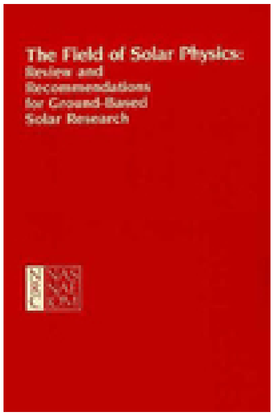

The Field of Solar Physics: Review and Recommendations for Ground-Based Solar Research

Committee on Solar Physics, National Research Council

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The Field of Solar Physics: Review and Recommendations for Ground-Based Solar Research

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Commission on Physical Sciences, Mathematics, and Resources
National Research Council

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Preface

Solar physics stands in a privileged position at the crossroad between laboratory-oriented experimental and theoretical physics and observationally oriented astrophysics. Many of the basic physical processes thought to be relevant to the workings of astrophysical systems—including nuclear energy sources, particle acceleration, production and excitation of highly charged atoms, and magnetic field generation, dissipation, and reconnection—as well as the tools for studying these processes were studied and developed in the solar context before they were applied to other problems in astrophysics.

Indeed, the history of astrophysics over the past several decades is replete with examples of the application of both instrumental designs and theoretical precepts transferred from the solar domain to more general astrophysical problems. Because physical conditions in the Sun's outer layers, which reach temperatures of up to 40 million K, are not unlike those encountered in laboratory studies of confined plasmas, the experimental and theoretical developments in solar physics have found immediate application in terrestrial laboratories as well. Thus the study of solar plasmas dates from the very beginnings of plasma diagnostics as a distinct discipline. Study of the Fraunhofer (discrete absorption line) solar spectrum, involving such great pioneers of atomic spectroscopy as G. R. Kirchhoff (who identified the sodium D lines in the solar spectrum), and application of the (then novel) atomic line Zeeman splitting in studies of sunspot magnetic fields led to the key realization that spectroscopy could be used to probe the physical condition of gases far removed from direct inspection. This opened up the possibility of studying detailed physical processes in otherwise inaccessible astronomical objects and laid the groundwork for much of today's astrophysics and laboratory plasma physics.

This report's aim is to consider the status of solar science today. Constituted by the National Research Council's Commission on Physical Sciences, Mathematics, and Resources at the behest of the National Science Foundation (NSF), the Committee on Solar Physics focused on those aspects of solar science that fall under the purview of the NSF. The specific charges for this committee were as follows:

1. A review of the present vitality, quality, and directions of solar research, starting with a number of existing studies as points of departure.
2. A determination of present and future needs of the solar community for ground-based observational facilities and instrumentation and for related analysis and theory, with emphasis on those aspects of the needs that are of relevance to NSF, and a determination of priorities.
3. An identification of possible institutional changes to help accomplish the program the committee will recommend over the long-term, i.e., changes that might be effected to make it possible for scientists to do their research.

Given these charges, this committee focused on those organizational aspects of solar science that involve primarily ground-based observations. However, because of the closely knit interactions between ground-based and space-based solar science, some commentary on possible ways to optimize these interactions and to improve the general health of solar science seemed to the committee both unavoidable and perfectly appropriate.

Chapter 1 is a summary of the committee's principal findings and recommendations. Chapter 2 provides a science overview of solar research today. Chapter 3 focuses on the principal science opportunities and initiatives in the four research areas currently at the forefront of solar physics: (1) probing the solar interior, (2) the physics at small spatial scales, (3) mechanisms underlying the solar cycle, and (4) the physics of transients. A discussion of institutional issues in solar physics leading to the committee's recommendations is presented in Chapter 4.

ROBERT ROSNER

CHAIRMAN

COMMITTEE ON SOLAR PHYSICS

Contents

1

Principal Findings

Solar physics has entered within the past half-decade a new realm of exciting observational and theoretical science. Although this renaissance in the science is widely appreciated, the committee finds that a variety of difficulties beset solar physics in the United States. The university role in solar physics is inadequate to sustain a vital science, support for solar physics by federal funding agencies has been dominated by mission-oriented approaches, funding for the National Solar Observatory and the High Altitude Observatory has declined during recent years, support for experimental and observational programs—in national centers and particularly in universities—has shrunk to the point that efforts in this area have declined to a critical level, and the funding of exciting new initiatives in the forefront of solar science has become enmeshed in the politics of budget cuts.

The central question is how each of these formidable issues can be addressed and resolved by the funding agencies and by the scientific community. If these problems are not resolved, the committee believes that the long-term future of solar physics in the United States will be bleak indeed. Given the nation's need for deficit reduction and fiscal restraint, it is unlikely that infusions of federal funds into solar physics will occur on the scale that occurred in the 1960s, nor would such infusions necessarily solve the problems. The problems enumerated above require, in the committee's opinion, solutions involving, first, a change in the structural foundation of federal sponsorship and, then, a modest level of appropriately directed additional funds for balanced support of solar physics research in the nation. Actions to achieve these solutions are discussed in full detail in this report.

Specifically, the committee's recommendations are that the National Science Foundation (NSF) work to accomplish the following:

1. **Develop a coherent, well-defined infrastructure for solar physics within NSF, with that agency properly assuming the lead role in support of basic research in ground-based solar physics. Thus the committee recommends that the internal structure for funding or solar research within NSF be changed so that support for both grants and centers is administered by a single entity within NSF whose primary responsibility is solar physics.** Such a reorganization will permit the development of appropriate advocacy within NSF, the definition of an overall coherent approach to the subject, a unified vision of the field's national facilities and university grants program—its scope and its development—and the implementation of new efforts. The directorate in which to place the recommended section could be either the Geosciences Directorate (the residence of support for solar-terrestrial sciences and the High Altitude Observatory) or the Mathematical and Physical Sciences Directorate (the residence of support for astronomy and the National Solar Observatory). Placement of the recommended section is a matter for NSF decision. The committee believes that such a section will benefit the nation's solar physics efforts.
2. **Support and encourage university programs in experimental and observational solar physics and take steps to strengthen the partnership between, on the one hand, federally supported research centers and, on the other hand, universities.** In particular, the committee recommends that specific programs to enhance education and training of students in solar instrumentation and observational techniques be established in the university community and that those universities willing to commit themselves to such programs receive support for the extended periods required to carry out such efforts. In addition, the committee recommends that more effective partnerships be forged between federally funded centers and universities—partnerships involving the exchange of faculty and technical staff, hardware and software, and workshops and short courses.
3. **Protect newly funded initiatives in solar physics by ensuring their continued support until they are completed.** Unless funding for such initiatives can be assured within the limits imposed by general federal budget restrictions, avoid pursuing additional new initiatives. The committee further recommends that NSF **refrain from commingling funds targeted for new initiatives with base-level support funds in response to budget-cutting pressures.**
4. **Provide funding for the highest-priority new initiatives in the four major areas at the forefront of solar research: (a) probing the solar interior, (b) the physics at small spatial scales, (c) mechanisms underlying**

the solar cycle, and (d) the physics of transients. Each of these initiatives, when completed, will result in significant new knowledge about the Sun, stars and the solar-stellar connection, and solar-terrestrial, physical, and astrophysical processes. The total funding required, although significant relative to the current overall level of funding for solar research, is small relative to the overall funds directed toward astrophysics in general. The scientific impact of the results from the initiatives will, the committee predicts, be large and will range far beyond the solar physics discipline. Clear identification of resources for these initiatives will signal to the community and to prospective students that the national interest will be properly served by modest but steady support of solar research.

5. **Give priority to the replacement of existing national solar telescopes with state-of-the-art instruments.** While the solar observing facilities of the National Solar Observatory in certain cases still represent the forefront of solar instrumentation in the world, this primacy is challenged by the current advent of the European solar telescopes in the Canary Islands, especially as these new telescopes are equipped with modern, state-of-the-art instruments. **The committee recommends that NSF vigorously support effort—possibly in collaboration with European scientists and others—to replace the National Solar Observatory facilities with a large-aperture solar telescope, and to do so at the best possible site. In particular; the committee most strongly recommends that NSF support activities lending to the definition and siting of this new telescope system. The committee further recommends that, when such new facilities become available and when they meet the needs of the U.S. solar community, NSF consider closing outmoded solar telescopes.**

2

Solar Research Today: A Science Overview

INTRODUCTION

In recent years, theory and observation have established that the Sun is a complex dynamical structure whose interior represents an active and mysterious universe of its own. There is no reason to doubt the basic features of stellar structure, but it must be remembered that the ideal standard stellar model contains many arbitrary assumptions. There is evidence from the study of meteorites that the relative atomic abundances may vary throughout the interior of a star. We know from spectroscopy that composition varies from one star to the next, as do the rotation rates and presumably the primordial magnetic fields. It must be remembered, too, that the Sun is the only star that has been studied in detail and that our only detailed information has come from scrutinizing its more or less inscrutable exterior. The interior possesses internal degrees of freedom that are only gradually being discovered and described, and, once described, are only gradually being understood.

The basic reality is that current knowledge of the solar interior is based entirely on theoretical deduction limited largely to simplified, static models constructed from the theoretical properties of particles and radiation as we now understand them. The deductions provide a static solar model whose radius and surface temperature can be adjusted to agree with observation, so that it represents a starting position for the next phase of the inquiry into the physics of a star. This is already well under way.

Now the dynamical effects ignored in the static models are already suggested by the static models. Thus, for instance, the calculated temperature gradients indicate the existence of the convection zone, extending down from the surface for a distance of about 0.3 solar radii. The gas continually overturns and operates as a heat engine. In fact the activity at the surface of the Sun is a direct manifestation of the convective heat engine and involves such diverse phenomena as sunspots, flares, coronal transients, the X-ray corona, and the solar wind.

It seems not to be generally recognized in astronomy and elsewhere that the precise causes of the activity are not yet reduced to hard science. Thus, for instance, it cannot be stated why the Sun, or any other solitary star, emits X-rays, nor can it be asserted why a star like the Sun is subject to a mass loss of 10^{12}g/s. Indeed, it is not altogether clear why the Sun operates on a 22-year magnetic cycle, producing the other phenomena related to the activity largely as by-products. This means, then, that we do not understand the origins of stellar X-ray emissions; this branch of X-ray astronomy, with its remarkable powers of penetration into the active component of the universe, is for the present limited largely to phenomenological interpretation. Indeed current ignorance about the Sun reflects the general lack of progress in understanding stellar activity of all kinds. We cannot fully interpret nuances of the surface emissions of the distant stars until we understand the physics of surface activity through close scrutiny of the Sun.

However, the problems are deeper than the puzzles of the Sun's surface activity. Mysteries are posed by the different surface abundances of lithium, beryllium, and boron and by the presence of more stable elements such as calcium and iron in some F and G dwarfs. Another puzzle is that theoretical evolutionary brightening predicts that the Sun was 30 percent fainter 3×10^9 or 4×10^9 years ago, whereas over the same period of time, mean temperatures on the terrestrial equator did not vary by more than a few degrees.

A more direct problem is that observations of solar neutrino emission have failed to corroborate the conventional theoretical models of the Sun. The failure to achieve such corroboration—now being confirmed by the independent Kamiokande II experiment—has stimulated a careful review of the theoretical complexities and uncertainties of the model. Nonetheless, the present discrepancy between the observed and predicted neutrino emission seems to be stuck at a factor of at least 3. If this dilemma can be resolved, we can limit the rest mass of the neutrino and the dark matter in the universe. Without this step, we cannot be sure of the theoretical evolution of a star on the main sequence. We cannot be sure of the age of globular clusters and the age of the galaxy. We cannot be sure of any theoretical interpretation of anomalous abundances in main sequence stars.

Helioseismology shows promise of providing a detailed and quantitative probe of the physical conditions (temperature, density, mean molecular weight, angular velocity, and magnetic field) throughout the entire Sun. Complete success depends on suitably long unbroken runs of data and on the detection and identification of *g*-modes. Analysis of currently available data points to peculiar and puzzling effects, including anomalous molecular weights, sound speeds and angular velocity, contradictions between the frequencies of different modes computed from standard models of the solar interior, and departures from the theoretically expected pattern of differential rotation. So again there is no easy confirmation of the standard model. How drastic the necessary revisions will ultimately be is a matter of conjecture. The present rapid development of seismological probing of other stars is an exciting and important adjunct to the exploration of the interior of the Sun.

It should be emphasized that there is far more at stake than the standard model of the solar interior. Our knowledge of the static structure of most stars is founded on the success of the solar model, and it is on the theoretical static structure of stars that our ideas of the age and evolution of the galaxy are based. So at present one of the fundamental tasks of solar physics is to develop independent observational checks on this central bastion of astrophysical knowledge.

The remarkably active state of the solar periphery, driven by the convective heat engine, has been studied with increasing angular resolution, spectral resolution, and wavelength range for several decades. Knowledge has expanded enormously without, however, bringing immediate theoretical understanding. To obtain some measure of the possible theoretical complexity, note that the Reynolds number N_R of the convective heat engine is on the order of 10^{12} to 10^{13}, which means that the fluid is active on all scales from 1 solar radius R down to the fraction $10^2/N_R$ of R, or approximately 10 cm. Hence the convection has approximately $(N_R/10^2)^3 = 10^{30}$ to 10^{33} degrees of freedom and for complete numerical simulation would require a grid with $N_R/10 = 10^{11}$ to 10^{12} intervals in each of three dimensions. What is more, the magnetohydrodynamic Reynolds number N_M is 10^{10}, whereas the terrestrial laboratory can achieve no more than 10^2 or 10^3, and so there is no general body of knowledge from which the subtleties of solar magnetic activity can be interpreted.

The enormous heat flux in the convective zone, producing the superadiabatic temperature gradient and driving the convective heat engine on all scales, and the extreme magnetohydrodynamic effects of solar activity combine to provide a dynamical scenario of exotic character that will be understood only after it has been described and studied in detail. Numerical modeling and theoretical studies of individual dynamical effects can be brought to bear on each aspect of the problem only after the observations have successfully described the situation. That is the nature of characterizing the activity of a star. There does not appear to be a single effect or a single new principle that will throw open the gates to a flood of understanding. The behavior of a convective, highly conducting fluid is a whole field of physics in its own right, which requires years of close theoretical and observational study, progressing past dozens of milestones and enjoying dozens of breakthroughs. The milestones and breakthroughs already add up to an impressive body of knowledge but represent only a beginning.

A particularly important milestone was reached about 2 decades ago, when detailed observational and theoretical considerations revealed that the magnetic field at the surface of the Sun, rather than being smoothly distributed as expected, is effectively discontinuous. The photospheric magnetic field consists of small, individual, intense and widely separated magnetic flux tubes of 1×10^3 to 2×10^3 Gauss. The mean field over any region is then a measure of the distance between the individual magnetic fibrils, because the individual fibrils or flux tubes are too small (about 200-km diameter), for the most part, to be resolved in a telescope.

The crucial information for understanding the large-scale behavior of the magnetic fields on the Sun (which are, it must be remembered, the perpetrators of the peculiar activity of the Sun) are (1) the structure and origin of the individual fibrils and (2) their individual motions (see Figure 2.1). So the pursuit of solar activity becomes solar "microscopy," a field in its infancy that has great potential through the development of adaptive optics on ground-based telescopes and the development of diffraction-limited telescope systems in space.

