High Altitude Observatory
National Center for Atmospheric Research
Boulder, Colorado 80307

This report covers research activities during the period October 1986 through September 1987.

I. INTRODUCTION

The High Altitude Observatory (HAO) focuses its research on solar and solar-terrestrial physics (including ionospheric physics and aeronomy) and related astrophysics. HAO is a division of the National Center for Atmospheric Research (NCAR), which is operated under the sponsorship of the National Science Foundation by the University Corporation for Atmospheric Research. Scientific research within HAO is aimed at: an understanding of the balance of energy and momentum transport throughout the solar atmosphere and its relationship to the physical structures that comprise the sun and the interplanetary medium; an understanding of the nature of the solar cycle, including the relation of solar internal processes and the various forms of the solar output; and an understanding of the coupling of the solar output into the global terrestrial system.

In 1987, Grant Athay was Acting Director until 1 March 1987 when Peter Gilman became the new director. Gilman was the head of HAO's Solar Interior scientific section. Research activities were reorganized into four sections and one group: Solar Atmosphere and Magnetic Fields (Andrew Skumanich, Head), Coronal and Interplanetary Physics (Boon Chye Low, Head), Solar Interiors (Peter Gilman and Tim Brown, Heads), Terrestrial Interactions (Raymond Roble, Head), and the Solar Maximum Mission Group (Arthur J. Hundhausen, Head). Support of research efforts was provided by the Computing Services Group, the Instrumentation Group, and the Research Support Group. The staff consisted of approximately 19 Ph.D. scientists and 45 support personnel. Also, research efforts were enhanced through an active visitor program, which supported 15-20 short- and long-term visiting scientists from the United States and abroad.

Research facilities, instrumentation, and resources included: An observing station in Hawaii, where the Mark III K-coronameter chromospheric variability monitor and the prominence monitor instruments are housed; the solar diameter instrument, located at the NCAR laboratory building in Boulder, Colorado; the Fourier tachometer (FT II), operated jointly with the staff of the National Solar Observatory (NSO) at Tucson, Arizona; the Solar Stellar Spectrophotometer located at Lowell Observatory operated jointly with the Universities of Pennsylvania and Illinois; instrumentation for coronal observations from space, including the SPARTAN, white-light coronagraph and a coronagraph/polarimeter on board the Solar Maximum Mission satellite; an array of computing facilities, including HAO's two VAX-11/750 and two Integrated Solutions computers and NCAR's Cray 1A and Cray XMP computers; and an extensive data bank of past ground-based and space observations of the solar corona and other solar features.

II. RESEARCH HIGHLIGHTS

The research goals of the High Altitude Observatory (HAO) cover a broad spectrum of problems encompassing the causal mechanisms and spectral form of solar variability together with its terrestrial consequences. Intense magnetic fields generated in the solar interior through the interaction of convection and rotation permeate the outer layers of the sun and the heliosphere, extending beyond the planetary system. In one form or another, these fields determine both the magnitude and form of solar variability. Interior magnetic fields alter the outward flow of energy—directly, by the fluid energy transformed into magnetic energy and by providing additional modes of energy transport to the outer layers, and indirectly, by altering both the convective and radiative transport efficiencies. In the solar atmosphere, the magnetic fields control the thermal and dynamic properties that, in turn, govern the form in which the variable energy flux emerges. In combination, these effects produce both a time-dependent solar constant and a redistribution of energy flux into high-energy photons and the solar wind. These latter energy fluxes play important roles in driving the outer layers of the terrestrial atmosphere.

During this report year, HAO continued to focus on research in four major subject areas represented by the four scientific sections, under its director, Peter Gilman. These sections are: Solar Interior, Solar Atmosphere and Magnetic Fields, Coronal/Interplanetary Physics, and Terrestrial Interactions. In the first three of these sections there is also significant work on problems of stellar physics analogous to the solar topics emphasized. The unusual breadth of the program strains the available resources but is necessary for a coherent approach to the understanding of solar variability and its consequences. Fortunately, the unifying theme of solar variability produces strongly overlapping interests in the four sections and leads to a healthy level of interaction and cooperation.

Significant Accomplishments

- Studies of coronal mass ejections and underlying dynamical changes in the chromosphere and corona indicate that, contrary to popular belief, solar flares are frequently not the driving mechanism for the mass ejection. Instead, more global rearrangement of magnetic field patterns appears to be responsible for both flares and mass ejections.

- Significant improvements have been made in the theory of stellar winds, using results previously derived for the solar wind. These include elucidating the role of Alfvén waves and dynamical as opposed to kinematic processes.

- Techniques for extracting magnetic field signatures from Stokes polarimeter data have been greatly improved and have been used to determine new features of the magnetic fields in sunspots. Design of the advanced Stokes polarimeter has also progressed.

- New evidence has been developed that He II is excited in hot, rather than cool, plasma in the solar atmosphere. This has important implications for the use of helium lines as diagnostic tools.

- Analysis of Fourier tachometer data reveals that the observed attitudinal differential rotation of the sun extends throughout the convection zone and partly into the interior, below which the sun is in solid rotation at a value that is intermediate between surface rates at the equator and poles. These results suggest that the convection zone and interior are in angular momentum balance and support the notion that the solar dynamo is seated at the interface between the convection zone and the interior.

