₀ of the temperature.

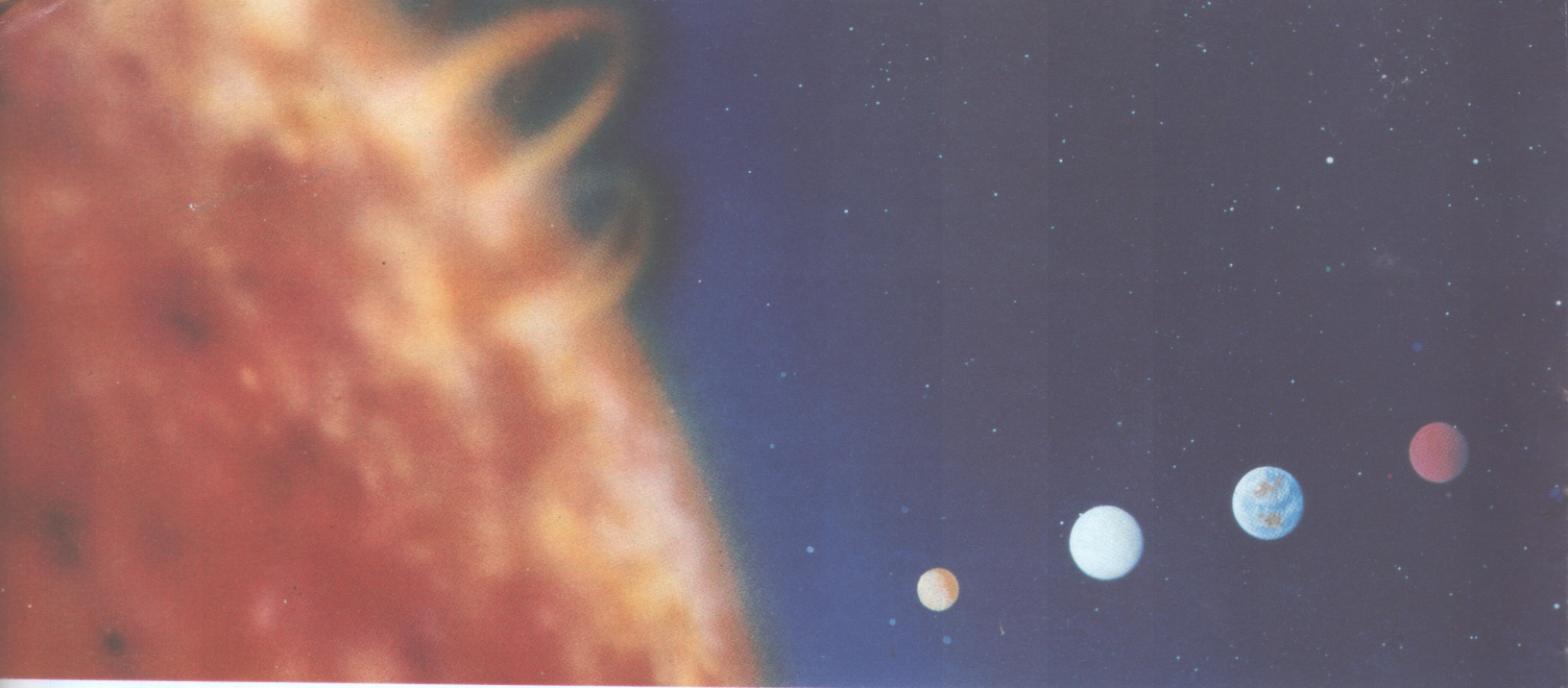
Current Picture of the Sun's Atmosphere and Convection Zone

The picture of the solar atmosphere and upper convection zone that has developed over the past three decades emphasizes the importance of magnetic fields and inhomogeneities. The solar atmosphere is never entirely homogeneous at any height. Material upwelling from the deep unobservable regions of the convection zone spills over into the stable photosphere, where two distinct scales of convective eddies are observed in the granulation and supergranulation flow patterns. Above the photosphere, jets of material called spicules shoot up from the top of the chromosphere to several thousands of kilometers into the corona. Strong, highly localized and essentially vertical magnetic fields extend from the subsurface regions through the photosphere. These strong fields spread out and weaken in the higher layers, forming large-scale regions of closed fields similar to those of a dipole, as well as large regions of open field lines extending into interplanetary space. Superimposed on this complex pattern of systematic and impulsive flows and magnetic fields is a spectrum of oscillations and waves on varying scales, ranging from coherent pulsations of the entire Sun with periods of up to almost 3 hours, to hydromagnetic waves localized to the photosphere and chromosphere with periods on the order of 1 minute.

Underlying this complex atmosphere is the solar convection zone, in which energy is transported by means of convective motions from the core where it is generated by nuclear reac-

tions to the overlying atmosphere. Since the convection zone is not directly observable in any wavelength, except at its upper boundary with the photosphere, its deeper structure can be known only from careful studies of oscillations observed at the solar surface (solar seismology) and from theoretical modeling. The only hope of understanding solar convection in detail, then, depends on using the boundary conditions obtained from observations at the surface and solving the differential equations of gas dynamics. To date, solar observations have yielded a picture of convection in which elongated, hexagonal cells extend to some currently undetermined depth of the convection zone and reveal themselves in the observable photosphere as the supergranulation flow pattern. Superimposed on this larger scale flow is the smaller scale motion observed at the level of the photosphere and called the granulation. Theoretical estimates of flow conditions in the low photosphere predict that this small-scale flow should be turbulent, and that is largely what is actually observed there. Two other scales of convection have been predicted theoretically, but neither has been reliably observed. These are (1) a very large-scale, "giant cell" with a scale length extending a significant fraction of a solar radius, and (2) a "mesoscale" convection, intermediate between the scales for granulation and supergranulation.

The question of the velocity structure of the convection zone, which is intrinsically interesting, also under-



4

lies one of the most fundamental problems in solar/stellar astrophysics: What is the character of the dynamo that generates the Sun's (or a star's) magnetic field? Since the motions of the subphotospheric solar plasma, coupled with the solar differential rotation, are ultimately responsible for the solar magnetic field, certain general constraints on the type of dynamo have already emerged from observations of the Sun's surface magnetic field. For example, the dynamo must be able to generate the cyclic behavior in the field over a 22-year period known as the solar cycle. Unfortunately, current limitations in the angular resolution of ground-based data prevent our constraining the current dynamo models enough to get an accurate picture of how the dynamo works or of why the scale of the surface magnetic flux tubes is so small. What is needed is the interaction between magnetic fields and fluid motions—which occurs on the small sub-arc-second scale of the flux tubes.

Let us move up higher into the solar atmosphere again. We now know that it is filled with numerous other features whose structure and dynamics are dominated largely by the magnetic field. This occurs because, above the chromosphere, the energy in the magnetic field exceeds that stored thermodynamically in the gas, reversing the picture that applied in the lower lying regions. Large-scale features, called prominences and filaments, are well observed structures that are still only partly understood solar phenomena for which the dominant parameter appears to be the local magnetic field, which determines the observed behavior. From time to time, magnetic energy is transformed into heat by a still poorly understood process that is observed in catastrophic events called solar flares. The solar atmosphere is clearly an ideal laboratory for studying many important plasma processes, which are also present in other types of stars.



Some Scientific Problems for the Solar Optical Telescope

1. SOLAR MAGNETIC FIELDS

The basic structure of the solar magnetic field is now thought to be the flux tube. The scale of these flux tubes in the photosphere is smaller than the resolving power of ground-based telescopes. The reason why much of the magnetic field in the photosphere is on such a small scale is not understood, although theories that address this problem have been proposed. The Solar Telescope will permit these theories to be checked, by obtaining high resolution data on both the magnetic fields and the associated gas flows in the magnetic field regions.

2. CONVECTIVE ENERGY TRANSPORT

Models for the velocity structure of the solar convection zone are currently being generated. One constraint on these models is the detailed behavior of the convection at the upper boundary of this region in the low photosphere. The Solar Optical Telescope will help solar physicists to resolve the complex velocity structure of this observable region. Superior models of convection zone dynamics will yield superior models for the dynamo that generates the Sun's magnetic field.

3. SOLAR ATMOSPHERIC HEATING

Because the last of the Orbiting Solar Observatories (OSO-8) demonstrated that there was insufficient energy in acoustic waves to heat the solar atmosphere above the chromosphere, solar physicists have sought evidence for hydromagnetic and plasma processes to heat the higher lying regions of the chromosphere, the transition region, and the corona. Many of these processes occur on a scale too small for detailed study with current telescopes. The Solar Optical Telescope will correct this situation.

