

A golden age for solar physics

New space probes—and a possible journey to the Sun—will maintain the fast pace of major advances in our understanding of the Sun's interior, coronae, winds, magnetic explosions and cycles of activity.

Arthur B. C. Walker Jr

The Sun occupies a unique position in astrophysics, because it is the only star we can examine in sufficient detail to learn about stellar phenomena at the level of the basic underlying atomic physics, nuclear physics, plasma physics and magnetohydrodynamics. Ongoing solar research affects a large number of models and theories of

stellar phenomena. These include the fundamental theory of the generation of thermonuclear energy in stars, theories of energy transport in stellar envelopes, models of stellar structure and evolution, theories of stellar rotation and cycles of activity, models of stellar winds and coronae, and theories of stellar magnetism and the explosive

release of stored magnetic energy, which accelerates particles to energies of billions of electron volts per nucleon.

We have greatly enhanced our understanding of these phenomena in various astrophysical contexts by comparing their solar and nonsolar manifestations. The solar observations allow us to study the phenomena in



considerable detail for a particular set of the basic stellar parameters—density, radius, rotation rate and chemical composition. The nonsolar observations allow us to determine how the phenomena are modified when these parameters vary.

This close connection between solar and nonsolar astrophysics was strongly emphasized by the Solar Physics Working Group of the National Academy of Sciences' Astronomy Survey Committee, whose recent study focused primarily on astronomy and astrophysics. Indeed, the Solar Physics Working Group concluded¹ that solar physics can be thought of as "a fundamental inquiry into the physics of the large-scale behavior of ionized gases in gravitational and electromagnetic fields."

However, it is also important to stress the Sun's fundamental role in shaping the interplanetary space within the solar system—the region known as the heliosphere. The heliosphere, and its interactions with planetary magnetospheres, ionospheres and atmospheres, is the subject of the discipline of space physics. And, as we shall see, the connection between solar physics and space physics is no less profound and fundamental than is the connection between solar physics and astrophysics.

Finally, the Sun and its variations² have a strong influence on Earth's ecosystem, and hence on humans. Life on Earth is possible only because of the Sun, and our lives depend principally on the use of solar energy, either stored or ambient.

In this article I will discuss the state of our knowledge in each of the major areas of solar physics. An examination of the outstanding scientific problems will give us an idea as to the direction of solar physics research in the next ten years. I will review the conclusions and recommendation of the Solar Physics Working Group¹ and its parent, the Astronomy Survey Committee,³ concerning the observational and theoretical programs that appear most likely to be scientifically productive. Let us begin with a look at the major themes of solar physics research and the major discoveries of the last decade.

Themes and discoveries

The discoveries of the past decade, and the new opportunities that technology such as large computers and the

A solar flare is the result of the explosive release of magnetic energy. This flare-associated eruption is seen in the light of the Lyman α line of helium II, at 304 Å. The photograph was made from Skylab with the Naval Research Laboratory's Objective Grating Spectroheliograph. (Photograph courtesy of Guenter Bruckner, Naval Research Laboratory.)

Figure 1

Space Shuttle have opened up in this decade, suggest that the following are potentially the most productive areas for concentration in the next decade:

- The development of observational techniques to probe the generation and transport of energy and the compositions and motion of the Sun's interior, thereby providing direct experimental tests of models of stellar energy generation, structure and evolution
- The study of the various "active phenomena" such as sunspots, the magnetic cycle, the corona, the solar wind and solar flares (see figure 1), and similar phenomena recently discovered on other stars; and the development of a comprehensive theory of the stellar rotation, magnetism and activity cycles that underlie these phenomena
- The study of the three-dimensional structure and dynamics of the heliosphere, and of its interaction with the interstellar medium and with planetary atmospheres and magnetospheres. As we pointed out above, this last theme includes the study of the nature of and the reasons for the correlation between variations in the heliosphere and climatic conditions on Earth.

In solar physics, major advances often arise when previously observed phenomena are studied at higher angular resolution or at a new wavelength that carries information from material of a different temperature. An example of this type of discovery is the realization that magnetic fields on the Sun are most likely composed of individual flux tubes with field strengths exceeding 1000 gauss. These tubes exist on a scale finer than can be resolved with present instruments, which have a resolution of about 200 kilometers. The magnetic structure of the solar surface depends, therefore, on the number density of these individual flux tubes rather than on the average field strength over the surface.

There are also major discoveries that depend on phenomena that manifest themselves only as subtle perturbations of basic solar properties. An example is the discovery that the "5-minute" oscillations of the solar atmosphere, which manifest themselves as small but systematic patterns in the velocity field at the photosphere, constitute a global phenomenon. The frequencies of the global oscillations put a complementary set of constraints on solar structure and ultimately may allow us to deduce the complete interior structure of the Sun. While the discoveries of flux tubes and oscillations challenge our understanding of the physics of stars, they give us an opportunity to make critical observational tests of stellar models.