- New techniques have been developed to estimate the way in which acoustic waves scatter off concentrations of magnetic flux, such as in sunspots and active regions. These techniques should allow better discrimination among various models for the structure of magnetic flux when they are applied to real data now being collected.

- A new technique has been developed to map high-latitude electric fields and currents in the upper atmosphere and their associated magnetic variations from sets of localized observational data. This technique is important for deriving the properties of the high-latitude magnetospheric convection pattern and its associated current systems needed for various campaigns of the Coupling, Energetics, and Dynamics of Atmospheric Regions program and for driving auroral forcings within the NCAR thermospheric general circulation model.

- The thermospheric general circulation model has been modified to calculate total temperature and distributions of the minor thermospheric species $N(^2D)$, $N(^4S)$, nitric oxide, helium, and argon. The model also self-consistently calculates neutral gas total heating and cooling rates which involve many complex physical processes.

Coronal/Interplanetary Physics Section

The long-range goals of the Coronal/Interplanetary Physics section (CIP) are to describe (observationally and theoretically) the physical properties of the solar corona and its interplanetary extension into the solar wind and to understand the physical processes that determine the state of this extended solar atmosphere as an integral physical system. Pursuit of these broad goals includes studies of the role of the large-scale solar magnetic field in coronal structure, specific relationships between phenomena in the corona and in the lower layers of the solar atmosphere, long-term variations in the coronal and solar wind characteristics, and effects of the solar wind upon the terrestrial environment. These studies lead to a substantial (and desirable) overlap in research and personnel with the other sections of the observatory.   The CIP's research program encompasses observing projects that use both ground-based and spacecraft-borne instruments, interpretative studies using these and other observations, and a theoretical effort aimed at understanding basic coronal and interplanetary physical processes, as well as specific phenomena revealed by observations.   The section's interests extend beyond the solar system to other space and astrophysical systems where similar phenomena may occur or similar physical processes may be important.

Coronal Magnetic Field

The corona is an excellent electrical conductor and the magnetic forces due to free-flowing electric currents give rise to a rich variety of quasi-steady plasma structures.   These range from coronal holes, where the solar wind escapes along open magnetic lines of force, to smaller-scale ultraviolet (UV) and X-ray loops associated with magnetic fields that close back on the sun. The energetics of these structures is also influenced by the magnetic field through heating by electric current dissipation and the inhibition of diffusion and conduction across magnetic field lines.   Thus, it is the magnetic field that determines the properties of these quasi-steady structures as well as the circumstances under which these structures become unstable, resulting in a host of dynamical phenomena observed and still being discovered in the corona. The study of coronal magnetic fields is central to CIP's program and is also a part of the observatory-wide effort, led by Thomas Holzer, in the numerical modeling of magnetohydrodynamic and radiative transfer systems.

An ongoing program in the section seeks to construct three-dimensional models of the corona using the approximation of taking the quiescent corona to be everywhere in a static state.   This is a reasonable approximation for the low corona where the effect of the solar wind is unimportant. The goals are to give insight into possible realistic magnetic structures in the low corona and to provide geometrically realistic models that can relate measurements of magnetic fields at the coronal base to observed density structures in the corona. Classes of magnetostatic solutions with the desired sophistication have previously been found by Boon Chye Low and Thomas Bogdan. In an ongoing project, Low, Arthur Hundhausen, You Qiu Hu (visitor, University of Science and Technology of China, Hefei) and Charles Kane (summer undergraduate student, now at Massachusetts Institute of Technology) extended the work of Bogdan and Low to allow for a magnetic field pattern having a part of its total flux open to infinity to simulate the effect of the solar wind on the

magnetic geometry. Theoretical global coronal models with single and multiple helmet-streamer belts have been constructed.

In a separate theoretical study, Hu considered the linear hydromagnetic stability of magnetostatic equilibrium states. The interplay among the magnetic force, pressure gradient, and gravitational force (or buoyancy force) renders quantitative treatment of stability not easily tractable. Hu found a general class of two-dimensional equilibrium states in which the electric currents maintain magnetic fields having field-line geometries identical to those of potential fields. The stability criteria take simple forms so that stable states can be readily identified.

The magnetic field in the corona can support hydromagnetic waves, and the idea that the dissipation of these waves may heat the corona has been pursued for two decades. Recent quantitative considerations and existing observational constraints do not rule out this process for the heating of coronal regions with open magnetic fields, such as the coronal holes, but do call into question the viability of this process as a heating mechanism for the corona over active regions where the magnetic fields are closed. An attractive alternative heating mechanism involving closed magnetic field lines is that suggested by Eugene Parker (University of Chicago), who has pointed out and demonstrated that a magnetic field with an arbitrarily prescribed field-line topology must, in general, form thin electric current sheets as it relaxes into an equilibrium state. In Parker's theory, coronal magnetic fields with both ends anchored in the dense lower solar atmosphere are continually twisted into complicated small-scale topologies by footpoint motions, spontaneously forming electric current sheets. The dissipation of these current sheets naturally heats the corona.