4. ATMOSPHERIC DYNAMICS

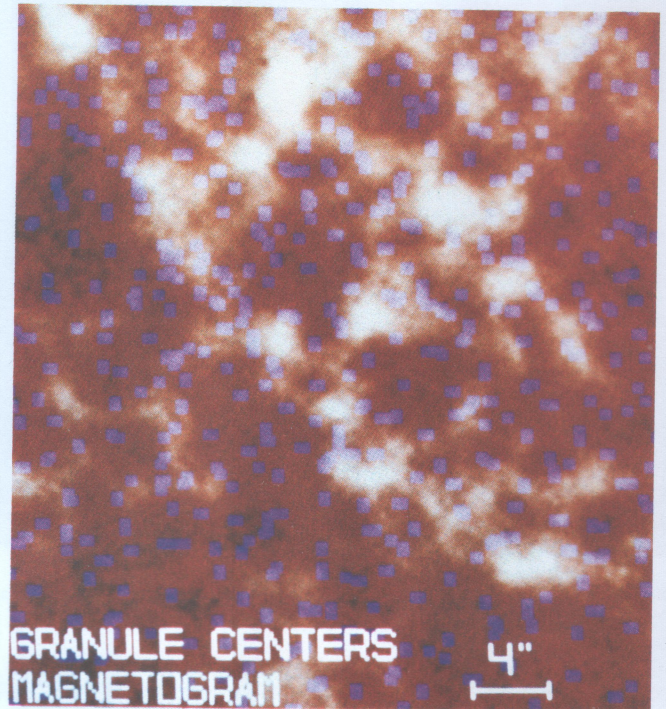
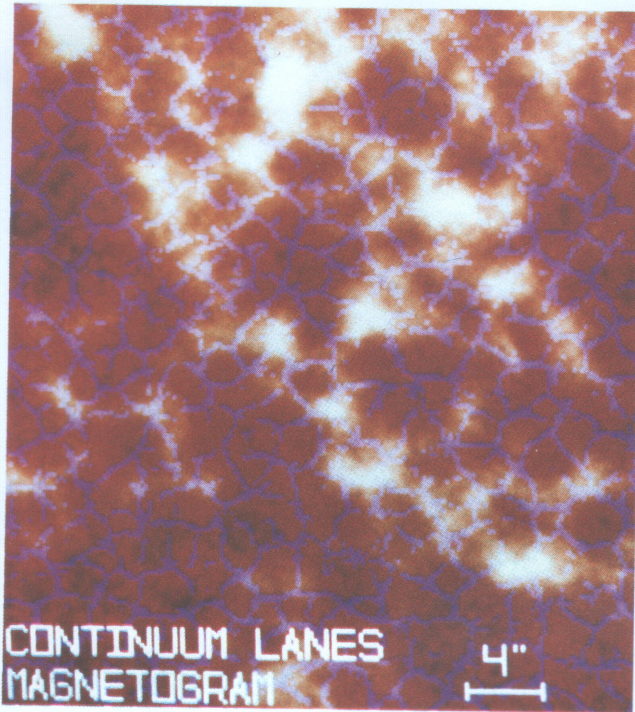
The mass balance between different regions of the solar atmosphere has long been a major problem in solar physics. The mass loss inferred from observed upward motions of spicules, whose internal motions cannot be resolved, is more than an order of magnitude larger than the measured mass loss in the solar wind at the Earth's orbit. The Solar Optical Telescope will resolve the smaller scale velocity fields that contribute to the overall mass balance.

5. SOLAR FLARES

The most difficult problem in the physics of solar flares has proven to be identifying a "trigger mechanism" whereby the enormous energy stored in the convoluted ambient magnetic field is suddenly and dramatically released. Since the triggering can involve plasma instabilities on unobservably small scales, even for the Solar Optical Telescope, the most productive approach has been to constrain the range of possible trigger mechanisms by observing the plasma changes on the smallest scale that can be observed. The Solar Optical Telescope will decrease the scale of observable changes by about one order of magnitude.

6. INSIGHTS INTO OTHER STARS

The Sun, by its proximity, is much more amenable to detailed study of many fundamental stellar processes than any other star. Again and again, processes first observed and understood on the Sun are used to explain similar phenomena observed on other stars. The latest example is the extrapolation, over much of the Hertzsprung-Russell diagram, of what is known about the solar chromosphere, corona and wind. Data from the International Ultraviolet Explorer and Einstein Observatories and advances in solar physics from the Solar Optical Telescope can be expected to play a similar role in stimulating stellar astrophysics in the future.



The two magnetograms shown above demonstrate the tendency for solar magnetic fields (yellowish emission) to be pushed toward continuum lanes (violet) by motion of granules.

6

Solar Magnetic Fields

We have already noted that the perplexing problem of the stability of small-scale flux tubes in the photosphere requires observations of the flux tubes on sub-arc-second scales. Since these flux tubes are thought to be just below the scale of current observations, and since definitive observations will have to include their associated gas flows, it is clear why the Solar Optical Telescope is needed to obtain the data needed for checking the theory. Magnetic fields in sunspots will also be studied at high resolutions, because the best current data show that the spot itself is composed of a complex, largely vertical magnetic field structure in the umbra and more nearly horizontal fields in the surrounding penumbra, where convective flows also appear to be taking place. Solution of the flux-tube stability problem has far-ranging possible applications. If,

according to one current picture, flux tubes "collapse" to an equilibrium configuration because of "downdrafts," then up-flows within a flux tube may cause expansion and may be associated with magnetic breakdown and diffusion at the edge of solar active regions. Also, by associating solar magnetic field structure with values for the densities and velocities in the solar photosphere, the stability theory would permit inferences to be made about scales for the magnetic elements in other stellar atmospheres for which model atmospheres and mean magnetic field strengths are available. Finally, sunspots offer an excellent laboratory for studying strong magnetic fields on other stars. Late M-type stars, for example, are known to have fields of several thousand gauss, comparable to sunspot fields.