Other major discoveries and achievements of the last decade that have

New instruments for astronomy

shaped our perception of the major problems to be addressed in the 1980s include:

- The direct study of the thermonuclear processes occurring in the solar core by the measurement of the accompanying flux of neutrinos. The disagreement between the observed and the predicted neutrino fluxes has caused researchers to reexamine models of the Sun's interior and to plan new measurements that have more definitive interpretations.
- The discovery that the damping of solar atmospheric waves driven by convection cannot account for the energy required to heat the corona and drive the solar wind. The observation of coronal phenomena in main-sequence stars in every part of the Hertzsprung–Russell diagram has reinforced the conclusion, drawn from solar observations, that magnetic effects underlie active phenomena in stellar atmospheres.
- The confirmation that the sunspot cycle and related phenomena of the solar activity cycle were largely absent for a period of 70 years in the seventeenth century. This episode is known as the Maunder Minimum. We now know that such periods of inactivity, as well as periods of hyperactivity, occur quasiregularly. Until recently it was assumed that the solar activity cycle² did not involve a sufficient change in the output of solar energy to affect the Earth's lower atmosphere and hence the weather and life on Earth (notwithstanding the many attempts to link the sunspot cycle to phenomena ranging from droughts to the condition of the stock market). However, solar scientists have now found² that there are correlations between solar activity and climate over periods of hundreds of years to millennia, although the fundamental causes of these correlations are not yet understood. Solar physics' connection with climate is certainly as important as its connections with astrophysics and space physics.
- The recognition that the energy released during the impulsive phase of a solar flare is largely or entirely contained in energetic particles accelerated during magnetic reconnection in the coronal field.
- The demonstration that the large-scale solar magnetic field is organized into two distinct types of structures: magnetically closed regions in which hot plasma confined in loops largely generates the x-ray corona, and magne-

tically open regions, or "coronal holes," which are the source of high-speed streams in the solar wind (figure 2).

This brief list of major new discoveries in solar physics serves to illustrate that although the Sun has been the subject of scientific study since the time of Galileo, solar physics—no less than other disciplines of astrophysics—is in a golden age of discovery.

Solar physics in the 1980s

The canonical models of stellar structure have been remarkably successful in explaining the fundamental properties of young stars, that is, the relation between temperature and luminosity for a star of given mass and chemical composition. These models are also successful in predicting the properties of evolved stars, which can be studied by observing the temperature-luminosity relationship (that is, the Hertzsprung-Russell diagram) of star clusters of various ages. However, detailed observational tests of stellar models have not been possible in the past. The first such detailed test was the direct measurement of the flux of high-energy solar neutrinos from the decay of excited boron-8 nuclei, which are an intermediate product of one of the branches of the proton-proton thermonuclear cycle from which the Sun derives its energy. The result was a measured flux only 30% of that predicted. One possible explanation of the discrepancy is that neutrinos have mass, and therefore, according to theory, oscillate between electron-neutrino, muon-neutrino and tau-neutrino states. Only particles in the electron-neutrino state would be counted by the chlorine-37 radiochemical detector used in the solar neutrino experiment.

However, if the present theory of the massless neutrino is correct, the assumptions of the canonical models of stellar structure and evolution may require significant revision. Among the alternative models that have been proposed are: models in which the assumption of uniform initial composition is relaxed; models that assume significant mixing of the stellar core in which thermonuclear reactions occur; models in which there is a rapidly rotating core; and models in which there is a large primordial magnetic field in the core. To decide which, if any, of these alternative stellar models is correct, it is necessary to compare their detailed predictions with observations. We must test the predicted variation with radius of such properties as temperature, density, rotation rate and composition, and the rates for the

Solar corona and coronal hole reflect the complexity of the Sun's magnetic field. This x-ray photograph of the Sun, taken 21 August 1973 with the American Science and Engineering instrument on Skylab, shows large coronal loop structures and many small bright knots thought to be loops that are too small to be resolved. A large coronal hole extending from the north pole across the equator is plainly visible. (Photograph courtesy of Allen S. Kreiger, American Science and Engineering.) Figure 2



various branch reactions of the proton-proton cycle. While we have three techniques for making such detailed comparisons for the Sun, it is not at present possible to do so for any other astrophysical object. One technique is to use a close gravitational probe to determine the detailed structure of the Sun's gravitational field. Another is to study the Sun's global oscillations. The third technique is to measure the solar neutrino flux with a series of radiochemical detectors sensitive to neutrinos of different energies.