While the validity of this promising theory awaits high-resolution observations of the future to be tested, a central issue being debated in the literature is the theoretical demonstration of the spontaneous formation of electric current sheets. Explicit examples provide instructive and direct demonstration of the physical process, and two classes of examples have been found by Low and Richard Wolfson (visitor, Middlebury College). Taking the coronal medium to be an inertialess perfect conductor as an idealization of the low β plasma, the equilibrium magnetic field is force free. The examples of Low and Wolfson show that the smooth boundary footpoint motions of a quadrupolar magnetic field that initially has no magnetic neutral points in the coronal medium can result in the formation of electric current sheets. It is of particular interest that these sheets may be of finite lengths even for infinitesimal footpoint motions at the boundary, so that their eventual dissipation may distribute energy over an extended spatial region. This property has important implications for the flare process.

Coronal Physical Properties

It is technically not feasible at the present to directly observe the coronal magnetic field with useful spatial resolutions. A main source of information on the corona is observations of coronal density made by coronagraphs registering photospheric radiation that is Thomson-scattered by coronal-free electrons. The HAO archive of coronagraph data has been gathered from the Skylab coronagraph observations of 1973–74, the Solar Maximum Mission (SMM) coronagraph/polarimeter (C/P) observations both during the original 1980 epoch terminated by its breakdown and during an almost continuous operation since its subsequent repair in space in 1984, and ground-based observations with the Mark III K-coronameter at the Mauna Loa Solar Observatory since 1980. In addition, there is the data set from earlier Mauna Loa instruments that began operation in 1964. During the past fiscal year, the Mark III K-coronameter continued operation, but it now breaks down so frequently that it must be refurbished to ensure adequate data coverage into the next maximum of solar activity, estimated to occur in 1991. The SMM C/P suffered a tape recorder failure on 7 December 1986. A rerouting of data stream was accomplished by O. Chris St. Cyr and David Kobe, and observation resumed on 30 March 1987.

Coronal images in the hydrogen-alpha ($H\alpha$) emission line of neutral hydrogen are also obtained at Mauna Loa and with the SMM C/P; these observations have proven to be a valuable diagnostic tool when combined with the coronagraph observations in the study of eruptive prominences and mass ejections. The Spartan program, under the supervision of David Sime, is intended to provide high-photometric-quality coronagraph data as well as scattered Lyman-alpha ($L\alpha$) and emission line measurements for use as diagnostics of coronal temperature and flow speeds. Construction of this instrument is in progress but is faced with the uncertainty of launch opportunity at the National Aeronautics and Space Administration (NASA) is uncertain.

The combined set of coronagraph data gathered since the Skylab epoch spans a period well over an 11-year solar activity cycle, presenting the first opportunity to study the variations of coronal physical properties with the solar cycle. Preliminary results indicate significant and physically interesting variations. As the effort continues, plans are being made to observe the ascension to the 1991 solar maximum.

As described in last year's report, the descending phase of the activity cycle to minimum was characterized by a simple large-scale pattern of coronal brightness (hence density) interpreted as due to a single belt of helmet streamers associated with a tilted dipole global magnetic field. The observations from both the Mauna Loa instruments and the SMM C/P showed that the tilt relative to the sun's rotational axis decreased to a minimum of about 5 to 10 degrees and then started to increase only slightly late in 1986. The configuration persisted into early 1987 with the helmet-streamer belt still loose to the solar equator, implying a flat, interplanetary neutral sheet, the absence of strong recurrent solar wind streams in the ecliptic plane, and

a low level of geomagnetic activity. In June/July 1987 an abrupt change occurred in the corona. The streamer belt became warped with two polar extensions of each polar hole per Carrington rotation. A stitched-baseball magnetic configuration is implied, with a four-sector, four-stream solar wind structure. This change has been seen before, but its abruptness is a surprise. This result, as well as the observation of mass ejections reported in the next subsection, points to the importance of continuous observation of the evolution of the corona to the next solar maximum.

Sime and Richard Fisher continue, in collaboration with Richard Altrock (National Solar Observatory or NSO), to analyze the long-time record of coronal measurements in the 5303-angstrom emission line of Fe XIV and to compare these measurements with those from the Mauna Loa coronameters. Earlier quantitative estimates of the integrated coronal Fe XIV emission line flux have been revised to account for a different calibration that Altrock has established. These results are qualitatively similar to the earlier ones, in that the variation over the activity cycle exceeds that which might be estimated from the variation of coronal mass (or density at a given height) as derived from white light coronagraph observations. Since the Fe XIV emission line flux originates from the hotter component of the coronal plasma, Sime investigated its relationship with the distribution of calcium plage, with the goal of understanding whether local coronal heating is related to features in chromospheric temperature distribution. Preliminary results indicate no simple relationships. Finally, Sime investigated whether the coronagraph data reveal any structure that might be consistent with Altrock's suggestion, based on the Fe XIV data, that structures of one cycle persist into the following cycle. No such effect was found in the Mauna Loa data, but it is possible that the white light data detect structures of a length scale different from those in the Fe XIV observations. In any case, the null result serves as a constraint on the Fe XIV result.