Indeed, the high-resolution ultraviolet (UV) observations from space, although not yet approaching the ultimate necessary resolution of 50 to 100 km, have already established the general occurrence of myriad tiny explosive events (nanoflares) and high-speed jets in the solar corona, providing a clue as to the heat input that causes the corona. The individual bursts of energy (10^{24} to 10^{27} ergs per event), and indeed the entire supply of energy to the corona, are evidently a result of the motions of the individual magnetic fibrils in the photospheric convection. The motions undoubtedly involve both jitter and intermixing of the individual fibrils, producing Alfven waves and a general wrapping, respectively, of the lines of force in the fields in the corona. But currently there is neither a direct measure of any aspect of the fibril. motions nor any direct detection of waves or wrapping in the coronal magnetic fields. Only the myriad small explosive nanoflares can be seen. So the causes of the solar and stellar corona, although extensively developed theoretically, are still without a hard observational foundation.

Another important milestone was the Skylab discovery of the frequent coronal transients involving the eruption of matter from the low corona outward into space, often accompanied by flare activity at the surface of the Sun. Several spacecraft epochs later, we are beginning to realize that these mass ejection events apparently result from large-scale magnetic field eruptions —but why they occur is not clear. Further, it is now suspected that these events precede solar flares or eruptive events rather than result from them. Thus they seemingly are the result of a form of solar activity not heretofore recognized. Their relation to the large-scale evolution of the solar magnetic field—and to stellar magnetic changes—is not clear at present.

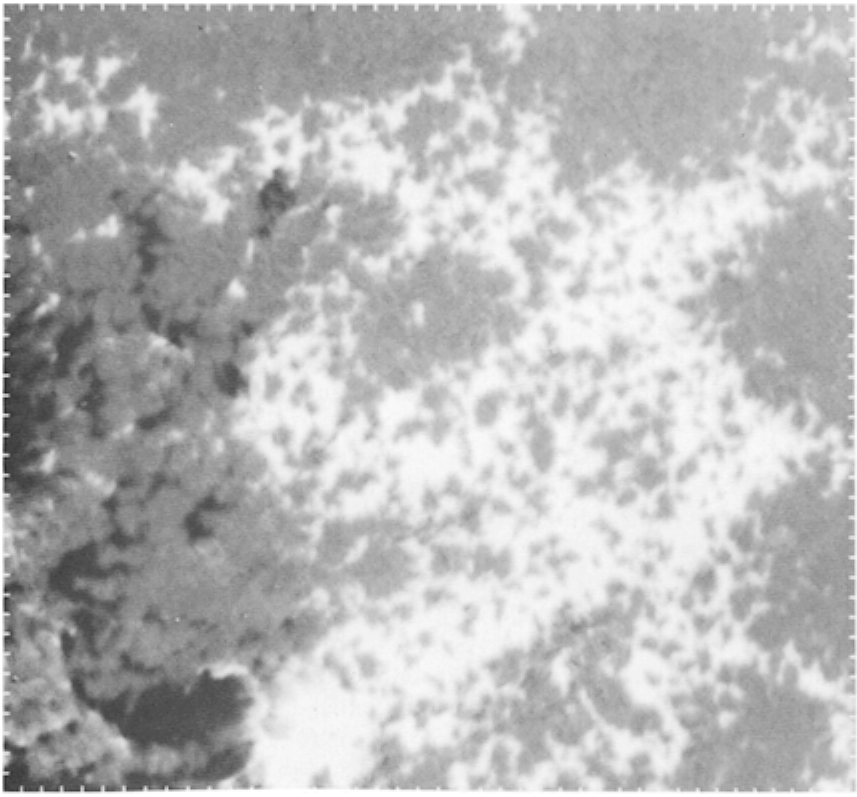

Figure 2.1
Small-scale solar magnetic fields in an active region, September 29, 1988. The line-of-sight component of the photospheric: magnetic field is shown as bright or dark, depending on polarity of the field, with an intensity proportional to field strength. Ticks correspond to 2 arcseconds, or about 1500-km spatial resolution. These observations were obtained by Lockheed Palo Alto Research Laboratory, with equipment developed for space flight, at the Swedish Solar Observatory at La Palma, Canary Islands, Spain. (Reproduced by permission of the Lockheed Palo Alto Research Laboratory.)

The remarkable X-ray photographs of the Sun, showing clearly the magnetic loop structure of the active corona and the interweaving coronal holes, have gone a long way toward allowing physicists to formulate the problem posed by the existence of the active X-ray emission. The high-speed streams of solar wind issuing from the coronal holes demonstrate the active nature of the corona outside the active corona. Combining the X-ray and extreme ultraviolet (EUV) studies of the corona of the Sun with the discovery by the Einstein X-ray Observatory that essentially all stars emit X-rays challenges scientists to understand why an ordinary star has such extreme suprathermal activity.

The ability to release energy impulsively and to accelerate particles is a common characteristic of cosmic plasmas at many sites throughout the universe, ranging from magnetospheres to active galaxies. Observations of gamma-rays and hard X-rays, radiations that can be unmistakably associated with accelerated particle interactions, as well as the direct detection of accelerated particles, for example the cosmic rays, strongly suggest that at many sites a significant fraction—and in some cases even a major fraction—of the available energy is converted into high-energy particles. The detailed understanding of the processes that accomplish this conversion is one of the major goals of astrophysics.

Solar flares offer an excellent opportunity for achieving this goal. A large solar flare releases as much as 10^{32} ergs, and a significant fraction of this energy appears in the form of accelerated particles. It is believed that the flare energy comes from the dissipation of the nonpotential components of strong magnetic fields in the solar atmosphere, possibly through magnetic reconnection. Immediate evidence for the presence of accelerated particles (electrons and ions) is provided by gamma-ray and hard X-ray continuum emissions, which result from electron bremsstrahlung, and gamma-ray line and pion decay emissions from nuclear interactions. Nuclear interactions also produce neutrons, which are likewise directly observable at Earth. The accelerated charged particles enter interplanetary space and arrive at Earth somewhat later, delayed by their circuitous paths of escape from the magnetic fields of the flare. The wide variation in the relative abundances of some isotopes and atomic numbers among the accelerated particles provides a direct view of the special aspects of the acceleration process in the flare.

These high-energy emissions are one of the best-known tools for studying acceleration processes in astrophysics. Solar flares are among the very few astrophysical sites for which it has been possible to study simultaneously the acceleration of electrons and protons and to directly detect and correlate the escaping accelerated particles with the electromagnetic radiations produced by the interaction particles (Figure 2.2). In addition, lower-energy emissions (soft X-ray, EUV, UV, and radio emissions), which are also observed from flares, reveal many of the detailed properties of the

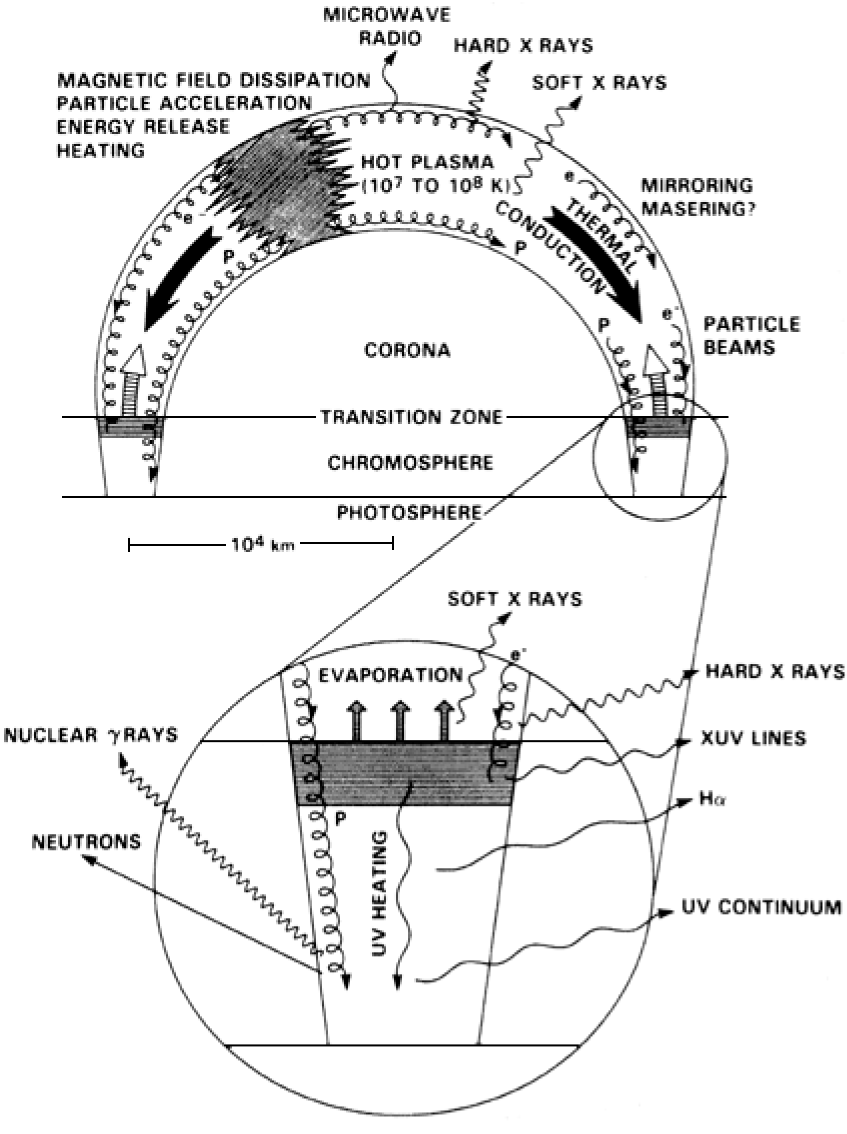

Figure 2.2
A possible solar flare scenario. As a result of the deposition of magnetic energy—most probably by magnetic reconnection—bulk plasma heating occurs and electrons and protons are impulsively accelerated. The high-energy emissions or signatures of these particles (e.g., nuclear deexcitation gamma rays from the protons and hard X rays from the electrons) peak simultaneously to within a few seconds, indicating that the protons and electrons are accelerated concurrently, possibly by a single mechanism such as shock or stochastic acceleration. (Reprinted from *NASA's Solar Maximum Mission: A Look at a New Sun* (1987), edited by J.B. Gurman, Goddard Space Flight Center, Greenbelt, Maryland.)

ambient plasma (e.g., temperature, density, and magnetic configuration) before, during, and after the flare.

This is the broad view of our understanding of the Sun and the stars. The specifics will provide many more problems, and it is essential, if we are to grasp the scope of the tasks before us, to spell out the problems in somewhat more detail. The next section, then, following the general principles described above, suggests some of the high-priority problems, measurements, observations, and theoretical studies that are necessary along the way to probe for greater understanding.

RESEARCH NEEDS

Detailed study of the Sun has established that the most common of stars is a complex dynamical system. Even the quietest regions on the surface of the Sun prove to be riotously active when scrutinized at sufficient magnification at the appropriate wavelengths. We are able to see the gross features of the activity at the surface, although much of the physics goes on at the small scales below the limit of telescopic resolution. There is no reason to think that the interior is any less active because we cannot see it. Indeed, studies of neutrino emission and helioseismology probe only the gross features of the interior, and they have already revealed mysteries of the most fundamental kind.

The effort to understand the physics of the Sun is motivated by recognition of the central astrophysical role of stellar mass, energy, and nucleosynthesis; by a general interest in physics; and particularly by the simple fact that the Sun is the basis for life on Earth. We are all subject to the vagaries of the Sun's highly variable emission of UV, X-rays, radio waves, gamma-rays, and fast particles; its short-term variations in luminosity; and in the long run, the evolution of solar luminosity and the temperature balance of our planet. The short period of time in which the Sun has been adequately monitored is insufficient to determine the full scope of the variability. For instance, terrestrial atmospheric ^{14}C production (by solar-modulated cosmic rays), as well as historical records, establish that the Sun operates for decades at a time in a state of suppressed activity (e.g., the Sporer Minimum of the fifteenth century and the Maunder Minimum of the seventeenth century) and at other times in a hyperactive state (e.g., during the twelfth century), in addition to the "normal" moderate level of activity that we are currently experiencing.

It is worth noting that, as far as the records go, the centuries of reduced solar activity coincide with the centuries of cold climate in the northern temperate zone, whereas the centuries of enhanced activity coincide with a particularly mild climate. No scientific connection has been proven or disproven. Observations indicate short-term variations in solar luminosity of as much as 1 part in 200, apparently in association with the short-term, daily fluctuations of solar activity. Perhaps more important is the observation, supported by the accumulating data from the Active Cavity Radiometer (ACRIM) onboard the *Solar Maximum Mission* satellite, that the luminosity of the Sun has varied by about 1 part in 1000 in step with the general 11-year activity cycle.

Now it may safely be assumed that the variability and activity of the Sun are typical of other stars, whose distance obscures their idiosyncrasies. Only in the more extreme cases are activity and variability obvious in other stars. The study of stellar activity was pioneered by O. C. Wilson, who traced the subtle variations of chromospheric line profiles of many stars over a period of years to reveal activity cycles similar in character to that so conspicuous in the Sun. This fundamental work has since been taken up and extended by a number of observers, so that there is today a substantial and rapidly expanding body of knowledge on precise stellar rotation rates, pulsations, magnetic cycles, and atmospheric variations in many different classes of stars. The work has led to the identification of patches of activity, gigantic flares, and cool patches (starspots) on the surfaces of many other stars. It provides a glimpse of the broad scope of stellar activity under a variety of circumstances. It is particularly puzzling, for instance, that some of the faint M dwarfs produce flares that have 1000 times more energy (but about the same duration) than the Sun's flares have and that some produce starspots 1000 times larger than the largest spots on the Sun, so that the starspot may cover half the visible disk of the star.

Once we can understand the cause of a sunspot, perhaps through seismological probing of its subsurface structure, it may be possible to appreciate the implications of these extreme phenomena in other stars. But that can be achieved only after the observational work on the Sun has progressed from exploration and preliminary description to hard science, which will require the facts eventually gained from low-energy neutrino observations, comprehensive solar seismology, and high-angular-resolution radio, infrared, visible, UV, and X-ray observations.

It is clear from the dilemmas presented by neutrino and helioseismological probing of the solar interior that some new ideas are needed on stellar interiors. The formation of a star may involve atomic abundances, rotation rates, and magnetic fields in different ways than those currently imagined. There may be more mixing of the interior than we realize, suggesting quite a different evolutionary track and a greatly different age for the Sun and other stars. It must be remembered that the current assessment of the age of the Sun is based only on geological evidence and on the assumption that the Earth was formed at the same time as the Sun. This is an entirely plausible assumption but by no means the only theoretical possibility.

We will certainly have to understand better than we do at present the large-scale circulation and convection in the Sun, and the associated magnetic effects. Neither the observational nor the theoretical picture is clear on meridional circulation, giant cells, and the radial and latitudinal variation of the angular velocity. The solar lithium, beryllium, and boron abundances suggest some limitations on the circulation, but we are mindful of the strikingly different abundances of these elements in certain other solar-type stars. Only when these questions are firmly and satisfactorily answered can we begin to attack the question of the loss of angular momentum from a star like the Sun, which is, of course, intimately tied up with magnetic fields and mass loss. And only then can we confidently pursue the theory of the various rotation rates of other stars. The accumulating information on the precise surface rotation rates of other stars, showing individual variations within a given class and age, provides an invaluable guide to the development of the theory. Solar and stellar seismology are essential for developing anything approaching a hard theory. It will be exciting to see how much progress can be made with ground-based seismology and then eventually with space-based instruments.