The solar cycle. The solar activity cycle, as manifested by the eleven-year variation in the number of sunspots, has been observed systematically for about 350 years. The intensity of the activity cycle, as measured by its peak annual mean sunspot count, has fluctuated by $\pm 30\%$ over this period. However, commencing around 1630–40, the sunspot count normally associated with the activity cycle's minimum persisted for approximately 70 years, as a graph of the number of sunspots versus the year shows clearly (see Gordon Newkirk Jr and Kendrick Frazier's article on the solar cycle, *PHYSICS TODAY*, April, page 25). During this period, in which there should have been seven cycles, the annual mean sunspot count did not exceed 10, which is only about 10% of the count associated with an average peak in the cycle. This period of abnormally low sunspot activity, the Maunder Minimum, was not a singular event. The level of solar activity over the past 5000 years, as derived from the study of the rate at which C^{14} is produced in the atmosphere and preserved in tree rings (C^{14} production is anticorrelated with solar activity), shows² six episodes of depressed activity and five episodes of elevated activity, each lasting approximately 100 years. Not only are periods of enhanced or depressed solar activity

frequent, they are well correlated with climatic conditions on Earth.

It is generally agreed that the activity cycle of the Sun is a magnetic phenomenon, caused by the interaction of convection and differential rotation. Convection is responsible for the transport of energy in the outer layers of the Sun; differential rotation refers to the fact that the Sun rotates more rapidly at its equator than near its poles. The interaction between the two causes the large-scale field of the Sun to vary from a predominantly polar field at sunspot minimum, to a toroidal field at sunspot maximum. The toroidal field in turn causes the eruption of magnetic flux through the solar surface at mid-latitudes. The sunspots, which are the aforementioned regions of locally strong magnetic field, appear dark because the strong field inhibits convective energy transport, thereby lowering the temperature by more than 1000 K.

Theoretical studies of the Sun's hydromagnetic structure involving any of a number of combinations of convection and nonuniform internal rotation can produce magnetic fields whose calculated behavior at the surface of the Sun mimics the migrations and reversals of the fields actually observed there. Further progress in the theory of stellar magnetic cycles awaits the development of a dynamical theory of convection and circulation in the stratified envelope of a spinning star. Such a theory would show which of the many "plausible" fluid motions consistent with the generation of stellar fields is the motion that actually occurs.

Progress in this direction depends upon the continuing studies of activity cycles in other stars to determine the range of variation to be expected. More directly, progress depends upon observing the large-scale circulation at the surface of the Sun, expected to be some

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1–100 m/sec, and the well-known non-uniform rotation of the Sun, so that theorists will be able to check their dynamical models as they are developed. An additional and equally important observational study involves the splitting of both the pressure and gravity modes of the Sun's global oscillations, from which we may deduce the rate of change of angular velocity with depth. It is essential to know how angular velocity varies with depth as a check on the dynamical theory; this information enters directly into the dynamo equations that determine the form and behavior of the magnetic fields. Therefore, the newly emerging field of solar seismology,² which is the study of the global oscillation modes of the Sun, is critical to further progress in modeling stellar activity.

Beyond this immediate problem of the dynamical theory of stellar magnetic cycles is the fascinating and more difficult problem posed by the long-term changes in the level of solar activity, such as the Maunder Minimum.

Stellar coronae and winds. Figure 2 is an x-ray photograph of the solar corona, taken during the manned Skylab space mission. This photograph reveals many of the characteristics of the corona that are presently the subject of intense study. The corona emits x rays because of its high temperature. Material ranges in temperature from 1.5×10^6 K to 6×10^6 K in the magnetically confined coronal loops (see figure 3), which have lifetimes of hours or days. The large areas of low x-ray emission are called "coronal holes" and are characterized by open magnetic field geometries, in contrast to the closed field geometries that characterize the "active regions" of high x-ray emission. The solar wind is hot plasma that is flowing away from the Sun because of the expansion of the corona. It originates predominantly in the open-field coronal hole regions. It is widely believed that the corona and the solar wind are powered principally by the conversion of magnetic energy, but the details of the energy and mass transport between the photosphere and the corona are not well understood.

To identify and model the mechanisms responsible for the transport of energy and mass in the outer solar atmosphere, we must be able to study the fine-scale structures that are controlled by the magnetic field. Ultimately, this will require observations on a scale of tens of kilometers. At present, the best resolution attainable is about 200 km, or 0.2–0.3 arc seconds as viewed from Earth, and even this is achieved only rarely. The Solar Optical Telescope, a 1.25-m visible-ultraviolet telescope that operates at the diffraction limit, is scheduled to be put