Coronal Mass Ejections

Coronal mass ejections as a conspicuous class of dynamical coronal phenomena continue to dominate the attention of a group of staff members and visitors at HAO, led by Hundhausen. As new data are added to the archive, continuing analysis of the data identifies physically interesting single events for detailed study, correlates mass ejections with other solar and interplanetary observations, and provides new findings to track the properties of mass ejections as functions of the solar activity cycle. A parallel theoretical effort addresses the issues of initiation and dynamical propagation of the mass ejections.

The mass ejection of 15 October 1986 was observed almost simultaneously with quality images from the Mark III coronameter and Hα monitor at Mauna Loa and the SMM C/P. For the first time, properly scaled and registered data from all three instruments were put together to reveal in detail the spatial relationships of the chromospheric and coronal events associated with a mass ejection. The prominence was revealed as an almost continuous, dense, looplike structure inside the cavity of the coronal mass ejection, with only a part of the prominence emitting in Hα. The timing and relative spatial positions of events suggest that the prominence does not drive the mass ejection but participates in the overall event as an outward expansion of a preexisting structure. Early in the event, the prominence is located to one side of the mass ejection cavity, but, as the mass ejection expands outward, the prominence becomes more centered. This event is not unique; two other events have been identified in the joint data sets.

The flare has been recognized as the most explosive phenomenon in the solar atmosphere for so long that when mass ejections were first observed and studied, there was a tendency to regard the mass ejection as a consequence of some suitable flaring mechanism. Largely through the results from the analysis of the SMM C/P and the Mauna Loa data and accompanying theoretical work, a radical change has taken place in our perception of the corona as a physical system. While some mass ejections are associated with flares, a much larger number are correlated with prominence eruptions without flares. For those flare-associated mass ejections, Richard Harrison (visitor, now at Rutherford-Appleton Laboratory, Chilton, England) has shown from observations from the C/P and X-ray instruments on the SMM and the Mauna Loa instruments show that the mass ejection begins some tens of minutes before the eruption of the associated flare. The corona appears to be dynamically active in its own right, erupting into mass ejections as magnetic fields are stressed to a point of nonequilibirum, perhaps as suggested by the theoretical calculations of Low and Wolfson. The flare and prominence eruption, as well as the mass ejection, are viewed to be different manifestations of the global magnetic structures going out of equilibrium. The mass ejection of 15 October described above and others to be analyzed are direct observations in support of such an interpretation. This once-radical view of the corona is now firmly established and may be expected to have a fundamental impact on coronal physics.

Rainer Illing (now at Ball Corp.) and Grant Athay completed a study of Hα emission in prominence material embedded in eight mass ejections observed by the SMM C/P. In a follow-up study, Athay, Low, and Bogdan Rompolt (visitor, Wroclaw University, Poland) used the characteristics of these Hα materials as tracers to infer the expansion of the mass ejection material, and they concluded that the inferred expansion of these eight events cannot be described by the self-similar theory of Low.

An earlier prediction based on the Skylab observations, that the rate of mass ejections correlates linearly with the sunspot number in the course of an activity cycle, was recently found not to be confirmed by the SMM C/P data. While the ejection rate varies significantly with the solar cycle, falling from about

one a day during the Skylab epoch to about one every ten days in 1986, its relationship with the sunspot number is not linear. This points to the fact that the sunspots themselves are physically remote from the coronal processes that generate the mass ejections. An empirical study by Sime shows that the rate of mass ejections and the time scale of change in the large-scale coronal structure are inversely proportional, the latter being defined in terms of the evolutionary time scale in synoptic observations provided by the Mauna Loa coronameter. This result seems to indicate that mass ejections are products of large-scale coronal evolution, a physical picture consistent with the idea of initiation mentioned above.

In early 1986, mass ejections occurred with low speeds of about 100 km/s near the equator where the streamer belt lies, with a low rate of about one every ten days. Late in 1986, as the new activity cycle commenced, mass ejections were seen in the high latitudes where presumably new magnetic fluxes had emerged. These mass ejections were characterized by higher speeds, but the rate remained at the same low level. Since the resumption of observations in March 1987, following the interruption of operation due to a tape recorder failure, more fast mass ejections in the high latitude have been observed, and a significant increase in the rate has taken place, especially in conjunction with the abrupt change of the large-scale structure in June/July. Of particular note is an increase in events, which is clearly associated with flare eruptions.

Theoretical study centered on the use of numerical models developed separately by Hu and Richard Steinolfson (visitor, University of Texas, Austin), each working in collaboration with Holzer, Hundhausen, and Low. Hundhausen, Holzer, and Low have pointed out that the speeds of the majority of observed mass ejections exceed the estimated sound speed but are less than the estimated Alfvén speed in the corona. This physical condition makes it unlikely for a fast magnetohydrodynamic shock to be attached to the moving mass ejection, but magnetohydrodynamic shocks of other kinds, principally the slow shock, cannot be ruled out. Following this initial suggestion, Hu developed a time-dependent, two-dimensional code based on a multistep implicit scheme to simulate mass ejection dynamics in the low β regime. Hu and Hundhausen explored the ejection of magnetic flux at various rates from the coronal base as a possible mechanism for the initiation of mass ejections. Hu, Hundhausen, Holzer, and Low carried out a study on the response of the background corona to the passage of a mass ejection, with the goal of simulating the formation of the slow shock. It was found that as an initial value problem, the formation of the slow shock associated with a supersonically but sub-Alfvénically moving mass ejection is significantly complicated by the fast-mode waves present. Further studies initiated by Steinolfson and Hundhausen on the formation of the slow shock show that the geometry of the wave front and the interaction between the different wave modes of the magnetohydrodynamic medium may require the

formation of multiple shock surfaces, including the presence of the intermediate shock. These studies have raised new physical questions to be answered in future work. The study of coronal mass ejections has thus motivated a fresh look into the theoretical properties and formation of magnetohydrodynamic shocks in a regime not previously explored.