Surface granulation on the Sun lies at the edge of the resolution of current ground-based telescopes. But adaptive optics with large diffraction-limited ground-based and orbiting telescopes should permit the study of the granular structure and its peculiar mode of formation and dispersal, currently revealed only grossly by a few of the best observations now being made. There may be a close link between the dynamics of the granule and the formation of the intense magnetic fibrils.

The internal structure of the individual fibrils must be determined from direct observation before we can be sure of their origin. The Fourier spectrum of their individual motions must be determined from observation if we are to assess their role in creating the active X-ray corona and their role in heating the coronal holes. As noted earlier, neither the X-ray emission nor the mass loss from the Sun can be understood until the precise form of the energy input from the fibril motions has been determined. In this connection it is essential to explore further the intense small-scale bursts of energy and the low-frequency radio microbursts throughout the transition region and corona, as well as the larger microflares and flares. The coronal transients are a product of stressed magnetic fields on both small and large scales, the proportion of small-and large-scale stresses determining the degree of flaring associated with the transient. These phenomena all occur in stressed magnetic fields in both quiet and active regions, and their character varies with the phase of the magnetic cycle, which we know is itself highly variable over periods of decades and centuries.

The physics of the Sun does not end with the corona, of course, because the outer corona continually accelerates outward into space, gaining speed with increasing distance to form the solar wind and the heliosphere, extending out a distance on the order of 100 AU into interstellar space. Flaring adds a fast-particle population to the heliosphere and produces transient bursts of hot gas—blast waves—to the wind. These blast waves, together with the strong shock interactions between the fast and slow streams of wind, make the heliosphere an active structure whose properties vary markedly with radial distance from the Sun. We are only beginning to get an idea of the detailed structure of the inner and middle heliosphere as the *Voyager* and *Pioneer* spacecraft journey past the outer planets. The interaction of the wind with the planetary magnetospheres, creating a local environment that is unique to each planet, is another interesting and important subject that is in a state of rapid development.

It should be emphasized in this overview of solar physics that the solar-stellar connection is an integral part of the physics of the Sun and the physics of stars in general. Other stars exhibit great complexity in those aspects that can be studied. Thus we may safely assume that most, if not all, stars would prove as active and complex as the Sun if we could observe them as closely. It is astonishing to see that some stars support gigantic flares and starspots. Some exhibit mass loss enormously greater than that of the Sun. Essentially all of them exhibit X-ray coronae, from which we may infer that their coronal gas expands along the more extended lines of force, carrying the field into space to form a stellar wind much like the solar wind. The general existence of X-ray coronae implies the same nanoflares and microflares and the same coronal transients as can now be observed on the Sun, although there is no foreseeable means for observing them individually on the distant stars. Similar complex magnetohydrodynamic and plasma processes must occur. The same puzzles concerning their internal structure, their internal rotation, and their dynamo confront us, except that it is not possible to come so directly to grips with these puzzles as it is with those posed by the Sun. The best that can be foreseen is to understand the Sun and then to infer the characteristics for the other stars.

It is essential, nevertheless, to study the oscillations and seismology of the other stars, to monitor their activity cycles over long-terms, and to make precise measurements of their rotation rates. Only in this way can we discover their individual quirks as well as determine the "average" behavior of each class of star. The deviation of the individual from the average provides insight into the variable conditions under which stars are formed, which then helps us to understand the idiosyncrasies of the Sun. Other stars of different ages may provide an idea of the Sun in its youth, to be compared with the geological record for clues to the effects on the planetary environment. The spinning down of the Sun at an early age may have involved conditions profoundly different from those that obtain today.

Finally, it should be noted that up to this point this discussion has focused on single stars, whereas many stars are binary. It is well known that the tidal effects of close binary stars have drastic effects on the behavior of the individual component stars. Perhaps one day we shall understand the internal dynamics of the Sun well enough to deduce what subtle effects may be expected from the tidal effects of distant, or even close, companion stars.

In concluding this general appraisal of current problems in the physics of a star like the Sun, it is appropriate to make some general comments on the future. It is too soon to guess where the neutrino observations will lead, but whatever the results obtained from the present gallium detectors, the implications for astronomy will be profound. Helioseismology may be expected to play an essential role in removing the ambiguities of anomalous neutrino fluxes, unless, of course, the discrepancy is entirely a matter of neutrino oscillations between three or more states, which would have deep cosmological implications. What is more, we can be sure that the investigation of the solar surface and the solar interior on so broad a front will provide surprises, perhaps of a fundamental nature. The present writing, and the list of opportunities and initiatives that follows, is based on contemporary knowledge and cannot anticipate what lies ahead when we probe into the unknown realm of the solar interior and the small-scale phenomena at the solar surface.[1]

[1] The reader is referred to the recent comprehensive reviews of contemporary knowledge of the Sun to be found in the three-volume work *The Physics of the Sun* (1986), D. Reidel Publishing Co., Dordrecht, The Netherlands, edited by P. A. Sturrock, T. E. Holzer, D. M. Mihalas and R. K. Ulrich; and Volume 100, *Solar Physics* (1986), D. Reidel Publishing Co., Dordrecht, The Netherlands, edited by C. de Jager and Z. Svestka. Indeed the tables of contents of these works provide a useful list of major topics in solar and stellar physics in greater detail than has been possible in the present writing. Further relevant information can be found in the reports listed in Appendix C.

3

Principal Science Opportunities and Initiatives for Ground-Based Solar Research

Advances in experimental and observational techniques now make it possible to observe aspects of the Sun that were previously unknown or unappreciated. The observations reveal a star of complex and mysterious behavior. Neutrino astronomy; helioseismology; high-resolution observations of the solar surface; radio, infrared, UV, X-ray, and gamma-ray observations of the outer atmosphere; vector magnetic field observations; and spacecraft observations of the secular changes in the solar luminosity have all uncovered new and puzzling aspects of the Sun. These fundamental investigations have been possible only because of the proximity of the Sun. One may infer that other stars are equally mysterious, but they cannot be resolved in the telescope and are too far away for the necessary close scrutiny.

In this chapter the committee explores in greater detail the principal needs and most promising opportunities for investigation over the coming 5 years in the four research areas at the forefront of solar physics today: (1) probing the solar interior, (2) the physics at small spatial scales, (3) the mechanisms underlying the solar cycle, and (4) the physics of transients. The committee interviewed leading solar physicists from all major solar physics research centers in the United States and solicited oral and written comments from the solar community at large.

PROBING THE SOLAR INTERIOR

The Basic Issues

Information from the interior of the Sun is needed to understand fluctuations in the Sun's radiative and nonradiative outputs, to verify the theory of stellar structure and evolution, to help develop an understanding of fluid motions in realms beyond laboratory and theoretical modeling, and to advance several areas of basic physics. Recent work suggests that significant revisions are required in our current concepts of all these topics and that the ramifications may extend far beyond the traditional range of solar physics.

One of the triumphs and major foundations of astrophysics is the theory of stellar structure and evolution. Much of what we understand about the universe derives from this theory. It is now possible to critically test the predictions of the theory for the case of the Sun, and the results are disturbing. The flux of neutrinos produced in the solar core has been measured since 1968 in a celebrated experiment located deep in the Homestake mine in South Dakota. Only one-third the flux of neutrinos predicted by the best models of the solar interior has been measured. A new experiment located at Kamioka, Japan, was started in 1987; the first results confirm that the neutrino flux is less than that predicted by solar models. This "neutrino problem" is larger than can be explained by current understanding and uncertainties of the relevant physics.

Another prediction from the theory of stellar structure concerns the frequencies of the normal modes of oscillation of the Sun. Helioseismological observations have measured these frequencies with a precision of a few parts per hundred thousand. There is a systematic discrepancy between the observations and the predictions of a few parts per thousand. Again, this discrepancy is larger than can be explained by current understanding of the relevant physics.

The theory of stellar evolution predicts that the Sun should have brightened by about 30 percent since the formation of the solar system. Geological and climatological evidence suggests that the change in solar luminosity has been much smaller. One proposed solution to this problem is to mix the solar interior to provide fresh fuel to the energy-generating core. Mixed models seem to be ruled out by current helioseismology results. Evolutionary theory also suggests that the interior of the Sun should be rotating much more rapidly than the surface layers, which have been braked by angular momentum transfer to the solar wind. Instead, helioseismology indicates that the interior is rotating very much as the surface rotates.

Theoretical understanding of circulation and convection inside the

Sun is not well advanced because of the intrinsic difficulty of the relevant physics, an inability to construct and run realistic numerical models, the large extrapolations required from laboratory experience, and the relative lack of observations of the solar interior to provide guidance. Existing models of motions within the convection zone have not been confirmed by observations. Predictions of a polar vortex, giant circulation cells, and strong variations in rotation rates with depth and latitude in the convection zone have not been supported by observation.

Evidence from a variety of observations suggests that nearly all stars with a mass of less than about 1.5 times the solar mass (and this means most stars) exhibit activity of the type that we observe in the Sun. We do not yet have a good understanding of how magnetic activity is produced even within the best observed star—the Sun. Much has been learned from observations of other stars that have a range of physical parameters different from those of the Sun. Probing the interior of the Sun can provide additional information about how stellar and solar activity is generated. Initial results from helioseismology indicate that the subsurface structure of sunspots and active regions does not agree with that described by current models. New models of the solar magnetic dynamo, which is thought to generate the solar activity cycle, are under development based on helioseismology.

The discrepancies between current models and current observations listed above have challenged many researchers to suggest innovative solutions. Some of these suggestions extend into the realm of exotic physics. A typical example is the hypothesis that there may exist weakly interacting massive particles (WIMPS or cosmions) within the solar interior (and elsewhere). Such cosmions could reduce the central temperature of the Sun and thereby explain the neutrino deficit. It is worth noting that a model of the Sun that includes cosmions predicts *p*-mode oscillation frequencies that are significantly closer to observations than are those predicted by standard solar models. It has also been suggested that neutrinos have a small rest mass, and even a magnetic moment, that could explain aspects of the neutrino problem. Laboratory results on this important physics question are conflicting, but future solar observations should help to verify or deny these suggestions.

Initiatives and Impacts

Researchers in the United States have led or participated in most investigations involving the solar interior. The United States has been particularly strong in observational work and can maintain a leading role in some areas and a presence in others by balancing support for continuing facilities and programs, initiating selected new programs, and collaborating with international partners where appropriate.

Theory and Modeling

The study of the solar interior depends intimately on predictions from theory and modeling. It is essential that support for this activity be accorded as much priority as observational programs. The United States can continue among the world leaders in this field by initiating and supporting collaborative as well as domestic work. A good example is a 6-month workshop planned for 1990 at the Institute for Theoretical Physics of the University of California, Santa Barbara.

Neutrino Observations

A survey of recent publications and plans for future projects clearly shows that the United States is heavily involved in neutrino observation, although not always in a leadership role. The committee urges that the United States maintain its presence in the field by continuing a few key experiments and supporting U.S. participation in international projects. Leading opportunities for initiatives include the following:

1. Continue operation of the ^{37}Cl experiment through the next solar maximum expected in 1991, and continue support of the Kamiokande II experiment, whose results are an important consistency check for the ^{37}Cl experiment. This will allow tests of suggested correlations of neutrino flux with the solar activity cycle and, more speculatively, with the Earth's heliocentric latitude. A confirmation of modulation of the neutrino flux will have a profound impact on solar physics, astrophysics, and particle physics.
2. Support U.S. participation in additional new international measurements of neutrinos from the Sun. Two experiments may be considered as examples. The first is the proposed ^{2}H experiment (Sudbury Solar Neutrino Observatory), a Canadian, U.S., and U.K. experimental collaboration, which will measure a variety of ^{8}B neutrino properties, including their spectrum; the second is a ^{40}A experiment, led by the Italians, which will provide an independent measurement of the ^{8}B neutrino properties. In addition to determining the production rates and spectra of the neutrinos, these experiments will address the question of the mass of the neutrino and the hypothesis that the neutrino problem is due to a change of one type of neutrino to other types in transit to the earth.
3. Support U.S. participation in international measurements of neutrinos from the main nuclear reaction that produces solar energy, although given the already existing strong international support for these projects, support might be more modest than the support for the preceding experiments. This next generation of experiments will enlarge the scope of neutrino measurements beyond that of the current experiments, which sample neutrinos from a minor nuclear reaction in one region of the solar core. Two experiments using ^{71}Ga are in preparation to do this. One is

primarily a European experiment, and the other is a Soviet experiment with limited U.S. participation. These experiments will detect neutrinos from the most common reaction that produces energy in the solar core. Results will indicate whether the neutrino problem originates in physics or astronomy.

4. Complete an experiment to deduce the average neutrino flux over the last several million years. Sometime in 1989, results are expected from ^{98}Tc extracted from about 20 boxcars of molybdenum ore mined from the Henderson mine in Colorado. This isotope is produced by absorption of neutrinos that have penetrated the 1500-m depth of the mine. Since the half-life of the isotope is a few million years, this difficult experiment may be able to measure the constancy of neutrino flux over the past several million years. If evidence for a changing flux is found, orthodox views of stellar evolution will need to be changed.

Helioseismology Projects

The United States is the world leader in helioseismology observations utilizing solar imagery. Europe leads in helioseismology of the Sun observed as a star. Both approaches enjoy unusually strong and stimulating international contributions and cooperation by observers and theoreticians. As a result, the field of helioseismology has expanded rapidly since its beginning in 1975. The literature comprised about 700 papers in mid-1987 and has doubled every 3 years. Work in this field (see, for example, Figure 3.1) has already answered some long-standing questions about the solar interior but has raised new questions of potentially wide-ranging significance throughout astrophysics and physics. To maintain leadership and momentum in this field, the United States should pursue a number of initiatives:

1. Support exploration of new observational methods and techniques. Groups at the California Institute of Technology; Stanford University; the Universities of Arizona, Delaware, Hawaii, and Southern California; the National Solar Observatory (NSO); the High Altitude Observatory (HAO); National Aeronautics and Space Administration (NASA)/Goddard; and elsewhere are advancing state-of-the-art observational helioseismology. A good example is the tomography of sunspot structure developed recently by researchers from NASA and the University of Hawaii using NSO/Kitt Peak facilities. The result of supporting innovative observational helioseismology will be the development of new and improved methods for probing the solar interior.
2. Support the Global Oscillations Network Group (GONG) project. This is a community project initiated by the NSO to provide continuous solar oscillation data for a period of 3 years. It was a response to an

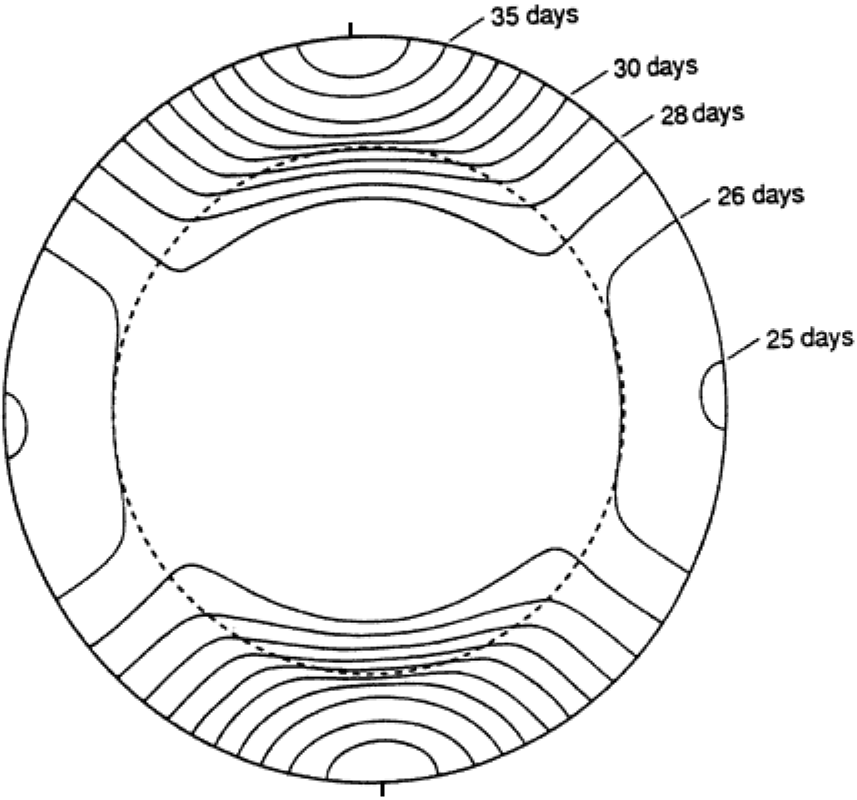

Figure 3.1
Contour plot: cross section through the Sun, with contours of constant rotation period as a function of latitude and depth in the solar interior. The dashed line marks the base of the solar convection zone. The picture is based on measurements of oscillations of the Sun's surface, which are a manifestation of sound waves traveling through the solar interior. The rotation rate is determined by comparing waves that travel east-to-west and west-to-east at different depths inside the Sun. Because of limitations in the current measurements, the results here are only accurate for radii larger than 0.4 solar radii. The results indicate that the Sun's surface rotation persists throughout the outer 30 percent of the Sun, where it is probably driven by large-scale convection. Below the convection zone the Sun appears to rotate nearly rigidly (with the possible exception of the deep interior) at a period of about 27 days.