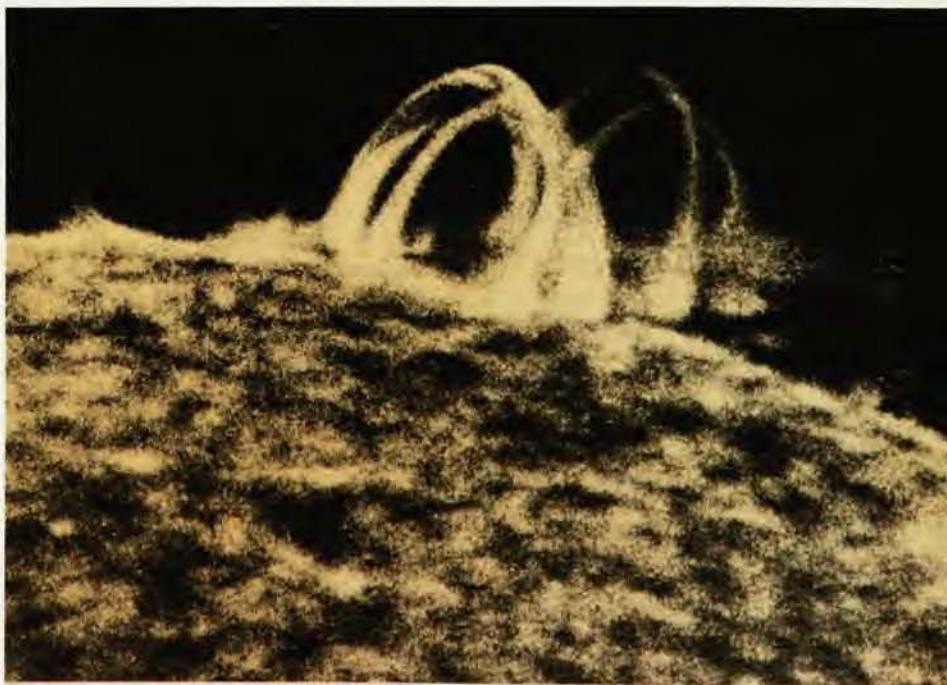
into operation by the Space Shuttle in 1989 (PHYSICS TODAY, September, page 17). This will be the first of a series of major solar facilities that can provide the observational data base required to address the problem of the structure and dynamics of the solar atmosphere at the level of the basic plasma physics and magnetohydrodynamics that govern the movement of energy and mass. Figure 4 illustrates the complex nature of these phenomena. It shows a field of structures called spicules, which are thought to be tubes of magnetic flux containing upwardly moving gas. The role spicules play in heating and populating the corona and the solar wind is not understood because these structures are at the limit of the resolving power of present instruments. We will not be able to study their interior dynamics until the Solar Optical Telescope becomes operational.

Figure 5 is an x-ray photograph of the Hyades star cluster,⁴ obtained by the Einstein x-ray observatory. It illustrates the fact that stellar coronae, and presumably stellar winds, are quite common features of stars. In fact, the Hyades dwarf G (solar type) stars have coronae whose x-ray emission is typically 30 times brighter than that of the Sun. The Einstein results⁵ strongly suggest a correlation between age and x-ray luminosity for stars like the Sun, which have convective envelopes. Younger stars, such as the Hyades

(about 10^9 years old), rotate more rapidly and presumably have stronger magnetic fields. Older stars, such as the Sun (about 5×10^9 years old), rotate more slowly because the braking action of their stellar winds has operated over a long period. This correlation appears to confirm the conclusion drawn from solar observations that stellar coronae and winds are byproducts of stellar magnetic activity. It is clear that the full development of an acceptable model of stellar atmospheres will require a coordinated effort involving both solar and nonsolar observations.

Magnetic explosions. Figure 1 represents one of the more spectacular manifestations of explosive phenomena in the solar atmosphere—the eruption and expulsion of large masses of hot gas. These events are variously called coronal transients or prominences, depending on their characteristics and duration. Such explosive phenomena, including the most well-known of these related events, the solar flare, are manifestations of the impulsive release of stored magnetic energy. It is not unusual for as much as 10^{32} ergs to be released in a period of a few minutes. Similar but even more energetic events are known to occur on other stars.

Despite the complexity of the phenomenon of flares, a conceptual model has recently gained wide acceptance. This model is based on high-resolution observations from the ground and from



Coronal loops have lifetimes of hours or days. These extreme-ultraviolet images of a complex of coronal loops were made from Skylab with the Naval Research Laboratory's Objective Grating Spectroheliograph. The instrument produced a series of overlapping images of the Sun in the light of the strongest emission lines present in the extreme-ultraviolet spectrum of the corona and chromosphere (about 170 Å to 600 Å). The brighter image is in the light of a transition of Ne VII, which is most efficiently excited at temperatures in excess of 500 000 K. (Courtesy Guenter Bruckner.)

Figure 3

the Orbiting Solar Observatory, Skylab, and Solar Maximum Mission spacecraft. The basic elements of the model are as follows.⁶ Prior to the onset of the flare, energy is stored in a current-carrying magnetic field that is in a metastable state. The sudden reconnection of this field releases its free energy, which appears in the form of energetic particles. These particles, mainly electrons in most models, interact with the atmosphere to produce heating and bursts of microwave radiation and hard x rays. The energy flux in this beam is high and leads to the explosive evaporation of the chromosphere, producing a dense plasma of temperature 10^7 K or more. This primary deposition of energy in turn accounts for many subsequently observed flare phenomena, including soft x rays, chromospheric radiation, solar cosmic-ray acceleration and far-ranging coronal mass transients and radio emission. Finally, the coronal region surrounding the initial event is left filled with a magnetically confined hot plasma that emits x-rays. This maintains the decay phase of the flare for hours.