Solar and Stellar Winds

A highlight of the CIP research activity in this area was the Sixth International Solar Wind Conference (SW6 Conference) hosted under the auspices of HAO in Estes Park, Colorado, in August 1987. The meeting, which was organized by Victor Pizzo (chairman), Holzer, and Sime, drew approximately 130 researchers from 14 nations. Some 30 invited papers and 60 contributed papers were presented in such diverse areas as the acceleration of solar and stellar winds, energetic particle acceleration in the interplanetary medium, the structure of the distant solar wind, slow shock development and evolution, and the physics of coronal mass ejections.

Solar and stellar wind studies at HAO are conducted in both the CIP and the Solar Activity and Magnetic Fields sections. The research program centers on the basic physical mechanisms important to the generation of the solar wind and in the evolution of solar wind structure, with particular emphasis on applying the physical insight gained in these studies to the theory of stellar winds. Holzer gave an invited review to the SW6 Conference. Taking the solar and stellar winds together as a general phenomenon, Holzer developed a framework for discussing a broad range of winds occurring in diverse astrophysical environments in terms of a relatively small number of basic effects and their general implications for the requirements of mass, momentum, and energy balance. Within this framework, we have a basis for both understanding and evaluating how important a variety of physical mechanisms may be for specific types of winds.

The CIP Section participates in space experiments to observe the properties of the solar wind, principally through Holzer, who is coinvestigator in experiments approved for the SPARTAN, ULYSSES and ISTP missions. These experiments hold prospects of obtaining valuable observational information on the physical conditions in the wind acceleration region of the corona that will help resolve various important theoretical issues. In an effort to evaluate diagnostic tools, Ruth Esser, Egil Leer (both visitors from University of Tromso, Norway), and Holzer performed a parametric study that illustrates the physical effects that can be studied by analyzing and interpreting observations of coronal minor ion spectral lines. The study showed that observations of minor ion line width, together with the coronal Lα line width and coronal white light, can yield important information concerning the transport and dissipation of energy carried outward from the coronal base by hydromagnetic waves.

Winds from early stars are thought to be driven by momentum imparted to stellar atmospheric gas

by the isotropic scattering of an intense, directional, photospheric radiation field. This radiation field arises from strong spectral lines formed in the flow. A popular model of this process was developed by John Castor, David Abbott and R. I. Klein in 1975 (the CAK model). In previous studies, the wind has been assumed to undergo spherical expansion in order to keep the problem simple. In a real wind, the expansion may not be spherical, a point well recognized in the case of the solar wind channeled by magnetic fields in the low β coronal environment. In a study extending the CAK model to allow for effects arising from nonspherical expansion, Keith MacGregor found that an isothermal wind with an expansion more rapid than an inverse square of the radial distance near the stellar surface may have its critical point drawn close to the photosphere. The radiative force is enhanced and large asymptotic flow speeds result even for a modest departure from spherical expansion, whereas the mass flux may remain essentially unchanged if the rapid flow divergence is located more than a few tenths of the stellar radius above the photosphere. In another study undertaken with Stanley Owocki (visitor, Bartol Research Institute, Newark, Deleware), MacGregor investigated the radiative amplification and damping of Alfvén waves in a wind-type stellar outflow. The scattering of photons coming from different directions that takes place near the stellar surface gives rise to a transverse radiative force that can act to amplify or damp Alfvén waves. This mechanism has been modeled in the linear wave, optically thin regime, and it was found not to be a strong effect for wave-driven winds from cool supergiant stars.

Various recurrent features in stellar spectra have for some time been attributed to steady, corotating interaction regions (CIRs) analogous to those found in the solar wind. However, the kinematic treatments in these stellar studies are known to be inadequate when applied to the solar wind. Claude Catala (visitor, Paris Observatory, France), MacGregor, and Pizzo have carried out a study of the CIRs in the stellar context by using a multidimensional dynamical model that Pizzo developed earlier for corotating solar wind structure. In a first study, stellar winds with rotation rates, mass fluxes, and magnetic fields close to those of the solar wind were chosen for investigation. It was found that strong dynamical effects act against the kinematic effects that produce the CIRs, so that the density and temperature variations produced are too low to support an explanation of the observations for this class of stars in terms of the CIR.

Chris Halvorson (HAO graduate student, University of Colorado) is investigating, under the supervision of MacGregor, the reversal of the accretion inflow which characterizes the latest stages in the formation of solar-type stars. Of particular interest is the response of the inflow to the variations of the base pressure and the deposition of momentum in the postaccretion shock gas arising from an outward-directed force.