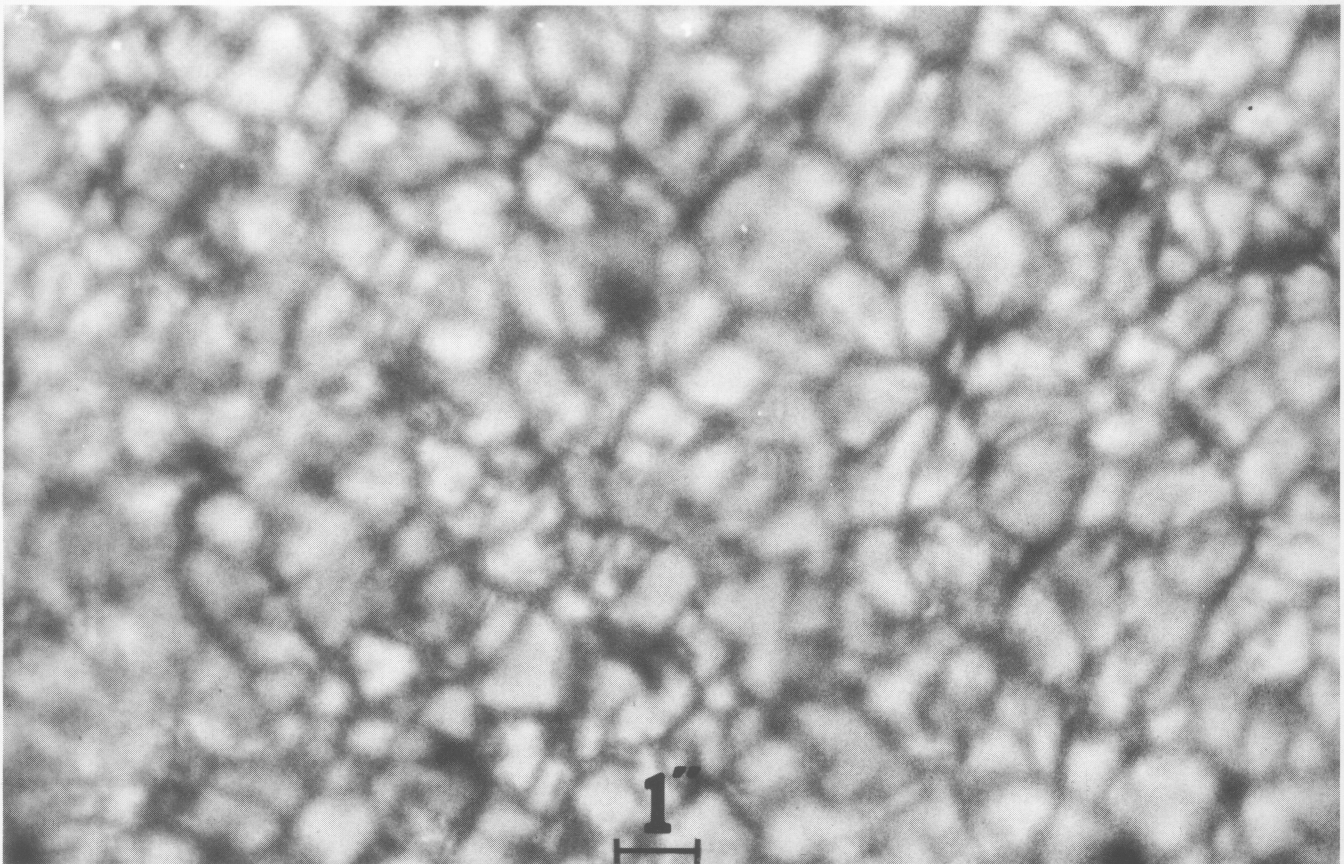
Convective Energy Transport

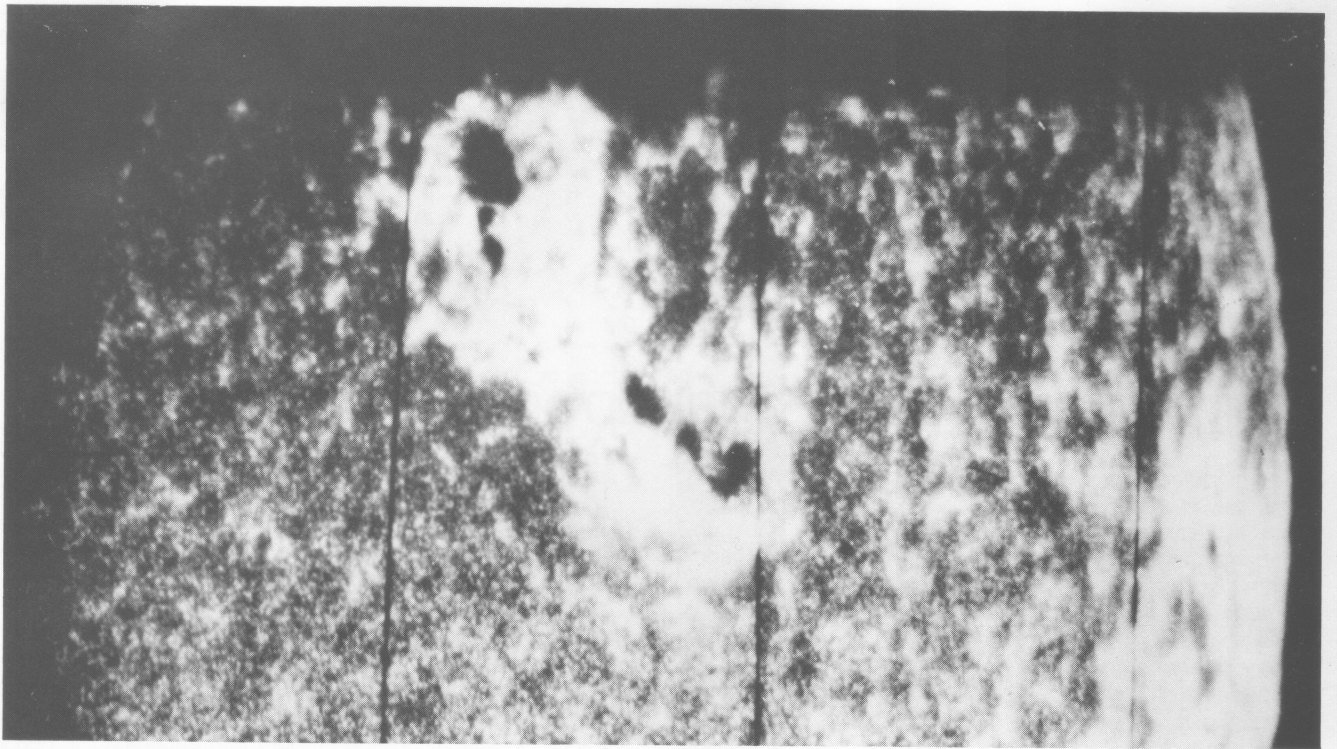
The granulation at the top of the solar convection zone is the visible evidence of turbulent convection at the upper boundary between this zone and the convectively stable upper photosphere. The granulation is important for a number of reasons. First, it is necessary to characterize the granulation flow field accurately in order to subtract it from the aggregate photospheric velocity field, which contains other systematic and oscillatory components one wishes to study. Separation of these different velocity fields, of different origins, is a challenging task that requires data of very high resolution in both spatial and temporal frequencies. The granulation is also intrinsically interesting as a boundary condition on convection

zone velocity models and as the source of numerous types of waves that transport energy to higher lying regions of the solar atmosphere. These waves can be acoustic waves in the absence of magnetic fields or hydromagnetic waves where local magnetic fields both enhance the power generated and direct the propagation upward. Of critical importance to computing the power generated in both cases are the high-frequency components of the granulation power spectrum (i.e., the small, short-lived elements). These components cannot be observed with present telescopes. The Solar Optical Telescope will be capable of observing them and obtaining the needed power spectra.

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Sacramento Peak photo of solar granulation.



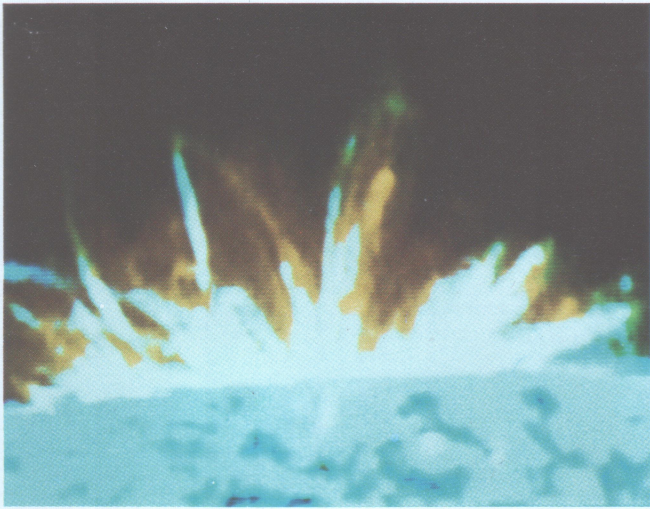


Sun's ultraviolet continuum seen by HRTS rocket. All of the bright emission is indicative of atmospheric heating.

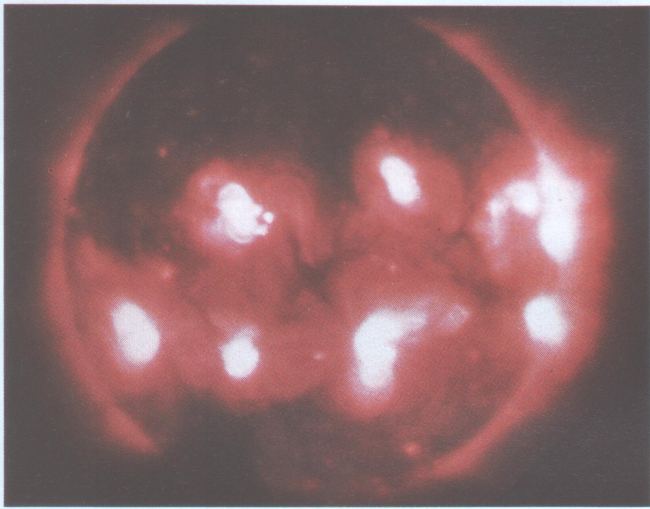
Solar Atmospheric Heating

Since OSO-8 observations have cast doubt on the hypothesis of wave heating of the solar atmosphere above the chromosphere, the hypothesis of heating by the dissipation of electric currents through local magnetic field annihilation has gained many adherents, particularly for the heating of coronal active-region loops. However, the wave-heating hypothesis is not entirely dead. In the presence of magnetic fields, many kinds of wave modes are possible. Some of these can penetrate through the chromosphere and transition region into the corona, or they can even be generated by turbulence in the transition region itself, as some of the Skylab observations have suggested. Moreover, a third possibility for heating the corona is by the dissipation of supersonic jets of the type ob-

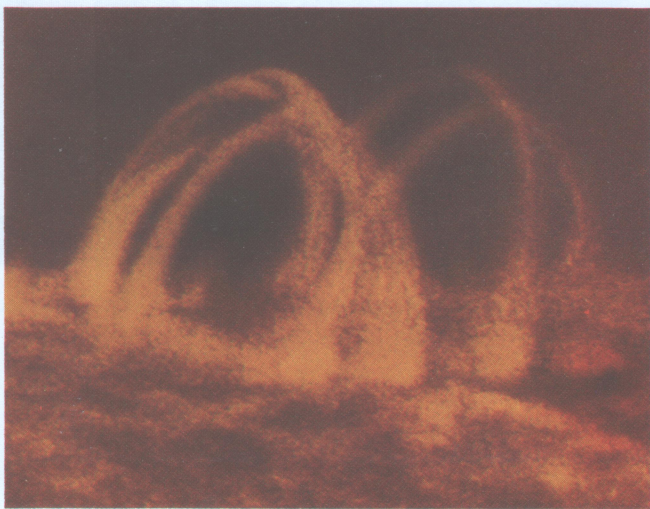
served with the HRTS sounding rocket ultraviolet spectrograph/spectroheliograph. The common characteristic of all of these heating mechanisms is their dependence on sharp spatial gradients in either the local magnetic field, the local velocity field, or both. In addition, the temporal history of the local temperature, and usually of other parameters, must be determined. Obtaining all of these data simultaneously with the required resolution over a field of view large enough to establish the context of the physical process present is beyond the power of any existing instrumentation. The Solar Optical Telescope, with the complete Combined Instrument Package as payload, will have this power.



Skylab image of coronal loops. Mass exchange with chromosphere is likely.



Skylab X-ray images of active regions. Detailed structure breaks up into loops (above).



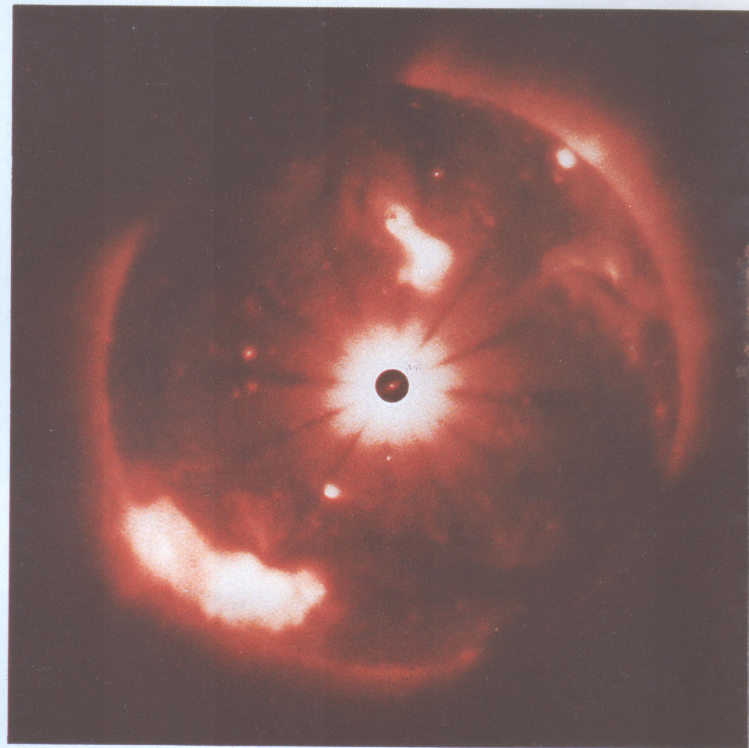
Dense active region loop material suspended in the corona.