Magnetic reconnection is the central process, both in the laboratory and in astrophysics, for the catastrophic release of the energy stored in a magnetically confined or stressed plasma. An improved understanding of this phenomenon would have important consequences in astrophysics, space physics and laboratory plasma physics. Under a wide variety of conditions, plasma tends to be frozen to magnetic-field lines. However, this constraint is not absolute. If it were, the perfect confinement of plasma would be possible in the laboratory, the Earth's magnetosphere would be isolated from the solar wind, matter would be less likely to escape from evolving stellar systems and there would be no convection in magnetized stars. Quite generally, the constraint breaks down locally in the vicinity of *singular* layers, sometimes called neutral sheets, where the magnetic field is locally orthogonal to an unstable perturbation of the global plasma structure. In the vicinity of these singular regions, the field is freed from the plasma and its inertia, and can rapidly reconnect into a topology that permits the spontaneous relaxation of stresses.

This reconnection, also called magnetic tearing, may occur either gradually or explosively. When it occurs explosively, it can lead to auroral substorms and solar flares. In the laboratory, it can lead to disruptions of the discharge channel in experiments with tokamaks. When it occurs gradually in interstellar space, in stellar convective layers, or on stellar surfaces, the results include the quasistatic but greatly enhanced dissipation of

Spicules are thought to be tubes of magnetic flux containing upwardly moving gas. This offband H α photograph of the solar limb emphasizes these spike-like structures. Spicules appear at the boundaries of large-scale convection cells called supergranules, which have diameters on the order of 20 000 km. Granules are the smallest observed convective structures, and are typically 1000 km across. Photo was obtained with the Vacuum Solar Telescope at Sacramento Peak. (Courtesy Jack Zirker, Sacramento Peak Observatory.) Figure 4



magnetic energy and the rearrangement of the field topology. Initially, accelerated electrons carry most of the energy generated by dynamic magnetic reconnection. These electrons, through collisional and collective-mode heating and bremsstrahlung, provide the observed low-energy and hard-radiation signatures of the classical solar flare.

The magnetic reconnection processes that underlie the explosive phenomena on the Sun are believed to occur on the very small scale of tens of kilometers or less. The processes involve nonthermal high-energy phenomena (particle acceleration), very rapid temporal changes and thermal or quasithermal plasmas ranging in temperature from 10^4 K to 10^8 K. To understand this phenomenon and its many manifestations fully, we need plasma diagnostics capable of very high resolution over the electromagnetic spectrum from low-frequency radio waves to gamma rays. We can achieve this capability by developing a facility containing an ensemble of large telescopes and other specialized instruments that can be placed in orbit and supported by the Space Shuttle. The development of this facility, the Advanced Solar Observatory, is the principal solar-oriented recommendation of the Astronomy Survey Committee.

The 100-AU-radius heliosphere. Exploration of previously unknown regions of our environment ended temporarily when we gained access to Earth's polar regions, its last unexplored land area. We have now resumed exploration of our environment with journeys to the depths of the oceans and into space. Our realization of the vastness and complexity of the heliosphere, the region of space controlled by the Sun, has

greatly expanded our concept of our environment.

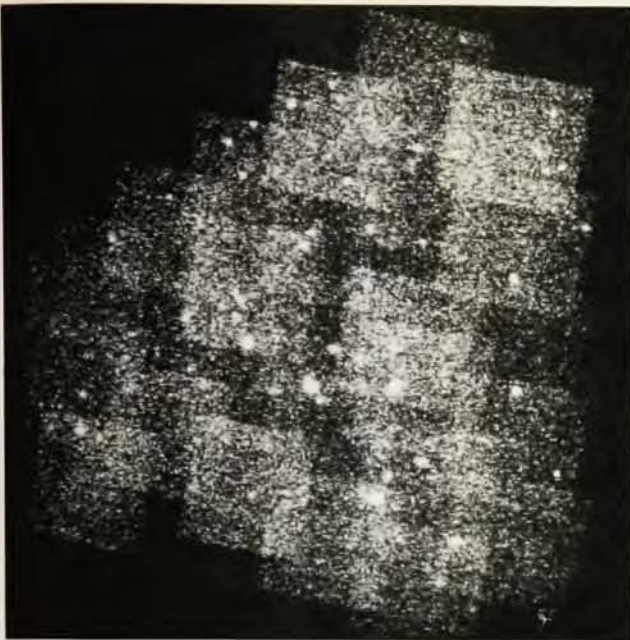
The heliosphere has four principal components:

- the solar wind—an extension of the solar corona, consisting of a thermal plasma flowing supersonically away from the Sun
- a magnetic field—part of the solar magnetic field carried into interplanetary space by the solar wind
- cosmic rays—particles accelerated to high energies in the solar atmosphere (solar cosmic rays), beyond interplanetary space (galactic cosmic rays), within interplanetary space or within planetary magnetospheres
- neutral gas—principally material that flows into interplanetary space from the interstellar medium.