MacGregor continues to study the rotational evolu-

tion of stars with masses less than a solar mass, from pre- to post-main-sequence stages. Combining a previously developed model for the stellar internal transport of angular momentum with a model for computing the angular momentum loss due to a magnetic stellar wind, he performed calculations for the transfer of angular momentum between these two regions to maintain equilibrium. The results indicate that the observed rapid spin-down of solar-type stars during the earliest stages of their main-sequence lifetimes can be accounted for if the time scale for angular momentum transfer is initially longer than the time scale for angular momentum removal from the convection zone by the stellar wind. In another study in collaboration with Ronald Gilliland, MacGregor considerd the development of an extended subphotospheric convection zone (both in radius and mass) as stars of one to 15 solar masses evolve out of the main sequence. Such stars have evolutionary paths located in the portion of the Hertzsprung-Russell (H-R) diagram where atmospheric thermal and dynamical properties are known to be significantly different from those of solar-type, main-sequence stars. Using a stellar evolution code to follow the evolution of a star, MacGregor and Gilliland found that an intermediate mass star develops a deep subphotospheric convection zone at the crossing of an empirically determined transition line that separates stars of different atmospheric properties in the H-R diagram. This result suggests that the change in the outer atmosphere may be due to adjustments in response to the changing interior structure.

Much of current theoretical knowledge of wind properties is based on one-dimensional models. To understand the effects of magnetic field and rotation quantitatively, an axisymmetric (two-dimensional) model is necessary, but this highly nonlinear system has remained largely intractable. In an invited review given to the SW6 Conference, Low described the basic structure of the governing equations and pointed out the obstacles to a successful model construction, drawing on selected previous work for illustration. A numerical investigation is being planned, but, for a successful effort, some intuition about this complex system must be developed. For this purpose, Low, Hu, and Kanaris Tsinganos (University of Crete, Greece) have developed a series of analytic models, and Low and Hu have constructed a new set of analytic models in which a magnetostatic lower atmosphere is matched to an accelerating hydromagnetic wind.

A purely fluid description of the solar wind is inadequate. Both the physics of cosmic ray acceleration and the energy transport associated with the wind flow require treatments based on particle kinetic theory. Martin Lee (University of New Hampshire), Edward Shoub (visitor, University of Colorado), and Bogdan have formed a collaboration to undertake a self-consistent wave-particle, quasi-linear calculation for the acceleration of particles in the neighborhood of traveling interplanetary shocks. In another collaboration, with Gary Webb (visitor, University of Arizona), Bogdan studies first-order Fermi acceleration, investigating the

influence of particle pitch-angle distribution on the energy spectrum of the accelerated particles and the nature of idealized particle spectra associated with astrophysical stand-off accretion shocks.

It has been suggested that the classical description of electron thermal conduction is inadequate in the corona and that the free streaming of free suprathermal electrons from the coronal base out into the wind may enhance the thermal flux well above that expected from the classical theory, so that the energy of the fast-stream solar wind may be accounted for without the need of special energy or momentum addition. Shoub gave an invited review on this subject at the SW6 Conference. He has developed a numerical kinetic model of the solar wind expansion incorporating the effect of anomalous electron thermal conduction. A project of this nature cannot avoid confronting difficult basic physical issues in kinetic plasma theory. In a recent study, Shoub showed that the Fokker-Planck approximation of the Boltzmann integral is an inadequate description of collisional relaxation caused by Coulomb interaction because of its inability to correctly describe large-angle scattering events. The failure is significant if the particle distribution is very far from equilibrium.

Solar Activity and Magnetic Fields Section

The solar photosphere can be characterized as a turbulent radiating plasma that is threaded more or less vertically by horizontally concentrated magnetic flux. In the part of the photosphere free of magnetic structures the energy is supplied by the diffusion of radiation from convective overshooting elements driven by subsurface convection. However, within the flux concentrations, free convection is suppressed and a radiative deficit occurs. For the small-scale magnetic features (flux tubes) lateral radiative channeling of heat from the surrounding hot convective region overrides the deficit and produces an apparent brightening of the feature. For the larger features (pores and spots) channeling becomes limited solely to the boundary, and the deficit remains so that the feature is dark. Associated with these features are locally induced subsonic flows which, in the case of spots, have been identified with the Evershed flow. The nature of the stability and thermodynamics of these magnetic concentrations is one of the major puzzles for solar physics.

The nature of the energy supply changes in the overlying chromosphere, which is transparent to the bulk of the photospheric continuum. It appears that dissipation of mechanical energy, possibly stored in field-aligned currents induced via horizontal motions of field footpoints, provides the main energy supply. Whether this energy is released in situ or propagates to this region from the corona via either energetic particles or conduction, or both, is poorly understood. What is evident is that associated transient motions are frequently nearly sonic yet they are contained, being "frozen in," by the local force-free magnetic field.

Such complex interactions between a flowing,

radiatively cooling plasma and the local magnetic field are evident over the entire solar surface, but are especially pronounced in active regions. For the most part these are regions of closed magnetic fields in which the corona, transition region, and chromosphere are intimately tied. The enhanced magnetic flux in the active regions is accompanied by enhanced radiative output as well as episodic flaring—the dramatic release of radiative energy, both thermal and nonthermal, often accompanied by violent injection of matter. Similar phenomena appear to occur on a reduced scale outside active regions, and, although the association with local magnetic fields is not always clearly demonstrated, the presumption is that this is the case.