This picture is based on helioseismology data obtained by K. Libbrecht at Big Bear Solar Observatory and on inversions of the data by J. Christensen-Dalsgaard and J. Schou, as well as by P. Goode and W. Dziembowski. (Reproduced by permission of the California Institute of Technology.)

obvious scientific need for such data and to an invitation by NSF for innovative projects. Motivation for the project is reduction of the noise and confusion introduced by nightly gaps in solar oscillation data obtained from single observatories. Continuous observation by means of a network of six sophisticated instruments around the world promises to reduce this problem by at least an order of magnitude. The impact of this project will be great improvements in the precision of *p*-mode oscillation frequencies and amplitudes for degrees up to about 300. This will permit definitive determinations of the temperature stratification and large-scale motions of most of the solar interior. It is important that funding also be provided to assist the helioseismology community to analyze and interpret the data from the GONG project.

3. Support the U.S. helioseismology experiment on the European Space Agency's (ESA) SOHO spacecraft. This experiment was selected by NASA and ESA as one of the major tasks for the SOHO spacecraft expected to be launched in 1995. Aside from the important advantage of continuous sunlight afforded by an orbit around the L1 Lagrangian point, the lack of atmospheric distortion will present unique opportunities to study oscillations of both high degrees and long periods. The impact of these observations will be a definitive determination of the stratification and motions of the upper layers of the convection zone, where our current understanding of the physics is quite uncertain.

Investigation of the Interiors of Other Solarlike Stars

The study of the solar interior gives us information about one star. It would be naive to think that we can safely extrapolate that information to other stars without some verification. Similarly, comparison of some of the characteristics of the solarlike stars, such as age, chemical composition, and rotational velocity, would provide a considerably sharper test of the theory of both solar and stellar structure and evolution. For example, the study of the depletion of light elements in a wide range of stars is a sensitive indicator of the maximum temperature to which convecting material is exposed in the outer layers of a star. In the Sun and several other stars, the outer layers appear to have been exposed to higher temperatures than can readily be explained by standard theory. While neutrino radiometry of other stars is currently beyond the capabilities of foreseeable technology, the prospects are good for seismic probing of solarlike stars. Already the first steps have been taken on both observational and theoretical fronts and have shown considerable promise. On the observational side, what is needed is a highly stable echelle spectrograph, fed by a several-meter-aperture telescope, and large blocks of contiguous night scheduling. A recent experiment involved 2 weeks of observing time with the Soviet 6-m telescope. A dedicated facility would be optimum because of the peculiar requirements of large amounts of observing time to do seismology of other stars, but a facility shared with other observing programs is also a feasible solution.

Another way of approaching this problem is to attempt precise photometry of members of stellar clusters. Although such work is best done from space, it may be possible to obtain sufficient accuracy with ground-based equipment. Such experiments should be supported.

The impact of work in this area will be to allow confident application of what we learn about the solar interior to other stars. The theory of stellar structure and evolution will be tested over a broader range of parameters than can be done using the Sun alone. There will also be feedback of information about other stars into the total picture of the solar interior.

THE PHYSICS AT SMALL SPATIAL SCALES

The Basic Issues

It is now well known that magnetic fields play a central role in the dynamics of the solar surface layers (for example, by ordering local transport coefficients such as thermal conductivity in an anisotropic fashion, by blocking convective transport, and by carrying the "mechanical" energy and momentum flux required for coronal plasma heating and acceleration of the solar wind); hence solar magnetic activity largely defines the interaction between the Sun's interior and atmosphere, and between the Sun's atmosphere and the heliosphere and terrestrial magnetosphere. The detailed physics by which the magnetic activity both arises in the solar interior and ultimately couples to the outer solar atmosphere and heliosphere remains a matter of active research. It is nevertheless clear that the answers lie in an understanding of the interaction between magnetic fields and turbulent conducting fluids and of the equilibrium and stability properties of magnetized plasmas, and in the realm of collective plasma behavior.

These issues of physics are intimately connected and are, furthermore, of great interest both to space physicists and terrestrially bound plasma physicists. Thus issues of plasma confinement (and their attendant problems of magnetohydrodynamic equilibrium and stability) and plasma heating (by wave and/or particle beam and plasma interaction) and transport are central to fusion plasma efforts. It should therefore not be surprising that, for example, current models for solar plasma heating borrow heavily from recent advances in the laboratory domain, and that, conversely, some of the early work on plasma confinement schemes grew out of work originally carried out in the astrophysical domain.

Because the phenomenology of the solar surface layers is so rich, one cannot hope to summarize fairly the entire range of current theoretical and observational work; hence the following represents an outline of what the committee perceives as the most exciting current research directions, with an emphasis on those that exemplify various aspects of the interaction between solar magnetohydrodynamics and plasma and space physics, plasma astrophysics in general, and the terrestrial fluid dynamics and laboratory plasma domains.

Magnetic Field Generation and Intermittency

Solar magnetic fields are striking in two very distinct respects: they persist in spite of the observed rapid diffusion of surface magnetic fields, and they are—whenever observed—spatially highly concentrated and inhomogeneous. It is commonly believed that these circumstances can be understood by appealing to the interaction between magnetic fields and turbulent shear flows. Thus much of the observed phenomenology associated with the solar magnetic cycle can be reproduced by kinematic magnetic dynamo models, and spatial intermittency is thought to result from "sweeping" initially homogeneous magnetic fields into regions of stagnant flow by organized cellular flows (viz, classic Benard convection cells).

Unfortunately, solar magnetic fields are relatively strong, so that it is dubious whether kinematic theories are an appropriate description of the physics underlying the solar dynamo; furthermore, the solar convection zone is far from laminar in behavior (the Rayleigh number is far above critical, and the Reynolds number exceeds unity by many orders of magnitude), so that it is unclear whether results from laminar theory can be immediately adopted. It is therefore not surprising that these issues are currently being attacked via sophisticated numerical simulation schemes, which include the effects of magnetoconvection and buoyancy. What is particularly fascinating about this work for (solar) fluid dynamicists and plasma physicists is that the Sun at present provides the only "laboratory" for testing theories of flux concentration and enhanced (turbulent) diffusion of magnetic fields.

Equilibrium and Stability Theory

Because magnetized plasma structures in the outer solar atmosphere—ranging from cool prominences to million-degree coronal "loops"—can show both periods of great quiescence and intervals of highly intermittent activity, there has been a concerted effort to understand the equilibrium configurations and stability properties of magnetic-pressure-dominated plasmas. There are of course obvious parallels to related work in the plasma-fusion community, and indeed the early solar studies anticipated related laboratory plasma studies. Stability calculations are being actively pursued today in the solar context, with substantial input from the now classic work from the laboratory domain. This includes use of the Bernstein "energy principle" and the concept of "line-tying" as applied to magnetic field lines entering the high-density photosphere from the overlying tenuous chromosphere and corona; application of helicity conservation in construction of equilibria; studies of the existence of equilibria under specified (realistic) boundary conditions; and study of field line stochasticity.

Rapid Magnetic Field Reconnection

The role played by collective effects in the solar atmosphere was first appreciated in the impulsive phenomenon known as the solar flare, commonly believed to occur when oppositely directed magnetic fields in the solar corona "reconnect," thereby releasing energy in the form of heat, particle acceleration, and induced rapid flows. It has long been evident that the observed short time scale of impulsive energy release demands a breakdown of the classical (high electrical conductivity) magnetohydrodynamic picture normally used to describe the solar outer atmosphere. As a result, a blossoming of interest in magnetic reconnection (driven also by observations of related impulsive phenomena in the terrestrial magnetotail) has occurred: steady-state fluid theory has been placed on a robust, formal footing; calculations have been extended to the collisionless domain; and extensive efforts at numerical simulation and laboratory modeling of reconnection are currently being conducted.

From the solar perspective, one needs to understand the geometric configuration of the reconnection site; to understand the conditions under which sudden energy release occurs; and to be able to estimate the energy released into fast particles, direct plasma heating, and flow acceleration. These questions are indeed common to the various disciplines in which field reconnection plays a role; the contribution of solar studies will be to extend significantly the parameter regimes in which reconnection can be studied.

The Physics of Thermal Heat Conduction

The rapid rise of the gas temperature above the solar photosphere to several million degrees within a few thousand kilometers has raised many questions, not the least of which is how one is to calculate the thermal transport coefficients properly. The classical Spitzer-Harm thermal conduction is inherently a linearization, entailing asymptotic expansion in the ratio of the thermal mean free path to the temperature gradient scale length. This has been shown to fail in laboratory studies of heat transport in hot plasmas for very small values of this ratio. In addition, inertial confinement studies suggest that microturbulent effects may also come into play. These terrestrial laboratory results are only now finding their way into the solar plasma physics domain, and it seems inevitable that rather significant changes in our understanding of the interchange of energy between the solar corona and the underlying photospheric gas will result.

The impact of these applications is in our understanding of the following: previous calculations of the (transition region) thermal heat flux may be in error; the large mean free path of coronal electrons may significantly alter the ionization balance of cooler, lower-lying layers (and thus upset standard plasma diagnostic techniques); and the nonlocal character of heat transport by long-ranging suprathermal electrons may vitiate previous hydrodynamic studies based on local theory.

Plasma Diagnostics, Heating, and Motions

The current state-of-the-art in remote-sensing plasma diagnostics finds solar plasma physics at the forefront. From the astronomical perspective, this is by design, for the Sun provides physical conditions that are not unlike those encountered in much of the rest of the universe (but at inaccessible distances) and reduces demands on instrumentation (because its proximity leads both to the availability of copious numbers of photons throughout the electromagnetic spectrum and to some useful degree of spatial resolution of the activity itself). Thus the Sun has been studied not only for its own sake but also as a test case for exploring new instrumentation and diagnostic concepts in a more familiar and accessible context. Today's frontiers of solar plasma diagnostics lie in the direction of nonequilibrium studies and in the exploitation of high-spectral-resolution observations, combined with high spatial and temporal resolution (particularly in wavelength domains heretofore relatively poorly explored with spectroscopic tools). This frontier area includes efforts to diagnose departures from ionizational equilibrium (using, for example, satellite lines of strong resonance lines) by observing detailed line profiles formed at transition-region and coronal temperatures (which allow one to test for Doppler broadening from the systematic motion of hot plasma associated either with flows or with quasi-periodic motions resulting from propagating or standing waves).

The latter studies have particular relevance to tests of theories for atmospheric plasma heating, to studies of mass exchange between the solar photosphere and the hotter overlying layers (as can occur during the course of solar flares), and to the classic problem of solar wind heating and acceleration in the immediate solar vicinity. High-resolution spectroscopy, when combined with high spatial resolution and the ability to measure polarization states (i.e., the Stokes parameters), also allows direct measurement of vector magnetic fields in the solar atmosphere and hence determination of the magnetic field topology in the solar corona. At very high photon energies, high-resolution hard X-ray and gamma-ray spectroscopy allows one to test detailed particle acceleration models (through interaction between these fast particles and ambient matter), whereas in the infrared, high-resolution (spectral and spatial) spectroscopy takes advantage of the fact that atomic line Zeeman splitting is proportional to the square of the line center wavelength to enable exploration of the magnetic field structure in the lower photosphere and chromosphere.

Initiatives and Impacts

It is evident from the foregoing discussion that studies of the physics of the Sun's outer layers will very likely involve substantially greater interaction with the laboratory and magnetospheric plasma physics communities and increasingly greater contact with observers and plasma theorists dealing with astrophysical plasmas in general. The rapid development of instrumentation capable of extremes in high spatial, temporal, and spectral resolution will challenge the modeling abilities of theorists; and, as has been the case in the magnetospheric domain, large-scale numerical simulations will play an increasingly important role. Because these research activities place solar physicists at the forefront of both experimental techniques and computational needs, the committee considers it important to ensure that the opportunities available in solar physics research are realized.

Thus, whereas the problem areas discussed above define the direction of research into the physics of the solar surface in the immediately forseeable future, it is of considerable importance to note that the success of these studies is predicated on the existence of the instrumentation to carry out these studies. Because the most promising directions in experimental research of the solar surface involve state-of-the-art technology and hence require both a cadre of highly qualified scientists and technologists and a significant investment in high-technology laboratory facilities (including computational resources), it is crucial to define, implement, and maintain a well-defined, long-range observational program. To simply maintain existing equipment without an active program for developing and implementing new instrumentation is a strategy ultimately certain to cripple the science.

High-Spatial-Resolution Visible and Infrared Observations

One of the great puzzles of solar physics is the observed clumping of magnetic field structures. An essential element in studying these structures is of course their observation. This task requires telescopes with high spatial resolution (well below 1.0 arcsecond), extremely well characterized polarization effects (to a level less than 1 percent), and high-photon-collection capability. Recent experiments at NSO/Kitt Peak have also shown the substantial benefits to be gained from infrared observations; at these long wavelengths, atomic line Zeeman splitting is sufficiently large that the pi and sigma components can be readily separated, with relatively little modeling effort needed to produce good magnetic field measurements. The missing ingredient is high spatial resolution: the NSO/Kitt Peak facilities have limited spatial resolution, and the Sacramento Peak Vacuum Tower telescope can produce subarcsecond resolution in the near infrared but cannot be used beyond a wavelength of 2.4 microns. Efforts to improve this situation (such as the HAO/NSO Advanced Stokes Polarimeter project) must be supported in order to advance in this area.