Atmospheric Dynamics

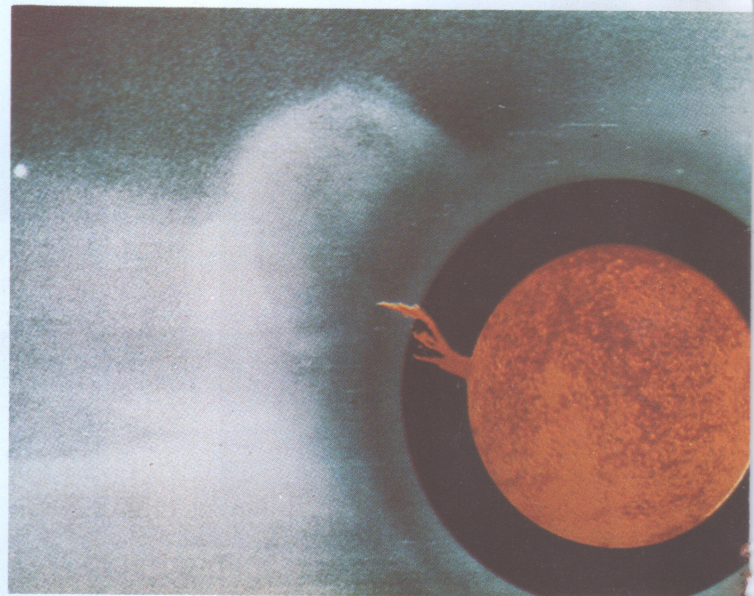
The question of mass balance between the chromospheric spicules and the solar wind is only one aspect of the dynamic behavior of the Sun's outer atmosphere that requires further attention. Recent observations have revealed a complex pattern of both vertical and horizontal flows in the chromosphere, in some cases with material moving both up and down in association with known features such as "bushes" of spicules (suggesting that the earlier picture that spicules represent only upward motion may be a highly misleading oversimplification). Very strong downflows, as well as dramatic, high-velocity jets of upward moving material, are also observed in the transition region line of CIV, formed at temperatures of 10^5 K. In addition, analyses of Skylab observations strongly suggest that a complex cycling of material occurs in association with the heating of coronal active regions. The corona is heated and, at very high temperatures, loses radiative cooling efficiency. Conduction of energy down to the chromosphere takes place in the presence of the sharp temperature gradient in the transition region, and chromospheric plasma is then heated and "boiled off" up into the corona, where it radiates away the residual excess energy from the original heating impulse. All of these processes, as well as others, must be studied at high spatial, spectral, and temporal resolution to clarify the dynamics of the Sun's atmosphere.

Solar Flares

The Solar Optical Telescope will decrease the scale on which changes can be observed in solar flares by about one order of magnitude, or more in some wavelengths. This increase in angular resolution, with corresponding changes in a more rapid temporal response to the rapidly changing conditions in a solar flare, will permit a much more accurate assessment to be made of the physical conditions within the flare. The strongest spectral line of four times ionized carbon, CIV, formed in the solar transition region at a temperature of 10^5 K, has been observed with the ultraviolet instrument on the SMM spacecraft at an angular resolution of 3 arc-seconds. With the Solar Optical Telescope, a factor of 30 increase in this angular resolution becomes possible, at even faster exposures than were possible with the SMM! When the resolution is improved dramatically, evidence for localized heating by highly collimated particle beams may become available. Also, the higher resolution may permit the extent to which the process of magnetic field annihilation is localized near the flare kernel to be determined. Gaining more information on such key energetic processes will greatly constrain what kinds of physical processes can trigger the flare in the first place. This is essential because the flare trigger could occur on the scale of the ion gyro-radius for a number of plasma instabilities, and this number is unobservably small — about 100 cm in the corona.



Solar flare seen in X-rays from Skylab (center of sun).



Ultraviolet image of solar eruption is superimposed on a coronogram of this event.

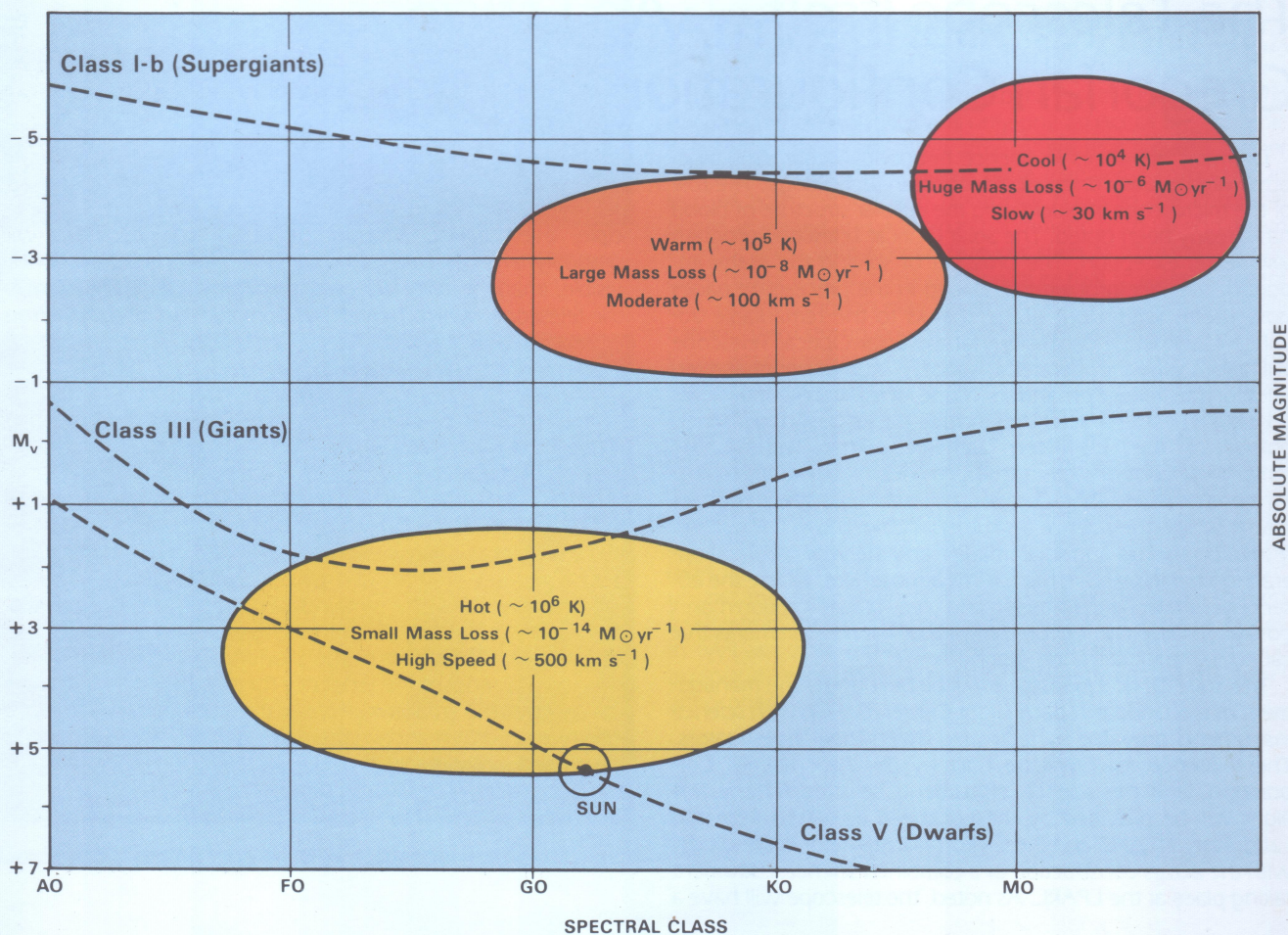
Insights into other Stars

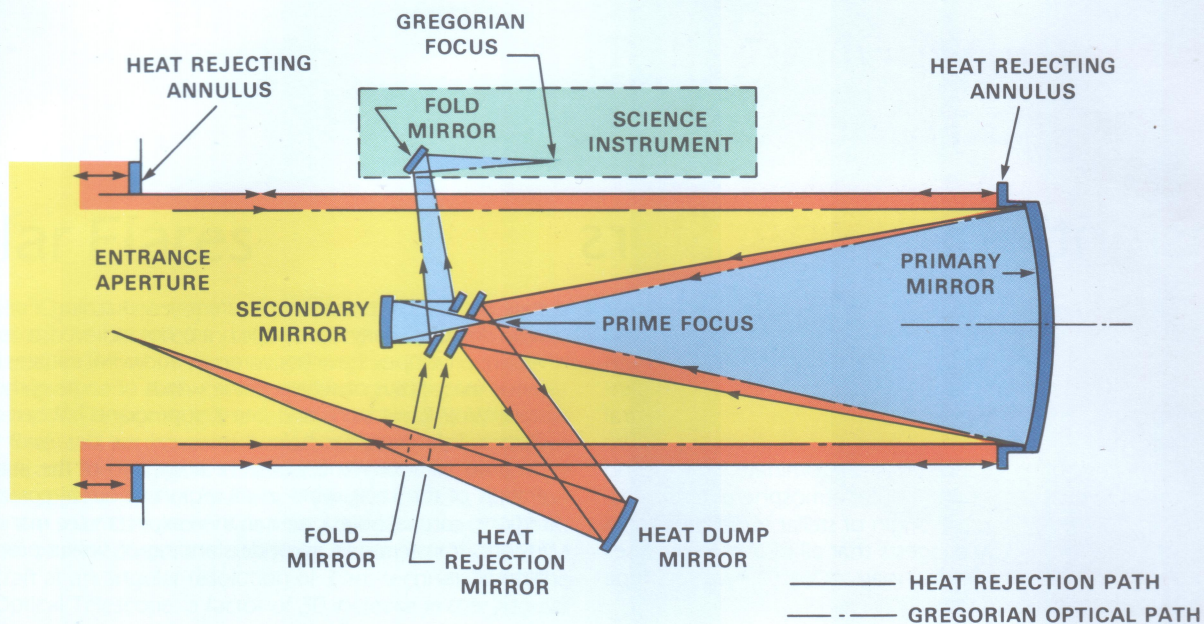
At least two problems of fundamental importance to stellar astrophysics are sure to be more amenable to solution when the Solar Optical Telescope has helped to clarify the situation on the Sun. The first is the nature of the dynamos, which generate magnetic fields on stars, particularly for stars of spectral type later than A on the Hertzsprung-Russell diagram, where convective envelopes are known to predominate. The second is the origin of high-temperature outer atmospheres (chromospheres and coronae) and the origin of stellar winds. In fact, a body of evidence already suggests that all of these processes are connected in some complex way, at least for the late-type