The long-range goal of the Solar Activity and Magnetic Fields section is to understand the physical processes present in the lower solar atmosphere. To do this, the section must develop three-dimensional radiative and magnetohydrodynamic (MHD) models of such quasi-steady magnetic features as sunspots, plages, and flux tube structures. For those features associated with open fields, the atmospheric expansion into interplanetary space must be included. These models, when developed, will include the complete energy and momentum balance. Their development presents a difficult challenge that will require several years of effort and a step-by-step approach involving both theoretical and observational programs. The effort will encompass other scientific sections of HAO as well as outside collaborators.

One important aspect of the overall goal involves progress in understanding the nature and modulation of energy transport and transformation in the solar atmosphere, including heating of the chromosphere, transition region, and corona and the transport of heat by thermal conduction and enthalpy flow. Achievement of this understanding also will require the same collaborative efforts as above.

The fields of expertise of the current staff of the Solar Activity and Magnetic Fields section are approximately balanced between radiative transfer and magnetohydrodynamics (MHD). The section attempts to maintain an appropriate balance among data analysis, theory, and modeling. Members of the section avail themselves of opportunities to conduct observations from both space- and ground-based facilities. In addition, members of the section are actively involved in the planning and execution of major new observing facilities, including an advanced Stokes polarimeter in collaboration with NSO, and the high resolution solar optical telescope (HRSO) to be flown by NASA in the early 1990s. HAO and NSO also are involved in the support of United States participation in the Large Earth-Based Solar Telescope Foundation Project (LEST).

Currently, the section operates no observing facilities. Nevertheless, data already on hand from HAO's previous Stokes programs and from the Orbiting Solar Observatory (OSO 8) and SMM satellite, as well as data

acquired during "observing runs" at national facilities, form an important component of the research effort. The following topical breakdown of work within the section emphasizes its interactive aspects rather than individual efforts.

Sunspots and Flux Tubes

Pizzo and Jack Miller have continued their work on a magnetostatic sunspot model that includes current sheets. They have recently incorporated a new boundary condition that better models the expansion of the field at large radial distances from the spot. A preliminary parametric study confirms the hypothesis (based on the smooth magnetic distribution generated in a previous study) that the compressive effects of the external photosphere on the depressed spot would tend to be concentrated near the periphery of the structure, i.e., near the current sheet. It appears that the overall shape of the magnetic structure is not terribly sensitive to whether the discontinuity at the sheet is sharp or is smeared out somewhat by the inclusion of horizontal pressure gradients in the interior of the spot. There are also intriguing indications that the (Wilson) depression of the optical surface may be much smaller than conventionally presumed (say, 200–300 km instead of 600–1,200 km). This supposition is based upon the fact that models of the deeper spots invariably produce significant enhancement in field strength near the edge of the structure (where the greatest constriction occurs), giving a magnetic profile across the spot that is contrary to the observations.

Pizzo has continued work on developing a numerical method for incorporating steady, subsonic flows into a self-consistent treatment of the force balance in long-lived magnetic structures like sunspots. A simplified version, valid in the limit of slow flows (where the changes in gas pressure due to the flows do not alter the magnetic structure, just the thermodynamic properties), is being adapted to the current sheet models to study the effects of flow fields on the Stokes profiles.

Paul Kunasz (unaffiliated), MacGregor, Dimitri Mihalas (University of Illinois), and Pizzo have begun a collaboration aimed at including the energy equation with its attendant radiative transfer effect within magnetostatic models of solar surface features such as flux tubes and sunspots. This will make use of Kunasz's methods of treating multidimensional radiative transfer with Pizzo's numerical magnetostatic models. They will begin with a grey atmosphere in a two-dimensional slab geometry and attempt to iterate to an equilibrium energy state by using temperature variations returned by the radiative transfer code to update and correct the pressure distribution required by the magnetostatic models.

Bruce Lites and Andrew Skumanich have continued their studies of the vector magnetic field structure of large sunspots observed during 1980 with the HAO Stokes II instrument. As a result of improved techniques for analysis of full Stokes polarization profiles, a picture of sunspot vector field structure is emerging that differs from that of previous studies. Some of the observed features are as follows: (1) near the outer edge of the penumbra the fields are elevated at about 35° with respect to the local horizontal direction, instead of being nearly horizontal; (2) an azimuthal twist of the field is sometimes present in the photosphere of sunspots, and this twist corresponds to spiraling patterns of the Hα fibril structure; (3) the field strength remains rather large (approximately 1,000 gauss) near the outer edge of penumbrae compared to the mean field, indicating a filamentary structure to the field; and (4) in addition to the twist seen in some sunspots, the radial component of the field shows a significant nonpotential character. These observations may now be used to guide theoretical MHD models of sunspots (such as the new boundary conditions in Pizzo's model, described at the beginning of this section). They also point to the need for observations of the vector field at much higher spatial resolution.

Flares, Prominences, and Active Regions

Several Stokes II data sets of active regions are now in the process of being analyzed with the goal of understanding the morphology of the photospheric vector field as the active region evolves. One serendipitous event was the observation of a flare during successive raster scans of a particular region. Skumanich and Lites, along with an undergraduate summer assistant, Kenneth Luther (Mt. Union College), are examining these data for changes in the vector field associated with this flare.