However, the key next step is to plan now for future observing capabilities that can provide a significant—and necessary—advance over what is currently available. With this goal in mind, the HAO scientists, acting as representatives of the interests of U.S. solar astronomy and recently joined by NSO scientists, have been involved in discussions with scientists from nine other countries on building a large-aperture ground-based telescope, whose goal is to obtain both high throughput and diffraction-limited images (the latter with the use of adaptive optics). This Large Earth-based Solar Telescope (referred to as the LEST project) addresses in a complementary fashion many of the scientific issues that are at the heart of NASA's Orbiting Solar Laboratory (OSL), a moderate-aperture, free-flying, visible-and UV-light space telescope. Table 3.1 provides some points of comparison for these two telescopes: the freedom from atmospheric distortion that allows the OSL to image relatively large structures on the solar surface with high angular resolution is traded off against the difficulty of placing very large aperture mirrors in space (the latter allowing for high-photon-collection capability and for the ultimate in diffraction-limited spatial resolution). In both cases, many of the scientific issues discussed above—including the structure of magnetic field concentrations and of convective overshoot, and the interaction between convection and magnetic fields—are directly addressed.

Infrared Telescope Instrumentation for Imaging and Spectroscopy

The infrared offers some unique physical diagnostic opportunities that have not been exploited. Because imaging improves substantially as one enters the infrared, there are substantial benefits to observing at these wavelengths from the ground. Indeed there are solid reasons for believing that optical interferometric measurements (including speckle interferometry and imaging) are best carried out in the infrared. At present, only the NSO/Kitt Peak facilities have any capability in the world in this regard, but this capability is highly compromised because available instrumentation is not optimized for such observations. Development of instrumentation to exploit these unique scientific advantages should receive continued support.

TABLE 3.1 Comparison of LEST and OSL Telescopes

Property	LEST	OSL
Field of view	a few arcseconds[a] to 3 arcminutes	3 arcminutes
Angular resolution (approx. 5,000 angstroms)	<0.1 arcsecond to >0.5 arcsecond[a]	0.13 arcsecond
Wavelength range	3,500–24,000	2,200–10,000[b]
Aperture	2.4 m	1.0 m
Polarization	low	compensated
Flexibility of focal plane instrument exchange/redesign	high	none
Continuous observing capability at shorter wavelengths	no	yes
Lifespan	decades	a few years

[a] Assumes successful implementation of adaptive optics.
[b] Upper wavelength limit set by instrumentation, not by optics.

High-Spatial-Resolution Microwave Instrumentation

The near-term potential for extremely high-resolution imaging of coronal and chromospheric structures is nowhere as great as at radio wavelengths; this is of course a consequence of the coherence of radio wavelengths over very large baselines, so that ground-based interferometric observations can relatively easily reach subarcsecond spatial resolution; in addition, with the aid of spectral resolution and polarimetry, it is possible to infer the structure of magnetic fields in the atmosphere overlying the solar surface. This area of research is only now coming into its own; and the possibilities of correlating radio emission structures with structures that will be seen in the UV and soft X-ray region by spacecraft now under construction in the United States, Europe, and Japan offer a totally novel way of understanding the structure of that part of the solar atmosphere that most directly influences the variability of our terrestrial magnetosphere and near-space environment. For these reasons, high-spatial-resolution microwave instrumentation requires support.

Theory and Modeling

The new high-spatial-resolution observations of the Sun are leading theorists into heretofore unexplored realms of hydrodynamics and magnetohydrodynamics. Without strong theoretical support, these observational programs are likely to lead to a plethora of data but only a modicum of understanding. In the case of space-based programs, the NASA Solar-Terrestrial Theory Program and the NASA-supported workshop series for the OSL go a long way toward providing the needed theoretical support and fostering the essential experimenter and theorist interactions. NSF should similarly ensure that the experimental programs it supports receive critical support in the theoretical area as well.

MECHANISMS UNDERLYING THE SOLAR CYCLE

The Basic Issues

The longer time scales of solar variability reflect the presence of ill-understood phenomena in the deep interior that link rotation, convection, and magnetism. Cyclic variations of magnetic activity occur in many other solar-type stars, but we still lack satisfactory theoretical explanations of the origin and development of stellar magnetic fields. Interest in solar variability has recently been stimulated by the discovery that solar luminosity varies on these longer time scales, evidently in step with the general level of magnetic activity. This discovery suggests that some past variations in terrestrial climate may have occurred in response to variations in the total solar luminosity as well as to the very large variations in the UV and in X-rays. These harder radiations cause enormous variations in stratospheric temperature, with complicated and still not fully understood effects on the troposphere. The conditions that support human life may be directly affected. On shorter time scales, the solar UV flux is known to control phenomena such as the orbital lifetimes of artificial satellites in low Earth orbit because it warms and inflates the upper atmosphere, producing increased drag. On longer time scales, we do not have a sufficiently long quantitative data base to definitively establish the terrestrial effects of solar variability.

The Causes of Solar Variability

We have known since Galileo's time of the imperfections of the Sun, and these hint at luminosity variations. We now have data that show these variations directly (Figure 3.2). Several different mechanisms affect luminosity, and each gives some information about the interior structure that produces the perturbation. The new, precise measures of the total solar irradiance shown in Figure 3.2 have given us several types of solar variability. Table 3.2 briefly describes the currently known contributors to these solar luminosity variations, as observed by the ACRIM instrument on board the *Solar Maximum Mission* spacecraft.

The tiniest variations yet observed are due to the global solar normal-mode oscillations (see section above, "Probing the Solar Interior"). The amplitude of a single *p*-mode is a few parts per million of solar luminosity.

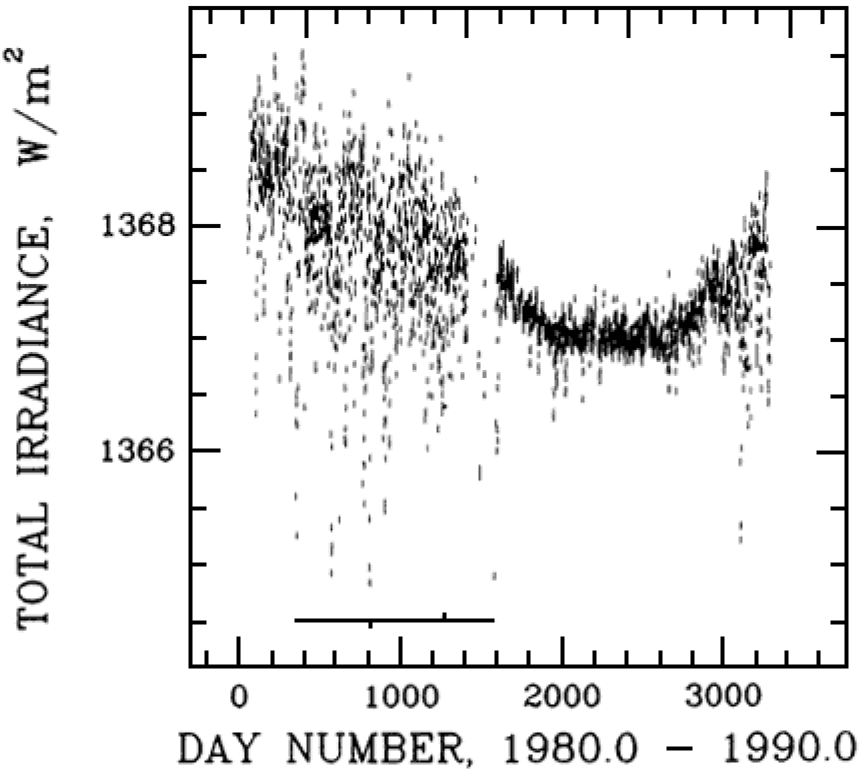

Figure 3.2
Daily values of the total solar irradiance (the "solar constant") as observed by the ACRIM instrument on board the Solar Maximum satellite since 1980. The data show striking dips of a few days' length due to the presence of large sunspots on the visible hemisphere. A general decline toward solar minimum, a flattening during the minimum years 1984 to 1987, and an upturn most recently suggest the existence of a solar-cycle modulation of about 0.1 percent in the solar bolometric luminosity. The data prior to day number 1600 have a reduced precision due to a spacecraft malfunction; Shuttle astronauts repaired it in orbit in 1984. (Courtesy of the National Aeronautics and Space Administration.)

Despite this small amplitude, an individual *p*-mode frequency can be measured to an accuracy approaching 0.001 percent. The distribution of sound speed throughout the solar interior is the main determining factor for the frequency of a *p*-mode, and the resulting sound-speed integrals represent the most precise information about interior structure and dynamics. Millions of normal modes of oscillation exist and appear to be permanently excited in the solar interior.

The sunspot cycle is perhaps the best studied of the solar variations, since some of the phenomenology has been known for hundreds of years.

TABLE 3.2 Identified Components of Solar Luminosity Variability

Cause	Time Scale	Amplitude
p-modes	5 min	a few ppm (rms) per mode
Granulation	1 hr	0.05% rms broadband
Sunspots	a few days	<0.2% peak to peak
Faculae	a few weeks	<0.05% peak to peak
Long-term	11 years?	about 0.1% peak to peak

In terms of solar luminosity variability, the solar cycle appears to produce a variation of some 0.1 percent, due to effects of solar magnetism that are at present poorly understood.

The Nature of Solar Magnetism

As time extends the record of variability, its interpretation becomes steadily more important in studies of solar interior dynamics. The mechanisms that create the solar magnetic field and distribute it through the interior and atmosphere present some of the most fascinating challenges of astrophysics; the solar dynamo, if understood quantitatively, might have analogs in regions as exotic as accretion disks around black holes. Observations of the solar global structure and its evolution, on active-region and solar cycle time scales, represent an observational prerequisite to solving this problem.

The Influences of the Sun on the Earth

Solar magnetic activity produces hard radiation that affects the Earth's atmosphere and has significant social and economic consequences. These effects include the inflation of the Earth's upper atmosphere in proportion to the degree of solar activity, with attendant orbital and pointing disruptions of low-altitude satellites, the disruption of electrical power distribution caused by ionospheric surges, disturbances of navigation systems, and hazards for spacecraft and astronauts via solar flare energetic particles. Also, solar variability must be studied in the context of its linkage to climate and climate change.

Much of the interest in applied solar physics centers on the need to predict solar activity for applications in the communications, navigation, electrical power, pipeline, oil exploration, and space industries. This problem is reminiscent of weather forecasting, but there are certain simplifications that might make the prediction of solar activity easier. In principle, we can obtain solar data of uniform quality across an entire hemisphere with good calibration and regular, frequent sampling. However, there are intangible uncertainties connected with the unknown physics of the subphotospheric magnetic fields; this latter problem impels us to study basic solar physics as vigorously as possible.

Initiatives and Impacts

Solar global observations include synoptic data, in which various tracers of solar activity are followed through the years in a semiquantitative manner. The conduct of such observations tends not to interest research-oriented solar physicists (nor most astronomers), in part because very long time scales are necessary to achieve results. Perhaps for a similar reason, potential commercial users have not stepped forward to support the creation of improved data bases.

In spite of this lack of attention, the U.S. program of synoptic solar data compilation and distribution by the National Oceanic and Atmospheric Administration's (NOAA) National Geophysical Data Center is the world's finest, presenting a large body of useful data ranging from white-light to cosmic-ray observations. Unfortunately, many of these data are of the qualitative classical type, benefiting little from recent technological developments in detectors and data-handling systems and reflecting an inadequate degree of access to the stable observing conditions of space.

A modern program of synoptic solar observation and data management is long overdue. Such a program would have interdisciplinary consequences, linking stellar, solar, and terrestrial researchers and applications users. It would also represent an interagency effort, since components of the current synoptic data come from the Department of Defense, NOAA, NSF, NASA, and other sources, none of whose mission responsibilities specifies an adequate program of solar data management.

The components of a new, comprehensive program of quantitative data management should conform to the policy and guidelines of the National Research Council's Committee on Geophysical Data report titled *Geophysical Data: Policy Issues* (National Academy Press, Washington, D.C., 1988) and the Committee on Solar-Terrestrial Research report titled *Long-Term Solar-Terrestial Observations* (National Academy Press, Washington, D.C., 1988). The synoptic solar observations would include, at a minimum, solar imagery at moderate spatial resolution in a number of key wavelengths, with a network of automated and carefully calibrated telescopes situated so as to minimize gaps (synoptic observations from space would also be an extremely attractive possibility). The time resolution of the observations should be high enough to permit characterization of rapid fluctuations (e.g., flares and *p*-modes). Grants for theoretical work, to be carried out hand-in-hand with the observational programs, should focus on solar interior dynamics, including dynamo problems, which include the processes that lead to the variability of the solar constant.

THE PHYSICS OF TRANSIENTS

The Basic Issues

A large solar flare releases as much as 10^{32} ergs in times as short as 100 to 1000 s. Much of this energy appears in the form of high. energy particles and hot plasma. It is believed that the flare energy comes from the dissipation of the nonpotential components of strong magnetic fields—coronal current systems—in the solar atmosphere, possibly through magnetic reconnection, but the details of the energy release process as well as the mechanism of particle acceleration are still only poorly understood. The interactions in the solar atmosphere of accelerated electrons produce radio emissions, and gamma-ray and hard X-ray bremsstrahlung, and the interactions of protons and nuclei produce gamma-ray line and neutron emissions. The combined observation of the time profiles of these emissions is one of the best-known tools for studying the temporal development of acceleration processes in astrophysics. For example, flares on the Sun are one of the very few astrophysical sites where it has been possible to study simultaneously the acceleration of electrons and protons. Solar flares are also among the few astrophysical sites from which the escaping accelerated particles can be directly detected. Furthermore, many closely correlated lower-energy phenomena (soft X-ray, EUV, UV, and radio emissions), some of which are the direct consequence of the interactions of accelerated particles, can be observed as well. These lower-energy observations reveal the properties (e.g., temperature, density, and magnetic configuration) of the ambient plasma prior to, during, and after the flare.

The imaging of flares in hard X-rays, the detection of gamma-ray lines and continue from many flares, and the direct detection of solar neutrons are the particularly significant results obtained from NASA's *Solar Maximum Mission* satellite and the Japanese Hinotori satellites. It has been known for some time that the hallmark of impulsive energy release in flares is the acceleration of electrons to tens of keV, as evidenced by hard X-ray emission. These nonrelativistic electrons probably contain a large fraction of the total flare energy. The hard X-ray images have shown that at least some of this energy is deposited at the footpoints of magnetic loops. The simultaneous brightening of distant footpoints suggests that energy released in the loops is transported to the footpoints by electron beams. The observation of impulsive gamma-ray emission from many flares has shown that the acceleration of protons and relativistic electrons is also a common property of the impulsive energy release. The gamma-ray and neutron observations have provided independent (albeit indirect) evidence that the accelerated particles interact at the footpoints. Both the hard X-ray and gamma-ray observations show that the acceleration is very impulsive. Gamma-ray observations have demonstrated that protons are accelerated to GeV energies and electrons to energies of tens of MeV in less than a few seconds. Furthermore, the acceleration of the protons and the electrons is practically simultaneous.

Particles in solar flares could be accelerated by shocks, turbulence, and large-scale electric fields, as well as by a variety of other possible mechanisms. Although it is quite clear that acceleration phenomena on the Sun occur at many sites and produce particle populations of widely different observational characteristics, it is not known whether a single mechanism is responsible for all of the observed acceleration phenomena or whether different mechanisms operate at different sites. Furthermore, it is not known whether particles are accelerated directly from the ambient plasma by a single mechanism or whether the particles are preaccelerated in a process that is distinct from the acceleration mechanism. And perhaps most importantly, it is not clear at all how any of the above mentioned mechanisms can accomplish the very rapid and efficient acceleration that is indicated by the observations.