stars; but the current stellar picture is very puzzling. For example, why do some early stars, which are not believed to have convective envelopes, have hot coronae, and what initiates the enormous mass flows observed in the winds of some early O and B stars, Wolf-Rayet stars, and late K supergiants? When the Solar Optical Telescope has helped to reveal the details of the solar dynamo, of solar atmospheric heating and of the initial acceleration of the solar wind in all regions (normal corona, active regions, coronal holes), we can then expect to see many of these insights transferred to an understanding of similar processes on other stars.

Understanding Late-Star Atmospheric Heating and Stellar Winds Relies Heavily on Knowledge Available from Solar Studies.

LATE-STAR OUTER ATMOSPHERES AND WINDS





The Telescope Itself — An Efficient Gregorian Configuration

Dramatic advances in science frequently occur simultaneously with equally dramatic advances in technology. The role of the microscope in elucidating the cellular structure of blood has already been noted. The Solar Optical Telescope program will be no exception. The prospect of solving the many important scientific problems described in the preceding pages now seems within our grasp, thanks to the remarkable advance in telescope capability that the Solar Optical Telescope will afford when it operates in space. A number of characteristics of the telescope and its mode of operation make this possible. These characteristics include the large light-gathering power of the 1.3-meter diameter primary mirror, the remarkable control system that provides high image stability for comparatively long-duration observations, the high data rate at which the science instrument payload can collect high resolution spectra and solar images, and the very nature of operating in space, above the Earth's atmosphere, where the absence of atmospheric scattering and ultraviolet absorption makes possible a large number of vitally important measurements that cannot be made from the ground.

The Solar Optical Telescope will be built under the management of the Goddard Space Flight Center (GSFC), with science instruments provided by teams led by Principal Investigators. The telescope itself will be built by the Perkin-Elmer Corporation, and the science instruments selected for the first flight will be provided by the Lockheed Palo Alto Research Laboratory (LPARL) and the California Institute of Technology, with the actual construction of a combined science instrument taking place at the LPARL. As noted, the telescope will have a

1.3-meter diameter primary mirror that will be capable of achieving diffraction-limited viewing in the visible of 0.1 arc second. Diffraction-limited viewing in the ultraviolet is, in principle, even better, although technical considerations will probably limit this to approximately the same value as in the visible. Image stability will be achieved by a control system in the telescope, which moves the primary and tertiary mirrors in tandem, and will be further enhanced by a correlation tracker in the combined science instrument.

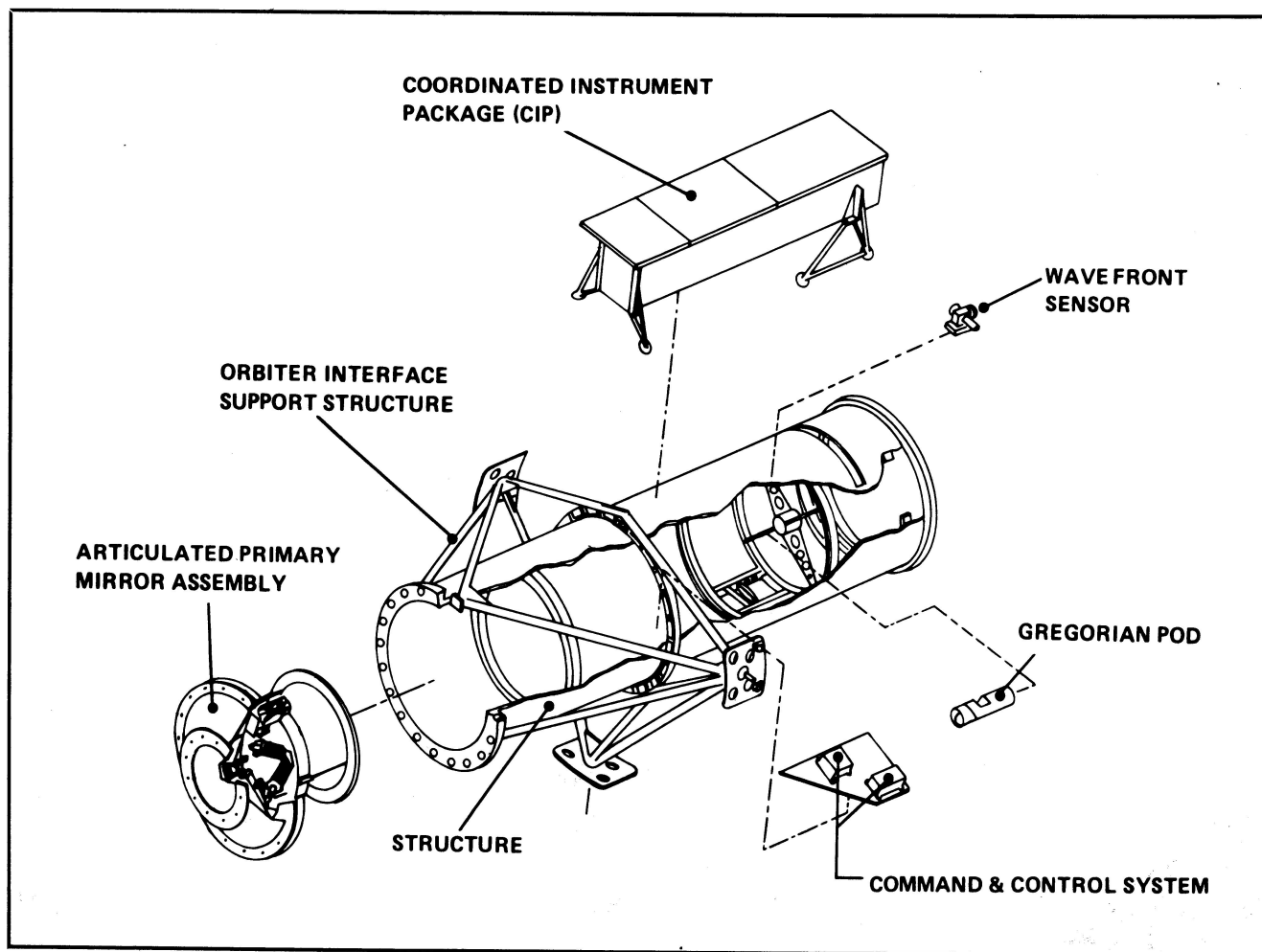
An on-axis Gregorian optical system was chosen for the Solar Optical Telescope because a field-stop and heat-rejection mirror can be located at the prime focus, protecting the subsequent optics from concentrated out-of-the-field solar radiation. A small hole at the center of this heat-rejection mirror allows radiation from about a 3-arc-minute diameter area of the Sun to pass through and impinge on the secondary optics. This area comprises only about 1 percent of the Sun's 32-arc-minute diameter disk. The remainder of the solar energy is radiated away, ultimately out of the front end of the telescope. Rejection of 99 percent of the incident solar radiation in this way greatly reduces the tendency for ambient impurities to be baked onto the smaller mirrors in the telescope, thus greatly enhancing performance in the ultraviolet. Careful attention to cleanliness, combined with this Gregorian design, will provide the greatest possible sensitivity at all wavelengths.

The Facility — Science Management, Contamination Control and Accessibility to the Instruments

To realize the exciting scientific goals of the Solar Optical Telescope, the solar physics community and NASA, working together, have developed a facility concept for the program. In practice, this concept will ensure that the telescope and its science instruments will be developed under NASA management for the solar physics community as a whole. The facility consists of the telescope and these science instruments. The scientific goals for the facility have been set by the Science Working Group (SWG), which comprises the Project Scientist at GSFC, the Program Scientist from NASA Headquarters, the two Principal Investigators, six Facility Scientists selected from the worldwide solar community, and one Telescope Scientist, who will monitor the development of the telescope. In addition, the Announcement of Opportunity (AO), on which the selection of the general SWG membership was based, also specified that some of the observing time should be set aside for guest investigators, to be selected from the broadly based solar community at a later date. The SWG and NASA will jointly plan the Guest Investigator Program for the first flight of the facility. NASA is also developing plans for further flights of the facility, and an even more extensive participation by the

scientific community is expected on these later flights.