Because the heliosphere is the outermost solar atmosphere, its study represents an integral part of solar physics. The heliosphere terminates with the boundary between the solar wind and the interstellar medium, possibly as far as 100 astronomical units from the Sun.

A collaborative program of coronal observations—most notably on Skylab—and *in situ* observations of plasmas, magnetic fields and energetic particles in interplanetary space has been the key element in our improved understanding of heliospheric structure and dynamics and its relationship to coronal structure and dynamics. During the past decade we have extended the region observed to within the orbit of Mercury and beyond the orbit of Saturn, but always in or near the ecliptic plane.

During the next decade the first observations out of the plane of the ecliptic will greatly accelerate this process of exploration. The Interna-



Mosaic of x-ray images covering the central region of the Hyades star cluster, obtained with the Einstein x-ray observatory. Such x-ray emissions indicate that coronae are a common feature of stars. More than 40 stellar x-ray sources have been identified as members of the Hyades cluster. Each of the individual images making up the mosaic is approximately one-half degree across. (Courtesy of Robert A. Stern, Jet Propulsion Laboratory.) Figure 5

tional Solar Polar Mission and instrumentation on the Solar Coronal Diagnostic Mission will make these measurements, and, for the first time, collect global data on the flow of the solar wind. In the 1990s, these explorations may extend directly into the corona itself, where the solar wind is accelerated. This could be done by a close-encounter space mission—the “Starprobe”—and by an Advanced Solar Observatory, which would make high-resolution observations of coronal transients, particle acceleration, solar wind flow and coronal magnetic structure.

Heliospheric studies will address a number of important scientific questions in the decade of the 1980s. We hope to identify the factors that control the mass and energy balance of the corona, and we hope to understand the implications of these factors for coronal

and solar wind temperature, composition and expansion, and the transport of angular momentum away from the Sun. We will try to determine the nature and dynamical behavior of the three-dimensional structure of the heliosphere, including the role of coronal mass ejection events. And we plan to identify the physical processes responsible for the acceleration of the solar wind and for the large variations in its observed composition.

Recommended programs

Because solar observations play an important role in space physics as well as in astrophysics, a number of observational programs that are important to solar physics fall outside of the domain of the Astronomy Survey Committee. Among these programs are the Starprobe, the Solar Polar Mission and the Advanced Interplanetary Explorer,

which are intended to make *in situ* observations in the heliosphere, and the Interplanetary Laboratory and the Solar Terrestrial Observatory, which are intended to study the Earth's atmosphere and magnetosphere. The Solar Physics Working Group of the Astronomy Survey Committee considered these programs, as we will in this article, so as to present a comprehensive view of solar and heliospheric physics in the next decade. There is a fuller account of the programs in the recent report⁷ of the Committee on Space and Solar Physics, one of the standing committees of the Space Science Board of the National Academy of Sciences.

Each of the various observational programs for solar physics recommended by the Astronomy Survey Committee related to one of the three major scientific themes that we identified earlier: the study of the Sun's interior structure, energy generation and evolution; the study of the Sun's active phenomena and variability, which are evidently manifestations of solar magnetism; and the study of the heliosphere's structure, dynamics and impact on Earth. There are, however, two major space programs, the Advanced Solar Observatory and the Starprobe, that address the full range of scientific questions relevant to the Sun. I will discuss these two programs in more depth later; first I will summarize them along with the other major recommended observational programs.

Solar physicists expect the Advanced Solar Observatory to be the single most important observational facility for solar studies over the next decade and beyond; a program for its development is one of the principal recommendations of the Astronomy Survey Committee. This observatory would be an ensemble of telescopes in space. The telescopes would have a very high

Advanced Solar Observatory. This artist's conception shows two of the observatory's major components being operated aboard the Space Shuttle. The Pinhole/Occluder, with its mask extended on a 50-meter boom, is at the left, and the Solar Optical Telescope is at the right. When the development of the observatory is complete, the large canister in which the telescope is mounted will also accommodate large-aperture gamma-ray, x-ray and extreme-ultraviolet telescopes. (Courtesy of Bill Roberts, Marshall Space Flight Center.) Figure 6



resolution—better than 0.1 arc second, or about 70 km on the Sun—and would be able to observe the solar atmosphere and the inner heliosphere over the full range of temperatures present (6000 K to over 20 million K).

The Starprobe mission is an exciting concept, which aims to send an instrumented probe directly into the solar corona. It would achieve a close encounter with the Sun, coming within 3 solar radii (0.015 AU) of the solar surface. The Starprobe mission would make direct measurements of the structure and dynamical behavior of the inner heliosphere and corona. It would measure the configuration of the Sun's gravitational field, from which we may infer the structure and dynamical state of the solar core, and it would make observations of the solar atmosphere at ultra high resolution—better than 10 km, which is equivalent to 0.01 arc seconds for an Earth-bound telescope.