Particle transport in magnetic flare loops is an interesting and exciting problem. The preferential detection of high-energy gamma-ray continue from flares close to the solar limb suggests that the angular distribution of relativistic electrons in the interaction region is anisotropic, peaking at directions tangential to the photosphere. The required anisotropy could result from magnetic mirroring and losses in a convergent chromospheric magnetic flux tube, provided that the axis of the tube is perpendicular to the photosphere. There is as yet no information on the angular distribution of the ions. Such information could be obtained by observing the shapes of gamma-ray lines with detectors having good energy resolution and by observing neutrons from flares at different locations on the Sun. Many of these observations remain to be carried out.

Abundances

Observations of X-ray and gamma-ray lines from solar flares have provided new techniques for determining abundances in the solar atmosphere. The time-dependent flux of the 2.223-MeV line can provide information on the abundance of ^{3}He in the photosphere, where it has not been obtained by any other method. This line results from neutron capture of hydrogen in the photosphere; ^{3}He is an important neutron sink, and therefore the observed 2.223-MeV line intensity and time profile depend on the ^{3}He/^{1}H ratio in the photosphere.

Nuclear deexcitation line fluences are directly proportional to the abundance of elements in the interaction region of the accelerated particles. This region is most likely located at chromospheric densities in flare loops. The abundances obtained from nuclear line spectroscopy can be compared with abundances obtained by atomic spectroscopy of the photosphere and corona. The results indicate that the abundances of carbon and oxygen relative to magnesium, silicon, and iron, as derived from the gamma-ray data, are suppressed in comparison with the corresponding ratios in the photosphere. It has been suggested that this suppression could be due to charge-dependent mass transport from the photosphere to the chromosphere. In addition to these elements, the abundance of neon has also been determined by gamma-ray spectroscopy. A surprising result is that the neon/oxygen ratio deduced from the gamma-ray data is significantly higher than the corresponding ratio in the corona or in the solar wind. The origin of this difference is not yet understood. It should be noted, however, that the photospheric neon abundance has not yet been measured.

Radiophysics and Plasma Dynamics

Electromagnetic radiation in the vast domain of radio astronomy has demonstrated great potential for diagnostic characterizing of solar structures and dynamics, especially in the corona. In addition to pure electromagnetic waves, the corona generates several other types of radiation, including hydromagnetic waves, Langmuir waves, and whistler waves. These radiations, although not propagating to Earth, still have important roles in energy transport and possibly in particle acceleration for many of the phenomena of solar activity.

The electromagnetic radiation sources include continue from the free-free, free-bound, gyroresonance, and synchrotron mechanisms; in addition, there may also be weak emission lines formed by upper-level transitions in hydrogen or other ions. The gyroresonance and synchrotron mechanisms exhibit strong dependence on the magnetic field intensity and orientation; in general, at centimeter and longer wavelengths the corona may become optically thick during flaring. For millimeter waves, unity optical depth occurs in the upper photosphere in normal free-free opacity. The submillimeter-far infrared spectrum then scans through the photospheric layers down to the opacity minimum at about 1.6 microns.

Plasma waves in general have a much more complex physics and may serve to couple particles and electromagnetic waves in coronal processes such as the Type I-V radio bursts observed in meter-wave dynamic spectra of the Sun. Further, masering cyclotron waves driven by anisotropic distribution functions have been implicated in flare energetics. In general, the numerous plasma wave modes provide a link to the distribution functions of energetic particles, one of the key links between laboratory plasma physics and astrophysical plasma applications.

Coronal Dynamics

The solar corona displays a wide variety of transient phenomena, including the radio bursts mentioned above. These constitute some of the most dramatic forms of solar activity and have yet-unresolved associations with the physics of classical solar flares. In some cases, a powerful flare will follow a white-light coronal transient and produce a clearly defined blast wave that propagates into the interplanetary medium. In other cases, transient phenomena occur in the corona without any soft X-ray or H-alpha manifestation at all—and sometimes from solar latitudes far above the sunspot zones. Current observations are extremely deficient in both synoptic and diagnostic leverage on these coronal phenomena, which is unfortunate because of the rich physics they could reveal. This physics all occurs in a region that is transparent to the observer, since the corona is optically thin. Thus we are not afflicted with the subtleties of radiative transfer theory; on the other hand, stereoscopic observations capable of tomographic reconstructions of the full three-dimensional geometry of these regions are quite feasible in principle.

The coupling of more ordinary flares to the corona also remains a frontier research area. We understand approximately what happens in closed magnetic loops, with powerful energy release signaled by the hard X-ray "impulsive phase," followed by the ablation of dense chromospheric gas up into these loops. Less intelligible are the processes associated with the open field lines known to exist from radio observations. Some flares, often those relatively deficient in hard X-ray and gamma-ray production, couple strongly into the interplanetary medium. Such flares are often associated with one form of "solar cosmic ray" acceleration and coronal transients responsible for geomagnetic perturbations. New observations comparing white-light coronal data with impulsive X-ray signatures suggest that the bulk coronal motions may often precede the impulsive burst, thus raising the possibility that the origin of the flare resides in large-scale magnetic field motions.

Initiatives and Impacts

Hard X-rays and Gamma-Rays

In the hard X-ray and gamma-ray area, observations with high spatial and energy resolution are needed. Hard X-ray imaging spectroscopy of sufficiently good sensitivity, energy coverage, and angular resolution will allow researchers to trace the evolution of the electron spectrum throughout the source so that they can determine the accelerated electron distribution, study the magnetic field geometry, and test theoretical transport models. Hard X-ray and gamma-ray spectroscopy with the keV-energy resolution now possible with high-purity germanium detectors will determine the angular distribution of the accelerated ions and electrons, measure abundances, and determine the temperature and density of the ambient plasma in flares. There are no plans to carry out such high-resolution observations with satellite-borne detectors during the upcoming solar maximum. Long-duration balloon flights therefore present an important alternative.

Neutron Monitors

Ground-based neutron monitors have turned out to be very useful for observing the neutrons produced at the Sun by accelerated particle interactions. Escaping neutrons have been directly detected from one flare by several neutron monitors (e.g., monitors on Jungfraujoch in Switzerland). Escaping neutrons were also detected by the *Solar Maximum Mission* satellite; furthermore, the protons resulting from the decay of the neutrons in interplanetary space were also observed. There are no U.S. plans to operate neutron monitors during the upcoming solar maximum. However, neutron monitors in Europe, the Soviet Union, Japan, and China will be used for solar flare study during this solar maximum.

Radio Observations

Radio observations allow us to study the solar atmosphere from approximately the temperature minimum region out to 1 AU, roughly corresponding to the wavelength range from 1 mm to 100 km. Observational technique at these wavelengths has sharpened to the point that interferometry can produce images at milliarcsecond resolution on the Sun. One milliarcsecond corresponds to only some 700 m!

At present, no large U.S. radio facilities are dedicated to solar observations, although glimpses with nonsolar instruments such as the very large array (VLA) radio telescopes have produced wonderful results. These results, together with the innovative "frequency-agile" observations at Owens Valley and U.S. and Japanese millimeter-wave work, have shown that short-wavelength radio astronomy should be considered seriously in the planning of new observations both for the active and the quiet Sun. A strong case can be made for a "mini-VLA" dedicated to frequency-agile microwave observations at arcsecond resolution; such a facility would be well within the technical state-of-the-art.

MAX-91

MAX-91 is a coordinated program of great value for the study of solar activity during the upcoming solar maximum. The core of the program consists of Japan's Solar A satellite, NASA's Gamma-Ray Observatory (with limited solar observing time), and the Global Geospace Program's WIND spacecraft. In addition, long-duration balloon flights will have a very important role in this program. These flights could carry out the hard X-ray and gamma-ray imaging and high-resolution spectroscopy observations that will not be carried out by the satellite-borne instruments. In addition, a variety of ground-based observations are planned to support these efforts. The scientific objectives of the MAX-91 effort are the study of energy buildup and flare onset and the characterization of energy release and transport mechanisms. As indicated earlier, these issues involve fundamentally high-energy phenomena intimately related to the problems of particle acceleration and transport.

Fast Optical Spectroscopy

Flares, and perhaps other high-energy events, accelerate particles downward into the chromosphere and lower regions of the solar atmosphere with dramatic effect. Observations of these events provide important information about energy and momentum balance in the flare process. The physics of shock formation, explosive evaporation of the chromosphere, and thermal conduction along magnetic flux tubes is vital to the flare process but is still not well understood. If we had a more thorough understanding of the physics of particle acceleration and propagation, we could interpret the older, classic observations such as H-alpha images of flares in new and more relevant ways.

The key observations are optical spectra of flare emission in Balmer and other chromospheric lines with arcsecond spatial resolution and subsecond time resolution. Only a few observations with relatively poor angular resolution and especially poor time resolution have been obtained up to the present time. These have been sufficient, nonetheless, to revolutionize our understanding of the lower parts of flares. Many more observations with better angular and temporal resolution are required. The development of improved instruments to rapidly obtain optical spectra should be supported. The impact of this initiative will be a better understanding of the chromospheric and upper photospheric parts of flares, improved quantitative information about energy and momentum balance in flares, and new diagnostics of thermal conduction along magnetic flux tubes.

Vector Magnetographs

It is evident that magnetic fields are responsible for nearly all solar activity. As a result, a great deal of effort has been devoted to observing magnetic fields in order to understand and predict solar activity. This effort has centered largely on observation of the line-of-sight component of the photospheric magnetic field because it is a fairly easy and robust measurement to make. Such observations give only one component at one level of a vector field that extends in three dimensions. Ideally, observations that yield the full vector field measured in a three-dimensional volume as a function of time are needed. This is a formidable observational task. The problem is complicated by requirements for excellent angular and spectral resolution, high sensitivity to linear and circular polarization, and freedom from polarization effects in telescopes. These requirements have frustrated most earlier efforts to observe the vector magnetic field, in spite of the importance of the task. Now we have improvements in detector technology, new image stabilization techniques, and powerful analysis programs. Thus the promise of obtaining useful vector field measurements, at least in the photosphere, is brighter than ever before. This has led to development activity at nearly every solar observatory. These activities should be supported, and the construction of a few of the most promising instruments should be fully funded.

The impact of a successful vector magnetograph on the study of high-energy solar phenomena will be profound. It will be possible to follow the buildup and storage of magnetic energy, which is thought to power high-energy events. It will also be possible to localize electric current systems, which may trigger explosive energy release. These capabilities offer the potential of predicting solar flare activity with far higher reliability than is currently possible.

Advanced Coronal Observations

As noted previously, it is now suspected that coronal transient phenomena result from the relaxation of stressed coronal magnetic fields. The coupling between this relaxation and the occurrence of associated solar flares or eruptive phenomena is currently unclear. Understanding the transient process requires high-temporal-resolution observations of the solar corona and a more precise understanding of the spatial and temporal relationship between coronal activity and near-surface phenomena. Current instrumentation is inadequate. Revolutionary new coronal observations will be carried out by instruments on board the SOHO spacecraft, and it is within our technical capability to extend coronal remote-sensing observations to 1 AU or beyond.

Limb observations of the innermost corona, with high spatial and spectral resolution, can be obtained effectively with a ground-based k-coronameter. A suitable k-coronameter will feature a sensitive system capable of observing the corona to within 50,000 km of the solar surface with high spatial and temporal resolution, employing the polarization selectivity necessary to observe the corona in the presence of sky light and its fluctuations. Such an instrument is required to examine the nature of the origin of coronal transient phenomena and the relation between transients and surface solar activity. The impact of these observations will be to illuminate the nature of the evolution of the solar large-scale magnetic field and the role of that evolution in generating solar activity.

4

Institutional Issues and Policy Recommendations

In contrast with the bright intellectual promise of solar physics, solar physics within the United States is, and has been, beset with a variety of problems—of which some have become institutionalized over a number of years. As a result, the United States is rapidly losing its leadership in solar physics. In this chapter, the committee surveys these problems, their origins, and their consequences, and it recommends actions designed to solve them. The committee expects that its recommendations, effectively pursued, will go a long way toward correcting the problems.

The scientific initiatives outlined in the foregoing sections are fundamentally interdisciplinary. Thus, for instance, solar neutrino observations affect particle physics, cosmology, solar physics, and the basic physics of stars. Variations in solar luminosity have an impact on atmospheric physics, solar-terrestrial physics, and stellar physics. Solar fine-scale structure involves both ground-based and orbiting observational instruments and has implications for the physics of solar and stellar activity, as well as solar-terrestrial physics. X-ray and gamma-ray observations involve both balloon-borne and orbiting instruments, with implications for high-energy astrophysics, particle acceleration, cosmic abundances of the elements, and the physics of solar and stellar activity. Ultraviolet observations carried out from space affect solar and stellar physics, as well as magnetospheric and ionospheric physics and atmospheric physics and chemistry. It is evident that effective prosecution of such interdisciplinary initiatives requires a high degree of coordination between diverse groups of scientists in widely separated geographical locations.

This requirement for effective interdisciplinary coordination, beyond the usual demands imposed by NSF funding and managing of grants and projects, must be clearly recognized if scientific opportunities are to be exploited in an economical and timely fashion.

It must also be recognized that the solar physics community is currently grappling with a number of internal problems—involving cutbacks in instrumentation, a demographic decline, and diminished representation on university faculty—that persist because they have become institutionalized (see Appendix A, Tables A.1 and A.2). This means that, with a few exceptions, the major observing instruments available to solar physics are usually in national facilities and laboratories. There is little university participation in instrument development, and few students are being trained in this crucial aspect of the science. The situation has developed over a decade or more and can be traced to many causes, such as ineffective representation of solar physics by the solar physicists themselves, a continual erosion in federal funds available for solar physics, and no major new initiatives for over a decade (until the GONG project). The essential point is that these institutionalized problems in solar physics must not be allowed to stand in the way of the scientific initiatives that lie before us.

STRUCTURE OF NSF MANAGEMENT OF SOLAR PROGRAMS

At present, support for solar physics within NSF occurs within the Geosciences Directorate's Atmospheric Sciences Division and Division of Polar Programs, and within the Mathematical and Physical Sciences Directorate's Astronomical Sciences Division (see Appendix B, Table B.1). None of these entities has responsibility to view solar physics as a whole, with its need for interdisciplinary research. Commendably, considerable coordination of scientific activities has occurred between these management structures, as has been evidenced most recently by support for the new initiative for studying the ongoing solar maximum.

This separation of research support reflects the great diversity of the solar physics enterprise, which spans an enormous range of physics, from the detailed plasma physics and hydrodynamics of the outer solar atmosphere and solar wind to the general behavior of the Sun as a star. However, since no single entity within NSF has responsibility for managing this overall research program, there is no coherent direction to the overall NSF solar program, strategic planning is lacking, and coordination and collaborative planning take place on an ad hoc and intermittent basis.

Advocacy for solar science within NSF is weakened because none of the responsible program managers can speak for the overall solar program, and no one has the totality of solar physics as a primary responsibility.

Part of this difficulty is relatively recent in origin. Until 1986, all solar science was carried out within one directorate (the former Astronomical, Atmospheric, Earth, and Ocean Sciences Directorate). The current divided advocacy for the overall solar program has evidenced a potential for severe erosion of individual programs in the competition for scarce resources.