The configuration of the Solar Optical Telescope Facility, which is illustrated on this page, has evolved, after extensive studies, into a closed cylindrical shell. This configuration appears to be optimum when weight, stiffness, mechanical resonances, thermal conditioning, minimization of contamination, and accessibility are all considered together. This shell—the inner cylinder in the illustration—houses the telescope optics, mechanisms, and sensors. It is also designed to support the science instruments, which are mounted externally onto the shell. Optimum contamination control is provided by enclosing the telescope optics within the inner, closed cylindrical shell. Optimum accessibility to the science instruments is achieved by mounting them externally to this inner structural shell. To further facilitate access to the instruments, the outer cylinder is a lightweight nonstructural thermal shroud composed of 24 individual removeable panels. The overall dimensions of the facility envelope are 7.3 meters in length and 4.4 meters in diameter (outer cylinder). Thus, the requirements for adding further science instruments to the facility for future flights have already been incorporated into this design.



The Scientific Instruments — A Coordinated Instrument Package for Unlocking the Sun's Secrets

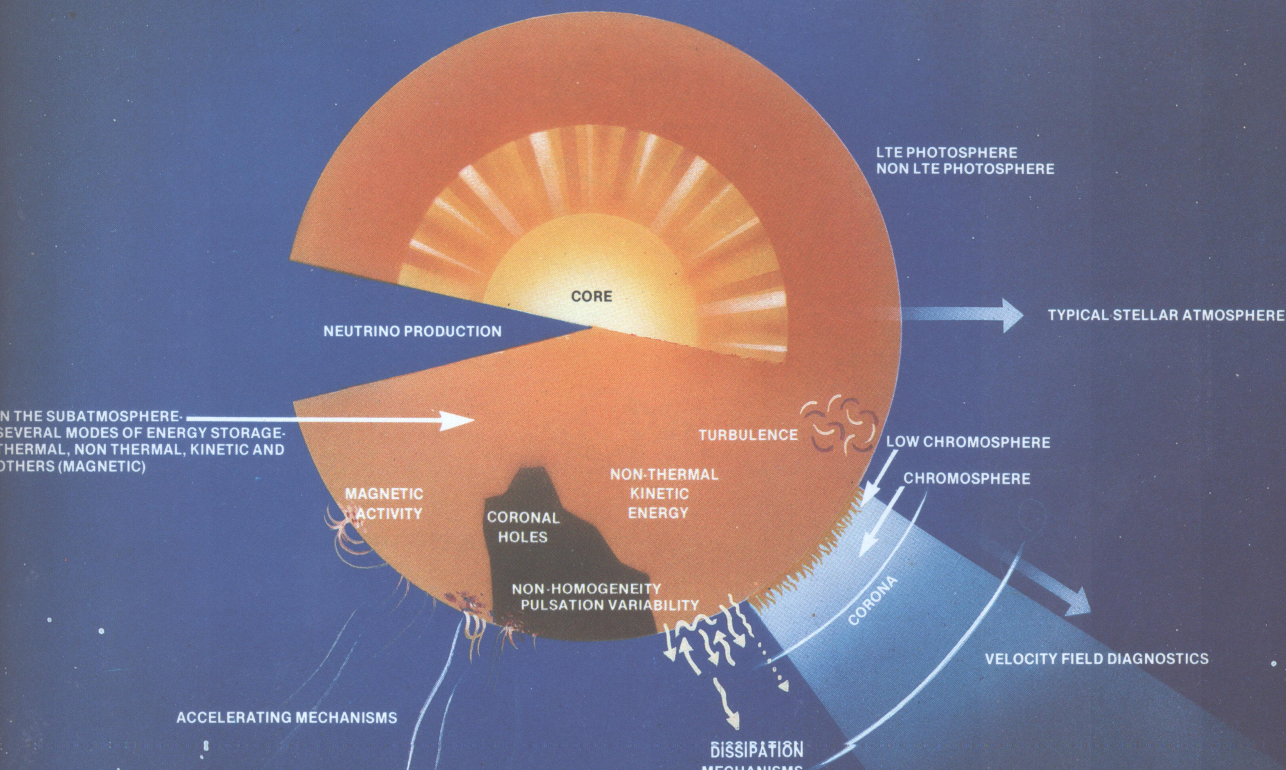
In order to understand the dynamic solar atmosphere, scientific instruments are needed that can transform the sunlight collected by the telescope into spectra and images of very high resolution. Only in this way can solar scientists determine values for densities, temperatures, velocities, and magnetic field strengths in the atmosphere, and only in this way can they demonstrate what physical processes are responsible for producing the local magnetic fields, heating the atmosphere, and accelerating the solar wind. Thus, the scientific instruments that operate with the telescope are the key to producing science data in the form needed to unlock many of the Sun's remaining mysteries.

Two science instruments were selected for the first flight of the Solar Optical Telescope, using the NASA AO process of peer review. These are (1) a coordinated filtergraph/spectrograph (CFS) proposed by the Lockheed Palo Alto Research Laboratory (LPARL), and (2) a photometric filtergraph instrument (PFI) proposed by the California Institute of Technology. The CFS consists of a visible-light tunable filtergraph/polarimeter, a visible spectrograph, and an ultraviolet spectrograph, along with a correlation tracker for maintaining image stability. The PFI consists of two film cameras that operate with film that is sensitive to visible light and in the near ultraviolet down to 2200 Å. The PFI will be combined with the CFS to form a single focal-plane instrument, the coordinated instrument package (CIP), which will be built by the LPARL group. The illustration on page 16 shows the layout of the CIP. Note that the visible and ultraviolet spectrographs form one major integrated component.

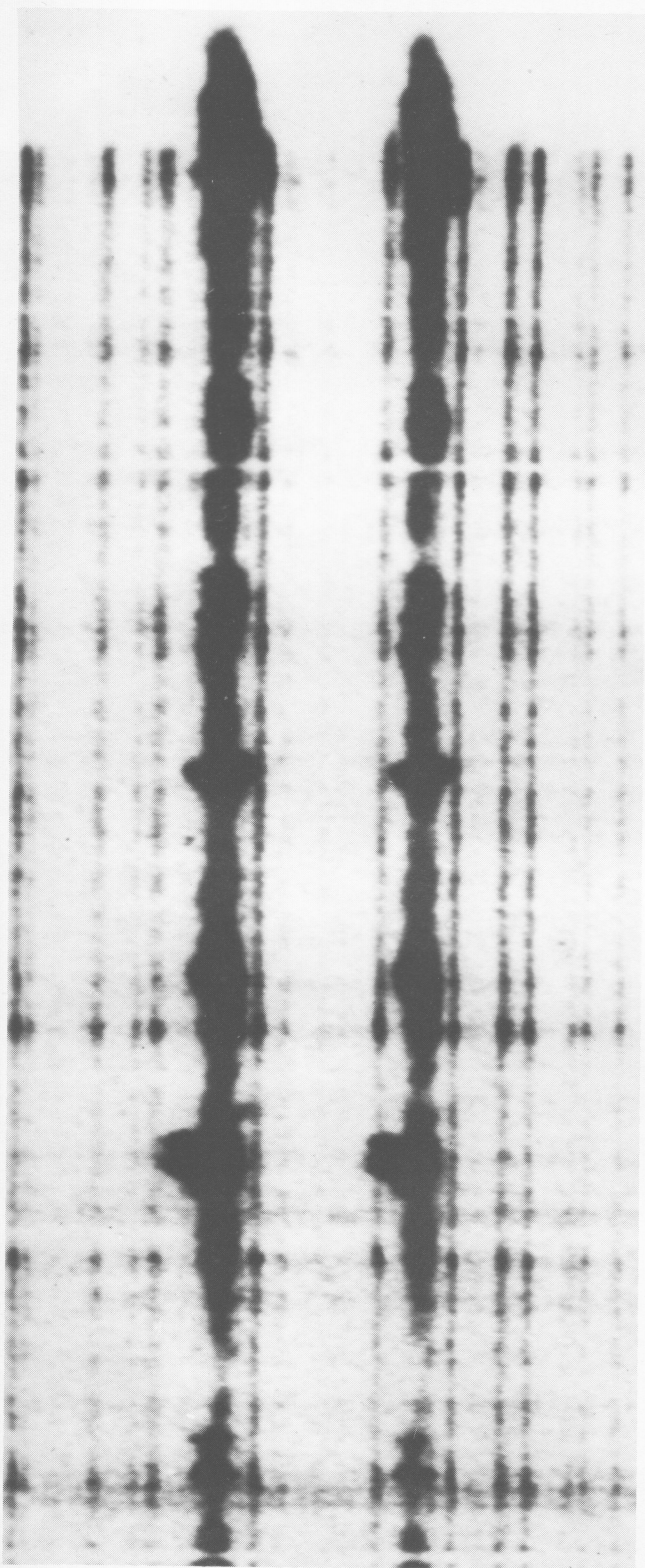
The CIP will be particularly well suited for obtaining ultra-high-resolution images and magnetograms for studying the Sun's magnetic field. It will also obtain high-resolution spectra needed for diagnosing local values of temperature, density,

and velocity in the solar atmosphere. Only when all of these data are obtained together over a broad range in atmospheric height can one perform adequate studies of the fundamental physical processes taking place. To achieve this, the imaging data, such as magnetograms and photographs, can be obtained simultaneously with either visible or ultraviolet spectra, and the switching between the visible and ultraviolet spectrographs is rapid. In this way, it will be possible to study how physical processes in the lower solar atmosphere (photosphere) are coupled, through magnetic fields, waves, and bulk motions, to conditions in the outer atmosphere (chromosphere, transition region, corona). Operationally, the CIP can operate in either of two modes: (1) the direct mode in which the entrance beam from the telescope goes directly to the two filtergraphs and does not strike the entrance slit of the spectrograph; and (2) the slit-jaw mode in which the beam strikes the entrance slit and the polished slit jaw reflects most of the beam to the filtergraphs, thus allowing spectra and imaging data to be obtained simultaneously.