Two major elements of the Astronomy Survey Committee's recommended program address questions relating to the Sun's interior and evolution. A gallium radiochemical detector would measure the low-energy solar neutrino flux. This flux is directly related to the total rate of thermonuclear reactions between protons in the solar core, the source of most of the Sun's energy. A Solar Interior Dynamics Mission⁸ in space would allow greatly refined measurements of solar oscillations. Both the Advanced Solar Observatory and the Starprobe missions will greatly enhance and extend the information obtained by these two programs.

The Advanced Solar Observatory is the major element of the recommended program to address questions relating to solar activity. However, the ultra-high resolution that Starprobe will achieve during its encounter with the Sun will be important to an ultimate understanding of how the various fine structures in the solar atmosphere—the spicules, magnetic flux tubes, granulation and coronal loops—transport energy and mass from the photosphere to the corona and solar wind.

As we will see below, many of the elements of the proposed Advanced Solar Observatory would first be deployed individually or in small groups on the Space Shuttle or on a space platform or station. Later these elements would be assembled into a long-duration observatory. One such assembly of instruments that has been well defined is the Solar Coronal Diagnostic Mission, which would study the structure, dynamics and evolution of the solar corona, and the origin of the solar wind.

Four major elements of the recommended program are aimed at studying the heliosphere:

► The International Solar Polar Mission was originally intended to explore the heliosphere outside the plane of the ecliptic with two spacecraft, one built by the European Space Agency and one by NASA. Although significantly downgraded by the cancellation of the NASA spacecraft, the mission will still be the first direct exploration of the heliosphere in the third dimension. At present, NASA is considering a new space mission—the Solar Interplanetary Satellite—which, if approved, is to be stationed in the Earth's orbit, but 90° behind the Earth in phase. The NASA satellite would be in place by the time of the passage of the European Solar Polar spacecraft over the Sun's pole in 1989. The Solar Interplanetary Satellite can achieve some, but not all, of the objectives of the cancelled Solar Polar spacecraft.

► The Interplanetary Laboratory is part of a four-spacecraft program called OPEN (Origin of Plasma in the Earth's Neighborhood), and is intended to study the structure and dynamics of the Earth's magnetosphere and its interaction with the solar wind. The Interplanetary Laboratory would be upstream of the magnetosphere—the boundary between the solar wind and the magnetosphere—where it would provide the critical information necessary to understand the interaction between the heliosphere and the magnetosphere. In collaboration with the Advanced Solar Observatory, the Interplanetary Laboratory could relate variations in the heliosphere directly to conditions in the solar corona.

► The Advanced Interplanetary Explorer is an interplanetary satellite that would study the transient high- and low-energy particle populations in the heliosphere. These populations are the result of dynamic and impulsive mechanisms of acceleration that operate in the solar corona. The Advanced Interplanetary Explorer in conjunction with the Advanced Solar Observatory should greatly increase our knowledge of the acceleration and propagation of particles in the corona and heliosphere.

► The Solar Terrestrial Observatory is a facility intended for the Space Shuttle and space platform or station. It would study the variability of the Earth's atmosphere and ionosphere to discover the mechanisms linking that variability to changes in the solar radiative flux and changes in the populations of particles in the heliosphere.

The spacecraft missions outlined above constitute an ambitious program, but one that has been very carefully developed after considerable study and review by the solar physics and space physics communities. Each element in the program addresses a set of fundamental scientific issues in a



Starprobe encounters the Sun. Artist's conception shows the spacecraft's primary thermal shield, which has a central aperture that allows instruments to image the Sun. Other instruments image the back-scattered light of the corona outside the trajectory of the spacecraft. A package of magnetic-field and particle-detection instruments (top) is mounted on a spinning platform at the apex of the volume that remains shaded by the primary shield at perihelion. The final major group of instruments is a drag-free subsystem that allows a precise determination of the spacecraft's orbit. (Courtesy of James Randolph, Jet Propulsion Laboratory.)

Figure 7

unique way, and the various elements operated in concert can greatly enhance the scientific return of the overall program.

The Advanced Solar Observatory

The Advanced Solar Observatory will ultimately consist of an ensemble of four groups of instruments. A High-Resolution Telescope Cluster would contain the Solar Optical Telescope (1100 Å to 10 000 Å), a soft-x-ray telescope (2 Å to 100 Å), an extreme-ultraviolet telescope (500 Å to 1200 Å), an xuv (x-ray-extreme-ultraviolet) telescope (100 Å to 500 Å) and instrumentation that would study the Sun's interior dynamics by observing its oscillations. A Pinhole/Occulter Facility would contain instruments requiring a long focal length (about 50 meters) for external occultation or the high-resolution imaging of hard x rays (energies greater than 10 keV). A High-Energy Facility would make gamma-ray and hard x-ray observations that do not require high angular resolution. Finally, the Advanced Solar Observatory would have a Low Frequency Radio Facility. Figure 6 is an artist's conception of two of these major facilities—the Solar Optical Telescope and the Pinhole/Occulter Facility, as they might appear deployed on the Shuttle.