Finally, because solar physics is only a part of the overall oversight responsibility of the grants and centers programs of the Atmospheric Sciences, Polar Programs, and Astronomical Sciences Divisions, it is organizationally difficult, if not impossible, to maintain an appropriate balance between the research grants, support for the national centers and observatories, and scientific justification for the facilities portions of the overall NSF solar physics effort. This imbalance can lead to a distorted perception of the size and vigor of the client scientific community. Thus the notion of "proposal pressure," often used by funding agencies to justify expansion of efforts in a particular area of research, is made meaningless if the university community of scientists can respond to the imbalance by shifting proposal submissions. In addition, the bureaucratic separation of the university grants programs in solar physics between at least two directorates has meant that no single office has responsibility for managing a coherent university program in solar physics.

The committee recommends that NSF develop a coherent, well-defined infrastructure for solar physics, with that agency properly assuming the lead role in support of basic research in ground-based solar physics. Thus the committee recommends that the internal structure for funding of solar research within NSF be changed so that support for both grants and centers is administered by a single entity within NSF whose primary responsibility is solar physics.

This key recommendation reflects the fact that the roots of solar physics indeed lie in the astronomical, astrophysical, and solar-terrestrial communities. The diversity of these roots is both an asset and a liability. It is an asset in the sense that efforts in solar research can span an enormous variety of subdisciplines, thereby offering the researcher a wide variety of intellectual challenges and a broad arena in which to operate. It is a liability in the sense that solar physics is rarely recognized as a core subject—an intellectual pursuit of value in itself. Solar physics currently is a minority subject within either the astronomical or the solar-terrestrial community at NSF, whose structure is typically built on traditional root areas; the issues raised above are symptomatic of this. Although solar physics is an interdisciplinary subject, the committee believes that a coherent national program administered from a single office is required to realize the benefits of interdisciplinary efforts.

The close connection of solar physics with space plasma science, magnetospheric physics, and solar-terrestrial studies suggests that the base of operations would fit most appropriately into NSF's Geosciences Directorate, which currently provides a major part of the NSF support for solar physics. On the other hand, the physics of stellar structure and activity, high-energy phenomena, and significant commonality of instrumentation argue for a close connection between solar physics and astronomy (and hence for a connection with the Mathematical and Physical Sciences Directorate). This committee sees the choice of appropriate directorate as properly an NSF decision; however, no matter which directorate is ultimately decided on, the recommended solar physics division or section—if it is not entitled as a division—should have budgetary authority and control comparable to those of a division. The office must be able to speak for itself, bear the responsibility for its initiatives, and have the freedom to develop the scientific liaisons that are essential to its projects. Obviously, the person chosen to direct this office, along with successful implementation of the necessary independence and responsibilities of the office, will be crucial to the success of the scientific initiative in solar physics.

OTHER MAJOR ISSUES AND NEEDED INSTITUTIONAL CHANGES: DIRECTING FUNDING APPROPRIATELY

Respond to Changing Demographics of Solar Physics

Solar physics is a research field abundant with exciting opportunities for new students as well as for those already working in the field. Indeed, scientific prospects have never been so promising. As a result, new people are entering the field in Europe, Japan, and China, and first-class students are receiving training and making careers in solar physics overseas in increasing numbers. A similar situation does not prevail in the United States. As detailed in Appendix A, the population of American solar physicists is nearly static and, as one result of the lack of a university presence, is not renewing itself sufficiently for the United States to maintain its leadership role. This is in marked contrast to the situation in, for example, European astronomy. Why?

The population of solar physicists in American colleges and universities is small compared to that of astronomy as a whole, and it is thinly dispersed. Although more than 50 universities and colleges have faculty who publish solar physics research, only a handful of academic groups are strong enough to attract and support good students. Most academic solar physics is deficient in numbers and scope, typically involving one or perhaps two faculty members working on theoretical studies. Fewer than a dozen academic groups are involved in developing solar physics experiments. This lack of experimental or observational effort in universities has also resulted in a critical shortage of students and young researchers with experimental skills. Furthermore, the very deficiencies in the university and college arena have led—to no one's surprise—to corresponding deficiencies in the current research community.

Thus all other factors being equal, solar physics in its minority status in most university departments is handicapped in recruiting enough qualified students. Part of this problem is that is is difficult for individuals or small groups to establish significant research programs, given the low and fluctuating level of NSF's astronomy grants for solar physics research. Another part of the problem is that students and faculty in most departments receive insufficient exposure to front-line solar research, particularly experimental and observational activities.

The National Science Foundation cannot easily remedy these demographic issues directly. However, the demographic problems are entwined with other difficulties faced by solar physics as a discipline. This committee firmly believes that in the course of addressing these other problems, NSF must act—whenever possible—to ameliorate the demographic problems. The following recommendations call attention to such possibilities.

Strengthen the Experimental Base of Universities and Encourage Interaction Between National Centers and Universities

The deficiencies in the research community engendered by the lack of strong experimental or observational efforts at universities will have serious consequences for the future conduct of solar research in the United States.

Whereas a growing number of universities provide, or are actively planning to provide, major nocturnal astronomical telescope facilities that in to exceed significantly the power of those at the NSF-supported national centers, no corresponding development of solar instrumentation is taking place at universities. Consequently, national centers play a more pivotal role in American solar physics than in astronomy or astrophysics. National centers, as principal employers of experimental and observational talent in the field, must assume greater responsibility for the generation of new talent in this area. Universities need support in this area for two reasons: Solar physics requires new talent able to implement new technology effectively, and friendly competition in the development of new techniques for acquiring and analyzing solar data is in the best long-term interests of the science. Such competition arises naturally in physics and in astronomy but evidently is lacking among university solar experimentalists who work in very small groups that are unable to contribute equally to the efforts carried out within the federally funded and government research centers.

The committee recommends that NSF support and encourage university programs in experimental and observational solar physics and take steps to strengthen the partnership between, on the one hand, federally supported research centers and, on the other hand, universities.

The committee recommends that NSF make incremental funding available for extended periods at several selected universities to establish programs directed toward the training of students in solar instrumental and observational techniques.

More specifically, the committee suggests that three or four universities be supported with long-term grants that would (1) enhance the universities' extant instrumentation (laboratory or observational), (2) support faculty and students specializing in instrumentation, and (3) encourage the development of new instrumentation utilizing new technology. The committee suggests that, in the last area particularly, more effective partnerships between universities and federal centers can be forged—partnerships involving the exchange of faculty and technical staff, hardware and software, and workshops and short courses.

Government, federally funded centers, and private industrial firms engaged in research and development have paid some attention to problems of education and support for university training, but their efforts have been inadequate, at least in the eyes of concerned university faculty. There has been suspicion, because university faculty feel that government and federally funded research centers compete unfairly for the limited federal dollars available for solar research. The same faculty question the balance of NSF funding between support for the national centers and grants to universities, wherein the national centers receive the majority of the funding. This imbalance is especially notable in the case of the Astronomical Sciences Division within the Mathematical and Physical Sciences Directorate.

The committee suggests that the centers more actively engage in the direct support of educational programs at universities and colleges by (1) offering summer undergraduate research opportunities in solar research, (2) supporting graduate research assistantships at universities, including opportunities for partial residency at the centers during a student's tenure, (3) offering postdoctoral appointments at the centers, and (4) sponsoring an active visiting scientist program for the benefit of university teaching and research faculty. The partnership will be real and effective when all centers apply an appropriate amount of their annual solar physics research budgets to the above programs (the historical level of such support at one of NSF's solar research centers has been an approximate level of about 10 percent). The infusion of funds for these educational purposes will clearly signal such a partnership and will enable university programs to advertise to prospective students and researchers both the existence of a stable base of funding for student and faculty support, and broader experimental, observational, and research opportunities.

Protect Newly Funded Initiatives by Ensuring Their Continued Support

The vigor of a scientific field is more accurately gauged by the vigor of new initiatives than by the size of the ongoing enterprise. Indeed solar physicists are initiating a number of new programs, discussed in Chapter 3 of this report, that couple novel observations with new theoretical work. This testifies to the basic health of the discipline; however, this committee has also identified a number of serious difficulties that cast the future of these initiatives into some doubt.

First, in contrast to the success of the large-scale, national initiatives at the proposal stage, such as the GONG project, which involves substantial participation of the solar community, smaller-scale, university-based initiatives have fared poorly. Indeed, virtually no funds from the Astronomical Sciences Division's instrumentation program are supporting efforts at universities to develop solar instruments; this is one of the elements contributing to the difficulties of training young experimentalists at universities.

Second, although NSF rightly encourages new initiatives, the evidence in solar research is that such initiatives do not receive the necessary commitment of clearly identified funds to carry them through to completion. Thus NSF effectively has allowed the funding for the GONG project, currently the only funded solar initiative, to be absorbed into the base budget of the National Optical Astronomy Observatories (NOAO). With the increasing curtailment of the NOAO base budget, this initiative is thus pitted against the NOAO base-level effort for scarce resources.

The disturbing tendency to allow funding for exciting new initiatives in the forefront of solar science to become enmeshed in the politics of budget cuts within the base budgets of the national centers forces a confrontation between activities that are really complementary. This NSF-imposed competition between initiatives and the base level of effort at national centers is well illustrated by the history of funding for the GONG project. A general turnover of scientific projects is healthy, but in the specific case of the national centers this competition pits projects that represent the most vital new science against ongoing and service activities at unique public facilities. The basic justification for national centers—to enhance resource utilization—needs to be reaffirmed.

The committee recommends that NSF protect newly funded initiatives in solar physics by ensuring their continued support

until they are completed. Unless funding for such initiatives can be assured within the limits imposed by general federal budget restrictions, NSF should avoid pursuing new initiatives. The committee further recommends that NSF refrain from commingling funds targeted for new initiatives with base-level support funds in response to budget-cutting pressures.

Provide Funding for Highest-Priority New Initiatives

The following recommendations for specific projects and initiatives are based on the discussions in Chapter 3 and on the committee's judgments of the most interesting and exciting science in the offing.

The committee recommends that NSF provide funding for the highest-priority new initiatives in the four major areas at the forefront of solar research: (1) probing the solar interior, (2) the physics at small spatial scales, (3) mechanisms underlying the solar cycle, and (4) the physics of transients.

Probing the Solar Interior

Until recently, all knowledge of the solar interior was limited to theoretical extrapolation from the visible surface of the Sun, using calculated opacities and an assumed age and chemical composition. The current probing of the solar interior, first through neutrino observations and more recently through helioseismology, has opened a new era in the physics of the Sun and stars.

Neutrino observations.

The results of the ^{37}Cl neutrino observations are well known: The detected flux of neutrinos in the 1-to 15-MeV range is about one-quarter of the best theoretical value. The discrepancy may lie in the physics of the neutrino, or it may lie in the physics of the Sun. A 5 percent downward adjustment of the theoretical temperature at the center of the Sun would resolve the dilemma. The possibilities involve such fundamental questions that new initiatives are under way to investigate further. The complete neutrino energy spectrum of the Sun would provide especially powerful quantitative constraints on the conditions in the central core, as an important part of determining conditions in the solar interior; measurement of the ^{8}B neutrino properties is particularly important in this regard. While these experiments are being planned and implemented, the suggestion from the ^{37}Cl neutrino detector, that the neutrino flux from the Sun varies with the magnetic cycle, makes it necessary for us to continue that experiment for another decade—to determine, if possible, the reality of the effect—and to continue support for the Kamiokande II experiment as well. If there is such a variation of the neutrino flux with the magnetic cycle, it implies that the neutrino has a small but nonvanishing magnetic moment.

Helioseismology projects.

The other partner in the direct probing of the solar interior is the new field of helioseismology, which, by inverting the observed frequency spectrum of global modes of oscillations, can be used to constrain the variation of temperature, molecular weight, and gas density as a function of depth below the surface. By measuring the splitting of the individual *p*-mode frequencies caused by rotation, helioseismology can constrain the variation of the angular velocity as a function of depth. By measuring local variations of the frequency and amplitude, helioseismology can provide a measure of the magnetic field structure below an active region or large sunspot.

The fundamental observational problem is to obtain large, unbroken runs of data for the precise determination of the individual mode frequencies. South Pole observations have obtained runs of a few days, demonstrating the feasibility of deduction of conditions down through the convective zone. The GONG project's worldwide network of six observing stations is the scientific initiative aimed at measuring *p*-modes with degrees from 0 to 300. The data from this project will greatly reduce noise and aliasing, providing a quantitative picture of roughly the outer two-thirds of the solar radius. Helioseismology also holds promise, with a reduced detector background, for the detection of the elusive *g*-modes. Detection of *g*-modes is essential for precise measurement of the temperature, density, and molecular weight in the central core, an important adjunct to the future neutrino initiatives in straightening out the puzzle of the physics of the solar interior.

The committee urges that the GONG project's network be completed and put into operation in a timely fashion.

The Physics at Small Spatial Scales

This report has described the important physical problems that can be illuminated by studying the small-scale structure of the solar atmosphere. Current efforts to develop instrumentation for observing and interpreting solar vector magnetic fields should be continued. Equally important are current efforts to develop adaptive optics to achieve high-angular-resolution observations from the ground.

But major progress in this area awaits the availability of a large-aperture solar telescope capable of observing the Sun with high angular resolution and high flux levels. Although the solar telescopes on Sacramento Peak and at Kitt Peak in certain cases still represent the forefront of solar instrumentation in the world, this primacy is being challenged now with the advent of the European solar telescopes in the Canary Islands, especially as the Europeans begin to fully equip their new telescopes with modern, state-of-the-art instruments.

The committee recommends that NSF give priority to the replacement of existing national solar telescopes with state-of-the-art instruments. NSF should vigorously support efforts to replace the National Solar Observatory facilities with a large-aperture solar telescope and should do so at the best possible site, possibly in collaboration with European scientists and others. In particular, the committee most strongly recommends that NSF support activities leading to the definition and siting of this new telescope system.

One option for pursuing this goal is substantial participation in the international LEST consortium. The NASA OSL would provide complementary observations, including data at shorter wavelengths.

The committee further recommends that, when such new facilities become available and when they meet the needs of the U.S. solar community, NSF consider closing outmoded solar telescopes.

Mechanisms Underling the Solar Cycle

The slow variations in the Sun's output are a consequence of processes in the solar interior that are very poorly understood. Fluctuations in the Sun's radiation are suspected to have significant longer-term climatic effects. They are known to have significant effects at wavelengths where flux increases on even short time scales can cause dramatic inflation of the terrestrial atmosphere. We must establish a sufficiently long and quantitative data base to be able to characterize the terrestrial effects of solar variability.

The time is ripe for a new direction in observations of solar variability, given the advance of technology and the renewed interest in the basic physics of solar variability and in its terrestrial consequences. The establishment of a ground-based network of well-calibrated automated telescopes capable of monitoring solar variability on a scale of many years would provide the needed observational capability. This capability should migrate into an observing site in space, such as a space station or preferably a platform at geosynchronous orbit, when that becomes available.

The Physics of Transients

Few natural phenomena in the solar system can rival solar flares and transients for the drama of their outbursts. Their indirect effects—such as the aurorae—have long been part or the human experience, and they continue to confront us most directly in the disruption of long-distance communications. Yet our understanding of these transients and the associated physical processes —from particle acceleration to radiative output—is primitive, and the effects of these transients on the terrestrial space environment are substantial. Thus aside from posing such questions of fundamental physics as how high-energy particles are accelerated, these transients also challenge our abilities to predict them and their terrestrial effects.