An important element of the CIP feed optics is the correlation tracker. Images recorded by the CCD camera of the filtergraph will be read into an image processor that can process them in near-real time. By tracking patterns of variable-contrast features, such as the granulation, in the field of view observed, the correlation tracker can detect shifts in the image field and provide signals for image stabilization, through servoing mirror M4 in the illustration on page 16. This capability is vital to obtaining magnetograms of high quality near the resolution limit of the telescope, because magnetograms are made by subtracting sequential right- and left-polarized images in the image processor. Since the difference between the two images will be small, it is extremely important that the solar image remain stable during the recording of the two images. The correlation tracker will do this.



Parameters of the Coordinated Instrument Package



Spectra of much higher resolution than 1 sec are needed for dynamical studies.

The photographic filtergraph will consist of feed optics, beam-steering optics, and two film cameras, each with its own filter wheel. The general characteristics of the photometric filtergraph are:

Spectral range: 2200 to 8000 Å

Spectral bandpass (FWHM): 0.4 to 200 Å, depending on filters

Field of view: 120 by 160 arc-seconds

Spatial resolution (on axis): Diffraction limit of the telescope

Typical exposure: 0.1 to 10 seconds

The tunable filtergraph will consist of a beam distributor, blocking filters, a tunable red filter, and two CCD cameras of array size to be determined by the availability of CCD chips. (Either 800 by 800 or 1024 by 1024 arrays will be used.) The tunable filtergraph has the following general characteristics:

Spectral range: 4600 to 7600 Å

Spectral bandpass (FWHM): 0.04 Å at 4600 Å, 0.125 Å at 7600 Å

Field of view (for 1024 by 1024 CCD array)

Background camera: 122 by 122 arc-seconds
High-resolution camera: 61 by 61 arc-seconds

Spatial resolution (on-axis)

Background camera: 0.24 arc-second/pixel
High-resolution camera: 0.06 arc-second/pixel

Typical exposure: 1 second

Polarization analyses: RCP, LCP, linear

The spectrograph system will consist of a slit jaw, a reimaging mirror, a collimator assembly, visible and ultraviolet gratings mounted on a carousel, a Schmidt camera mirror, and two focal planes with four CCD cameras in the visible focal plane and two CCD cameras in the ultraviolet focal plane. The general characteristics of the spectrograph system are:

Spectral range

Visible: 2800 to 10,000 Å
Ultraviolet: 1200 to 2000 Å

Spectral bandpass (FWHM)

Visible: 0.004 Å at 2800 Å, 0.016 Å at 10,000 Å
Ultraviolet: 0.03 Å at 1200 Å, 0.06 Å at 2000 Å

Field of view (slit size): 61 by 0.08 arc-seconds

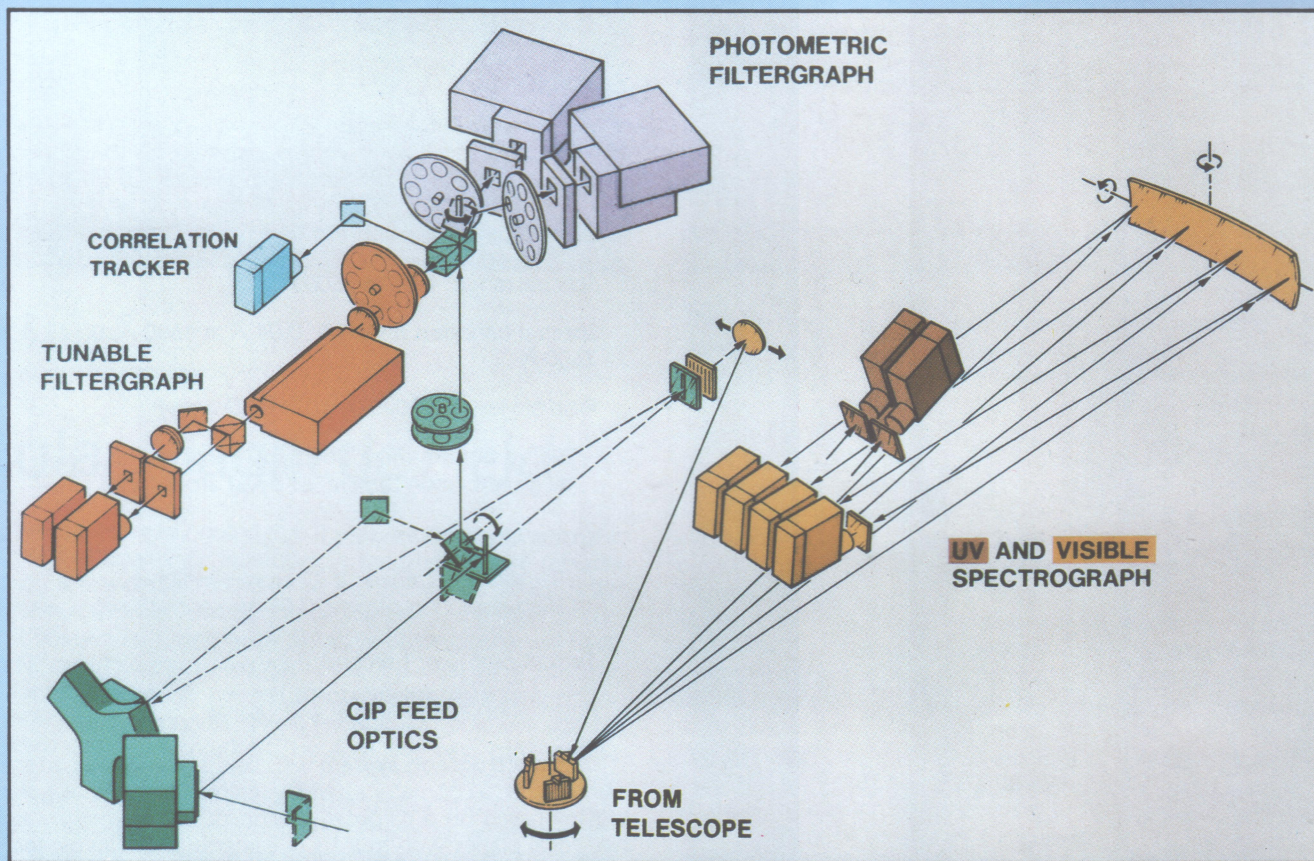
Spatial resolution (on axis): 0.08 arc-second/pixel

Typical exposure: 0.001 to 10 seconds

Polarization analyses: RCP, LCP, linear

Coordinated Instrument Package

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Science Operations from the Shuttle

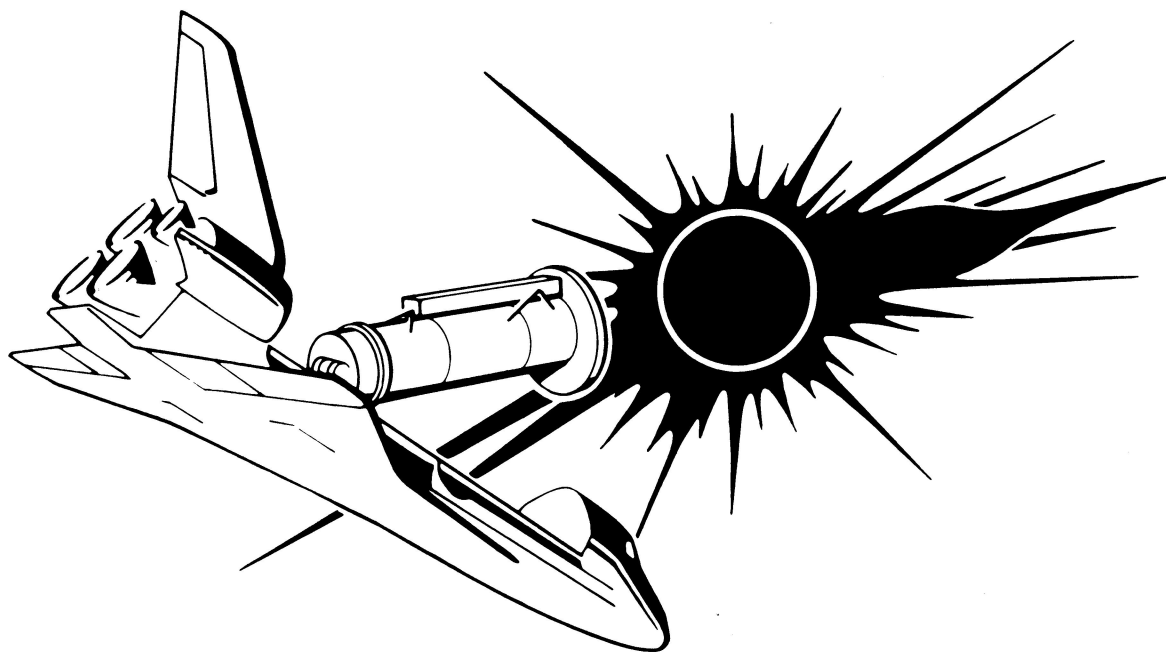
The Solar Optical Telescope will be the largest science facility that NASA currently plans to operate from the Shuttle. It will follow in the footsteps of, and benefit from the precedent of, the highly successful solar experiments carried on the manned Skylab in 1973. The instruments on Skylab were deployed and pointed by a large solar-oriented assembly called the Apollo Telescope Mount. The solar experiments were performed by astronauts housed in the Skylab who maintained voice contact with scientists on the ground at the Johnson Space Center. In many respects, the operation of the Solar Optical Telescope will be similar, with Payload and Mission Specialists on board the Orbiter performing much of the "hands-on" implementation of experiments, while scientists on the ground determine which experiments or observing programs should be performed. However, there will be two significant differences between these two missions favoring the Solar Optical Telescope. The spatial resolution, or magnifying power, of the Solar Optical Telescope will typically be a factor of 30 to 50 higher than that provided by the Skylab experiments, and the rate at which scientific data can be collected by the new telescope and its detectors will greatly exceed that of the digital recorders on Skylab.