The Solar Optical Telescope will be the first major solar space instrument to be developed. This telescope will be developed by a consortium consisting of the Perkin-Elmer Corporation and TRW, Inc., under the direction of the NASA Goddard Space Flight Center. It should resolve features as small as 70 km on the Sun in the visible, and even finer features in the ultraviolet. As figure 6 illustrates, the Solar Optical Telescope will be enclosed in a large canister, 3.8 m in diameter, the limiting diameter of the Shuttle cargo bay. It is scheduled for a Shuttle flight in 1989.

The other components of the High-Resolution Telescope Cluster—a 0.8 m soft-x-ray telescope using a grazing incidence mirror, a 0.9-m normal-incidence extreme-ultraviolet telescope, a 0.4-m grazing-incidence xuv telescope and a group of specialized instruments for the study of solar oscillations—will be integrated into a modified Solar Optical Telescope canister as they are developed. Each of these major telescope facilities will be able to resolve features near the 100-km limit. And they will possess extensive spectroscopic capability, allowing the study of line profiles, temperature and density structure, velocity profiles, abundances and other parameters in the various domains of the solar plasma. Together, as the Advanced Solar Observatory High-Resolution Telescope Cluster, these instruments will constitute an

extremely powerful diagnostic tool for the study of the structure and dynamical behavior of a stellar atmosphere.

The second major component of the Advanced Solar Observatory, the Pinhole/Occulter Facility, will use several novel imaging techniques to allow major advances in observational capability in two areas. First, by utilizing the hard x rays (10–100 keV) that are characteristic of the accelerated particles responsible for the initial manifestation of flares, it would be able to image the impulsive phase of flares in the corona. Second, the facility would allow us to study the large-scale structure and dynamics of the corona and solar wind. The Pinhole/Occulter Facility consists of a 50-meter boom (see figure 6) that separates an occulting mask from an array of detectors and telescopes. The mask contains an array of pinholes or small apertures that produce a "transform" x-ray image with the equivalent of 0.2 arc seconds angular resolution. This technique allows imaging at x-ray energies much higher than practicable with grazing-incidence optics. The mask will also contain an occulting element, or "artificial moon," that will create an artificial solar eclipse, allowing the first visible and ultraviolet coronal observations with large-aperture telescopes. This equipment will have significantly higher resolution and sensitivity than coronagraphs on the ground, and it will be able to operate at shorter wavelengths.

The other two components of the Advanced Solar Observatory—the High-Energy Facility and the Low-Frequency Radio Facility—will principally study particle acceleration in the solar atmosphere. According to current plans, once the majority of the component instruments of the Advanced Solar Observatory are developed and tested on the Shuttle, they will be assembled into the observatory on a space platform or station and will operate as a national solar space observatory for a decade or more, much as will the Space Telescope and the Advanced X-ray Astronomy Facility discussed elsewhere in this issue. (See the articles by E. Joseph Wampler on page 44 and by George Clark on page 26.) The Marshall Space Flight Center of NASA is currently developing plans for the implementation of the full Advanced Solar Observatory. Solar scientists hope to see these plans carried out within a few years of the first deployment of the initial component, the Solar Optical Telescope.

Journey to a star

The deep-space probes to the other planets of our solar system, and the missions planned to study Halley's comet, are exciting voyages of discov-

ery that have fired the imaginations of both scientists and nonscientists. Perhaps the ultimate voyage of discovery within our solar system is a close encounter with its central object, the Sun. This would be an opportunity to sample the Sun's corona directly, to study the detailed dynamical behavior of the solar plasma by resolving its finest structures, and to probe the internal structure of the Sun by mapping its gravitational potential. Such a voyage would certainly revolutionize our understanding of the physics of stars.

Diverse questions such as the role of mixing within the solar core, the impact of mixing on the evolution of the Sun, the rotation rate of the solar core, the mechanism of acceleration of the solar wind and the mechanism by which the mass and energy lost to the solar wind escape from the photosphere into the corona, may well require a close encounter with the Sun for their final resolution. Such a mission, called Starprobe, has been proposed and is currently under study by NASA (see figure 7). Clearly, Starprobe presents formidable technical problems in terms of the survival of its instrument package in the intense heat of the Sun and the transmission of observational data through the high-density plasma of the outer corona. However, the studies carried out so far by the Jet Propulsion Laboratory of the California Institute of Technology suggest that we can overcome these problems. Starprobe will be an expensive program, so we must think of it as a long-range project. But its scientific return will be enormous and its impact as a voyage of discovery for humanity will be as significant as its scientific return.

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