With the imminence of the next solar maximum, the current plans of NSF to support related experimental, observational, and theoretical studies are to be applauded. This program, under the aegis of the MAX-91 initiative, is planned to be carried out in coordination with complementary programs conducted under the purview of NASA. The committee supports these plans fully and commends both NSF and NASA for this successful interagency planning effort.

Appendixes

Appendix A

The Demographics of Solar Physics

Age Distribution

Questionnaires eliciting age by decadal grouping were mailed to 275 of the 301 current U.S. members of the Solar Physics Division of the American Astronomical Society, which kindly provided address labels for this purpose. This committee received 200 returns—124 from individuals and 76 from respondents who provided information for the solar physics staff members of their institutions (16 returns were excluded because of the possibility of duplicate counting). For clarity, the committee therefore presents the individual and institutional responses separately (Table A.1). The analysis is limited to PhDs. Table A.1 shows a trend that is consistent with recent independent studies of the age distribution of U.S. natural scientists and engineers, namely that these populations are not replacing themselves.

Workplace Distribution

The type of institution employing PhD solar physicists in 1987 is shown in Table A.2. Parallel information for PhD astronomers as a whole is also given for comparison. Data for the solar physicists were obtained from the American Astronomical Society's Solar Physics Division mailing list provided to the committee for this report. Data for the type of employment for PhDs working in astronomy were provided by the Education and Employment Division of the American Institute of Physics. Table A.2 indicates that solar physics researchers are significantly more represented at the few government laboratories and underrepresented at the many universities, compared, for example, to astronomers as a whole.

TABLE A.1 Age Distribution of PhD Scientists in the Field of Solar Physics Responding to Questionnaires

	Age Group						
Questionnaires Returned	20–29	30–39	40–49	50–59	60–69	70+	Total
Individual returns	4	35	47	18	15	5	124
Institutional returns	10	19	18	6	6	1	60
Total	14	54	65	24	21	6	184

TABLE A.2 Type of Employment in 1987 for PhDs Working in Solar Physics Compared to That for PhDs Working in Astronomy, by Percent

Workplace	Solar Physicists	Astronomers*
University or college	32	58
Industry	10	3
Government	29	18
FFRDC** and research institute	12	21
Other+	17	-
Total	100	100

* Based on a sample survey conducted by the American Institute of Physics (sample size: 134 for PhDs working in astronomy).
** FFRDC, federally funded research and development center.
+ Includes 26 non-U.S. scientists and 26 scientists who provided home addresses only and could not be otherwise classified by the committee.

Appendix B

National Science Foundation Funding for Solar Physics

Currently solar physics research is supported by three divisions in two separate directorates within the National Science Foundation (NSF). Originally the Astronomical, Atmospheric, Earth, and Ocean Sciences Directorate provided support for solar physics within a single directorate. In 1986 the Division of Astronomical Sciences was moved to the Mathematical and Physical Sciences Directorate, and at the same time NSF formed a new Geosciences Directorate consisting of the Atmospheric Sciences, Earth Sciences, and Ocean Sciences Divisions, plus the Division of Polar Programs. The Geosciences Directorate now provides a major source of funding for solar physics.

Geosciences Directorate

Grant support to individual scientists for solar physics research is provided by the Atmospheric Sciences Division, which also supports studies of solar activity as it relates to an understanding of the solar influences on the Earth's upper atmosphere and near-space environment. In addition, support is provided for the High Altitude Observatory (HAO) of the National Center for Atmospheric Research. The HAO is one of the largest solar research institutions in the United States, with a permanent staff of approximately 15 PhD scientists and the addition of about a dozen visiting scientists each year with substantial funding from other agencies. In addition, a small number of grants for solar physics research conducted in the polar regions is provided by the Division of Polar Programs. Each division also has a Facilities Section with separate responsibility for supporting necessary facilities, maintenance, and instrumentation.

Mathematical and Physical Sciences Directorate

The Astronomical Sciences Division provides grants to individual scientists for research in solar physics and the solar-stellar connection. In addition, solar physics support is provided by an NSF contract to the Association of Universities for Research in Astronomy, Inc. (AURA) for the National Optical Astronomy Observatories (NOAO), which manages and provides funding support for the National Solar Observatory (NSO), Tucson, Arizona, also one of the largest solar research institutions in the United States, with 15 PhD scientists and 10 affiliated PhD scientists funded by non-NSF sources.

National Science Foundation Budget for Solar Physics

Table B.1, a summary of the NSF budget for solar physics for FY 1985 through FY 1988, shows the breakdown of support for grants and for centers and initiatives.

Table B.1 shows that solar physics funding for both the HAO and the NSO has declined in terms of constant dollars (1982 = 100) from FY 1985 through FY 1988. The subtotal for grants has increased for these same years, although the significant part of that increase has come from the Division of Atmospheric Sciences. Overall, NSF support for the field of solar physics has remained approximately level in terms of constant dollars from FY 1985 through FY 1988, except for the funding for the Global Oscillations Network Group (GONG) initiative, included as part of the NSO budget. However, when the GONG program is completed, if not before, both the HAO and NSO, which have already sustained budget cuts, will need significant funding to retain their vital roles as national centers.

TABLE B.1 NSF Summary Budget Breakdown of Support for Solar Physics Research (millions of dollars, corrected for inflation, FY 1982 = 100*)

	Fiscal Year			
	1985	1986	1987	1988
Grants**				
ATM	1.40	1.52	1.43	1.75
ASM	0.64	0.62	0.98	0.72
DPP	0.09	0.09	0.09	0.25
Subtotal grants	2.13	2.23	2.50	2.72
Centers and initiatives**				
HAO/NCAR	3.36	3.10	2.95	2.86
NSO/NOAO	2.67	2.50	2.60	2.61
NSO/GONG initiative	0.22	0.31	0.90	0.93
Subtotal centers and initiatives	6.25	5.91	6.45	6.40
Total solar physics	8.38	8.14	8.95	9.12

SOURCE: Personal communication, NSF program directors: grants ATM, Dennis Peacock; grants ASM, G. Siegfried Kutter; grants DPP, John Lynch; HAO/NCAR, Giorgio Tesi; NSO/NOAO and NSO/GONG, Seth Tuttle.

* Inflation adjustments (tailored to fiscal year basis using quarters 4, 1, 2, 3) from Table 7.4, Implicit Price Deflators (1982 = 100), Survey of Current Business, Vol. 68, No. 7, July 1988, p. 90, U.S. Department of Commerce, Bureau of Economic Analysis, Washington, DC 20230. Personal communication, Shelby Herman, for final quarter, 1988, final estimate. FY 1985, 108.5; FY 1986, 110.6; FY 1987, 111.5; FY 1988, 114.5.

** ATM—Atmospheric Sciences Division; ASM—Astronomical Sciences Division; DPP—Division of Polar Programs; HAO/NCAR—High Altitude Observatory, National Center for Atmospheric Research; NSO/NOAO—National Solar Observatory, National Optical Astronomy Observatories; NSO/GONG—National Solar Observatory, Global Oscillations Network Group.

Appendix C

Previous Relevant National Research Council Reports

1. *Space Plasma Physics: The Study of Solar-System Plasmas* (Colgate Report), National Academy Press, Washington, D.C. 1978.

Recommended that solar-system plasma physics have high priority in order to remain an integral part of the space-science research effort of the United States. Rapidly evolving theory and new technology require that planning and implementation be regularly updated. Recommended problem-oriented missions, vigorous improvements in theory development, combined with data management, and ground-based observations.

2. *Solar-System Space Physics in the 1980's: A Research Strategy* (Kennel Report), National Academy Press, Washington, D.C. 1980.

Focused primarily on a balanced program of space observations. Established scientific goals that remain the guiding force of this science: "The objectives of solar-system space research are to understand the physics of the Sun, the heliosphere, the magnetospheres, ionospheres, and upper atmospheres of the Earth, other planets, and comets. Studies of the interaction processes that generate solar radiation and link it to the Earth should be emphasized, because they reveal basic physical mechanisms and have useful applications."

3. *Solar-Terrestrial Research for the 1980's*, National Academy Press, Washington, D.C. 1981.

Emphasized the importance of the coupling processes in the large scheme of energy transfer from the sun to the troposphere of the earth and stressed a unified set of scientific recommendations for a broadly based program of theory and ground-based and spaceborne observations.

This decadal strategic planning document also recommended that national programs of solar-terrestrial research be coordinated among the interested federal agencies.

4. *Astronomy and Astrophysics for the 1980's: Vol 1: Report of the Astronomy Survey Committee*, National Academy Press, Washington, D.C., 1982; *Vol 2: Report of the Panels* (Field Report), National Academy Press, Washington, D.C. 1983.

Described decadal research strategy for the 1980s for astronomy and astrophysics. Established foundation for major space-and earth-based observation systems. Emphasized linkage between NSF's Astronomical Sciences Division ground-based program and the NASA space-based program as a partnership. These two reports are expected to be followed by a similar decadal research strategy report in 1992.

5. *The Role of Theory in Space Science*, National Academy Press, Washington, D.C. 1983.

Emphasized the conclusion that 20 years of space research had taught that the physical processes that we study in the solar and planetary system occur throughout the astrophysical universe. The same discipline—plasma physics—defines a basic language used in both fusion (a source of clean energy) and space research. The report concluded that theory in solar-system plasma physics serves in many ways as a model for theory development in space research and astrophysics, particularly as it becomes a quantitative science.

6. *Challenges to Astronomy and Astrophysics: Working Documents of the Astronomy Survey (Field) Committee*, National Academy Press, Washington, D.C. 1983.

Presented report of the Working Group on Solar Physics (Chairman Arthur B. C. Walker) to the parent Astronomy Survey Committee (Chairman George B. Field). The working group was "greatly alarmed by the rarity of solar research programs at U.S. universities" (p. 96) due in part to the mission orientation of the funding agencies. Recommended competitive awards to young astronomers, core support for universities plus instrumentation support, sufficient funding for Sacramento Peak and Kitt Peak National Solar Observatories to carry out their missions, and support for solar radio astronomy.

7. *An International Discussion on Research in Solar and Space Physics* , National Academy Press, Washington, D.C. 1983.

Report of a workshop sponsored jointly by the National Research Council's Space Science Board and the European Space Agency's Space Science Committee. Recommended the establishment of an international program in solar and space physics in which major projects identified by NASA and ESA would form complementary elements, improved data exchange, and strengthening of the teaching of solar and space physics in physical science curricula.

8. *National Solar-Terrestrial Research Program*, National Academy Press, Washington, D.C. 1984.

Presented an implementation strategy for the recommendations contained in *Solar-Terrestrial Research for the 1980's* (No. 3 above). Recommended a national solar-terrestrial research (STR) program, funded by interested federal agencies and built around the International Solar-Terrestrial Physics Program (ISTP), a key NASA program. ISTP, the Upper Atmosphere Research Satellite (UARS), and the Solar Optical Telescope (SOT) are the integral elements, along with several data management initiatives, of the national STR program recommended.

9. *A Strategy for the Explorer Program for Solar and Space Physics* , National Academy Press, Washington, D.C. 1984.

Recommended a number of limited objective, scientific problems at the forefront of the discipline that could be addressed in the future with spacecraft of the Explorer class. The Committee on Solar and Space Physics identified Explorer spacecraft as ideal for the specific problem-oriented studies essential to the field, while recognizing that major global objectives must be addressed by observatory-class missions. Recommended an average of approximately one Explorer satellite launch per year, commensurate with the scientific opportunities for solar and space physics research.

10. *Solar Terrestrial Data Access, Distribution and Archiving*, National Academy Press, Washington, D.C. 1984.

Provided detailed recommendations for implementing an effective approach to what is perceived as a key functional problem, and therefore a key objective, of solar-terrestrial data management—to provide flexible, evolutionary data accessibility.

11. *The Physics of the Sun*, National Academy Press, Washington, D.C. 1985.

Undertook to provide future scientific directions for the study of solar physics of the kind that the Colgate report (No. 1 above) provided for space-plasma physics. It stressed the important relationships of solar physics to astrophysics and physics. Both ground-based and space-based observations were considered. Concluded that the remarkable advances in the power of space observations, as well as advances in solar neutrino astronomy and solar seismology in the past quarter-century, have once again brought solar physics to the forefront. Recommended a special need to encourage and support the university role in solar physics. Found that because solar physics is currently observation limited, more numerous space and ground observations will be required, interpreted through improved numerical modeling. An Advocacy Panel, appointed by the Space Science Board, recommended a vigorous NASA solar research program planned in such a way as to promote strong interaction between researchers in solar physics, solar-terrestrial physics, stellar physics, and other areas of astrophysics and physics.

12. *An Implementation Plan for Priorities in Solar-System Space Physics* , National Academy Press, Washington, D.C. 1985.

Updated the scientific objectives of *Solar-System Space Physics in the 1980's: A Research Strategy* (No. 2 above) and described a plan for implementing the objectives. The major missions recommended for NASA included previously approved programs (the Upper Atmosphere Research Satellite (LIARS) and the Solar Optical Telescope (SOT)) and the free flyers—the International Solar Terrestrial Physics Program (ISTP), the Solar Probe (SP), and the Solar Polar Orbiter (SPO). ISTP was identified as the highest-priority unfunded program. Moderate programs for use of Explorer-class satellites (see No. 8 above) were recommended at a one-per-year rate. Evolution toward two solar system space physics facilities on the Space Station—the Advanced Solar Observatory and the Solar Terrestrial Observatory—was foreseen.

13. *Solar and Space Physics*, in the compendium volumes titled *Space Science in the Twenty-First Century: Imperatives for the Decades 1995 to 2015*, National Academy Press, Washington, D.C 1988.

Developed an overall space-based program that addresses the most significant topics in solar and space physics, clearly defines the priority of investigations, and will be affordable by NASA. Assuming that planned programs of NASA are carried out by 1995, defined the scientific objectives for the subsequent decades through 2015 and specified new programs to carry out these objectives. A key portion of this report is the definition of technological developments that will be required to support the space missions of that era.

14. *Long-Term Solar-Terrestrial Observations*, National Academy Press, Washington, D.C. 1988.

This report of the panel established by the Committee on Solar-Terrestrial Research found that data acquisition, i.e., making observations year after year as required—is insufficient to ensure the health and vitality of solar-terrestrial research and operational services that satisfy important national needs, such as worldwide communication and navigation systems; transmission lines for oil, gas, and electricity; geological prospecting; global environmental change; lifetime of earth-orbiting satellites and spacecraft; and physical safety of astronauts. Identified a set of observations to specify the links coupling the earth to the sun. Recommended that these observations be taken continuously to provide the data bases with which to answer the essential questions in solar-terrestrial physics and to support numerical modeling. Recommended strengthening scientific and federal agency support for improved data management centers to ensure data accessibility.

Recommended a scientific body to oversee the changing science priorities and to evaluate the quality, viability, continuity, preservation, and accessibility of long-term solar-terrestrial data necessary for research and theory development.

15. *Geophysical Data: Policy Issues*, National Academy Press, Washington, D.C., 1988.

Concluded that geophysical data, including solar data, often collected at enormous expense, represent a national resource that must be preserved and made available, tasks for which current management policies and procedures are inadequate. Recommended adoption of specific policy guidelines by each federal agency and scientist engaged in geophysical and solar physical activities.