Launch and operation of the Solar Optical Telescope on the Shuttle is scheduled for the early 1990's. An Instrument Pointing System attached to the Shuttle by means of a Spacelab pallet will point the telescope, and maximum use of Shuttle and Spacelab standard support subsystems is envisioned. The first flight is planned as a 7-day mission, during which more than 10^{12} digital data bits and 50,000 frames of film will be accumulated during approximately 100 hours of actual scientific data collection. To maximize solar observing time, a high-inclination orbit will be sought. The anticipated Orbiter attitude is a modification of one of the NASA standard three-axis stabilized attitudes in which the longitudinal axis of the Orbiter

is perpendicular to the orbital plane and the Orbiter's three principal axes maintain a constant orientation, less orbital precession, with respect to a nonrotating coordinate system centered on the Earth. The Tracking and Data Relay Satellite (TDRS) Ku-band link will be used for data Transmission to ground.

Command and control of the telescope and the science instruments can be accomplished both on board and from the ground. As noted, onboard commands are implemented by Payload and Mission specialists from the Orbiter Aft Flight Deck, and ground-based commands will originate in a Payload Operations Control Center (POCC). Because the TDRS link will permit near-real-time two-way communications between the Orbiter and the POCC, near-real-time data assessment and command response from the ground will be possible for much of the mission. The experiment command software will consist of a reasonable number of high-level commands that will actuate entire observing programs, along with the constituent "building-block" programs from which modified high-level commands can be constructed in rapid response to existing observational opportunities. This optimizes the joining of a basic, simple scientific timeline with some flexibility to meet changing conditions, a lesson learned during the solar observations from Skylab.

Video-disk recording of the digital science data is tentatively planned, pending further studies of anticipated technical advances in this field, which will include an assessment of general availability of high-quality video-disk readers to the scientific user community. If implemented as planned, guest investigators will receive the disks from the experimenters and/or NASA and will perform their scientific investigations at their home institutions, using their locally available video-disk readers and their own scientific software and computer facilities.



The Dynamic Solar Atmosphere

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Only within the past few decades, thanks in part to observations made from space, has the dynamic character of the solar atmosphere been revealed in its presently known aspects. The ubiquity of plasma motions observed thus far has revealed both a great diversity of phenomena and a staggering complexity of structure, as well as many hints of an underlying and unifying picture of the basic physical processes that are occurring. A good example of this complexity which suggests unity is the currently known, but poorly understood, picture of the Sun's magnetic field. All of the diverse solar features whose properties are clearly strongly influenced, if not determined, by the magnetic field may ultimately depend on the detailed characteristics of the subsurface dynamo which generates that field. To penetrate to a better understanding of both the individual features and of the underlying physical processes that produce them, many examples are given here to show that observations on the small scales for energy transfer by radiation and gas motions in the solar atmosphere are necessary.

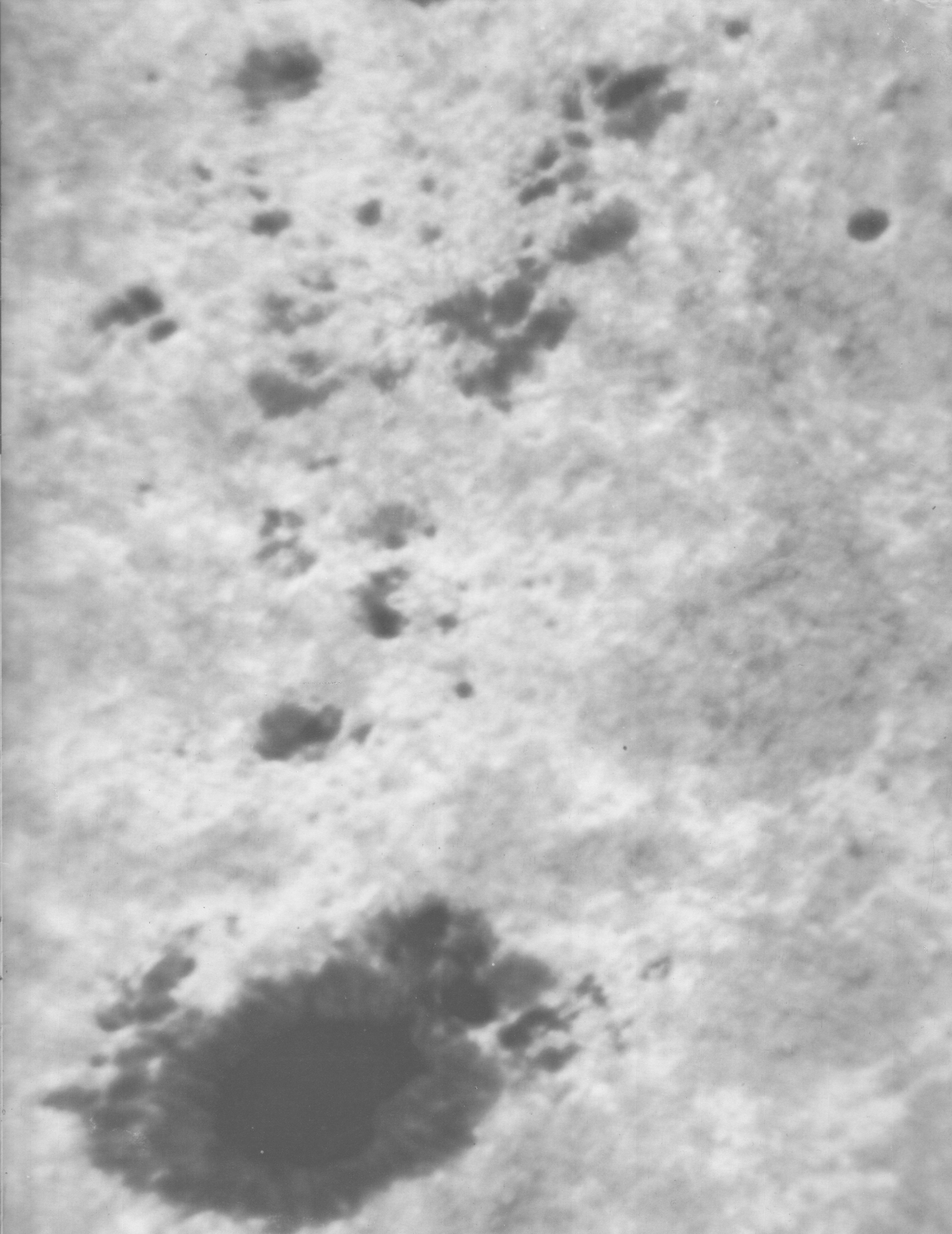
The illustration on page 19 reveals some of the features in the solar atmosphere that the Solar Optical Telescope will help us to understand. The sunspot in the lower left-hand corner has a structured magnetic field of several thousand gauss. Why the magnetic field is stable on this scale, as well as on the scale of the smallest bright elements lying outside the spot, is a

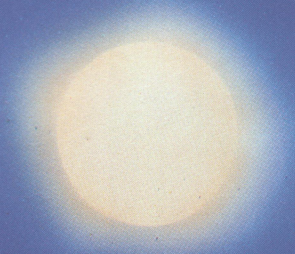
question that we need to answer in order to understand solar and stellar magnetism. We also need to know the dynamics (movement) of the magnetic field elements both in the large area of bright emission (known as an active region) and outside this area, particularly on the boundary, because this movement is related to the type of dynamo that generates the field.

In the lower right-hand side of the photograph appear several approximately circular regions of "quiet" atmosphere surrounded by rings of bright emission. These are the supergranulation cells, whose dynamics will influence the diffusion of the magnetic field across the solar surface and whose internal motions are a signature of subsurface convection. Within these cells, we see a mottled appearance, with bright specks of emission showing up here and there. Perhaps these specks are the rising elements called bright granules that have overshoot the upper boundary of the turbulent convective region, or perhaps they are rising wave trains generated by lower lying granulation that is already beginning to dump energy into the atmosphere as weak shocks.

These and other solar phenomena that occur on scales too small to be observed with contemporary solar instruments can be studied adequately only with the capabilities of the Solar Optical Telescope.

Ground-based photograph of large sunspot and associated atmospheric structures.





Summary

THE SOLAR OPTICAL TELESCOPE WILL . . .

- STUDY THE PHYSICS OF THE SUN ON THE SCALE AT WHICH MANY OF THE PHYSICAL PROCESSES OCCUR
- ADVANCE OUR FUNDAMENTAL KNOWLEDGE OF MANY SOLAR ASTROPHYSICAL PROCESSES
 - magnetic fields
 - convective energy transport
 - atmospheric heating
 - atmospheric dynamics
 - flares
- PROVIDE THE KNOWLEDGE NEEDED TO UNDERSTAND MANY FUNDAMENTAL ASTROPHYSICAL PROCESSES ON OTHER STARS
- OPERATE FROM THE SHUTTLE AS NASA'S MAJOR SOLAR FACILITY FOR THE EARLY 1990'S

Looking Ahead

- THE SOLAR OPTICAL TELESCOPE BECOMES THE NUCLEUS OF AN ADVANCED SOLAR OBSERVATORY ON THE SPACE STATION.

Acknowledgments

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