D. Tod Woods (now at Princeton University), in collaboration with Holzer and MacGregor, studied the energy and momentum balance of the transition layer in active regions between chromosphere and corona for Woods's thesis. By a systematic modeling of the effects of classical thermal conduction, radiative cooling, differing heating mechanisms, and momentum addition by hydromagnetic waves, they were able to place significant constraints on the nature of viable models. They found that the observationally inferred emission measure curve implies a near balance between heating and radiative cooling in the lower temperature transition region, and that the presence of strong hydrogen Lyα cooling leads to the existence of singularities in the solutions of the force balance and energy balance equations when such a near balance between heating and cooling is assumed. These singularities place strong constraints on the nature of viable models of the lower transition region and must be considered when Lyα cooling is important. The specific effects of hydromagnetic waves were considered in the models. It was found that when the heating required by the observed lower transition region emission is supplied by the degradation of an energy flux carried by hydromagnetic waves, the wave pressure gradient force dominates momentum balance to such an extent that models involving heating by hydromagnetic waves are not viable. Even when local heating is not associated with the dissipation of a wave flux, the presence of even

modest energy fluxes in the transition region can have a significant impact on local momentum balance.

Active regions are exceedingly dynamic in their outer layers, with bulk motions of the plasma frequently approaching the sound speed. An understanding of the nature of these motions and how they vary with height (temperature) is crucial to our understanding of the energy and momentum balance of the sun. Small-scale bulk motions broaden spectral lines and can be measured from the nonthermal component of observed line widths. Studies of available data, mostly from satellite and rocket experiments, have led to a coarse determination of the amplitude of the small-scale velocity as a function of temperature through the chromosphere and lower transition region (with temperature less than approximately 10^5 K). Large-scale motions, however, have proven far more difficult to study. These are measured through the Doppler shifts of spectral lines and are known to depend sensitively on the spatial resolution in the data. A necessary step in the study of such motions, therefore, is to establish just how the velocity amplitude varies with spatial resolution as well as with temperature.

Athay has completed the first phase of a study of line shifts using data from the ultraviolet spectrophotometer (UVSP) experiment on the SMM satellite. This is the largest data set available for such studies but is limited in spatial resolution to pixels of 3 × 3 arc seconds, which is known to produce some blurring of the velocity signal. The results from analysis of four spectral lines formed over a temperature range of 8,000 to 10^5 K show that the large-scale velocity amplitudes vary more rapidly with ion temperature (i.e., with ion species) than do the amplitudes of the small-scale velocity. In addition, the small-scale velocity amplitude exceeds the measured large-scale velocity amplitude at all temperatures. The second phase of the study is under way using 1 × 1 arc second data from the Naval Research Laboratory's high resolution telescope and spectrograph (HRTS) experiment on the Spacelab II shuttle mission. These data are less extensive than the SMM data, but that drawback is offset by the much improved spatial resolution. A comparison of results from the two data sets will provide both a valuable clue to the nature of the motion and a guide to improved observations in future space missions.

The derived relationship between velocity amplitude and ion temperature has been used by Athay in a separate study to determine the conditions under which lines of He II are excited in the solar spectrum. These lines have strong potential for diagnostic purposes provided the temperature at which they are formed can be determined. A controversy beginning some 50 years ago and continuing to the present has surrounded these lines. One faction maintains the lines are excited predominantly in a relatively cool plasma (less than 2 × 10^4 K) by the downward penetration of high-energy photons from the corona, whereas a second faction favors a predominance of collisional excitations in a hot plasma (8 × 10^4 K). Athay's study, using data both

from the SMM satellite and from earlier experiments, demonstrates that both the small- and large-scale velocity amplitudes observed in the 1640 *angstrom* line of He II (3-2 transition) strongly favor the hot plasma model.

Stokes Polarimetry

Lites and Skumanich, along with David Rees (visitor, University of Sydney) and Graham Murphy (HAO graduate student, University of Sydney), have made considerable progress on the problem of inversion of Stokes profiles of strong lines formed out of local thermodynamic equilibrium. The purpose of this effort is to develop the means to measure the vector magnetic field at heights in the atmosphere well above the photosphere. In this region the field is expected both to be more uniform laterally and to better obey the "force-free" condition. Numerical extrapolation of vector fields into the corona will be considerably eased if the force-free condition is approximately met. Provided the fundamental flare instability occurs in the corona, the measurement of changes in the chromospheric vector field during flares will be much more representative of the flare process itself. Observed changes in photospheric fields will be influenced more strongly by photospheric and subphotospheric fluid motions. Their work gives, for the first time, an algorithm that recovers the vector magnetic fields used to compute synthetic Stokes profiles of the Mg I b-lines in a model sunspot atmosphere. One key to its success is the simultaneous inversion of Stokes profiles of two members of the Mg I multiplet. This technique has been applied to Stokes I observations taken by the instrument of the Mg I lines in sunspots.

Simulations of photospheric Stokes spectra in model sunspots indicate that multiplets can be used to powerful advantage in the lower atmosphere as well. In order for this technique to work well, the lines must be observed in strict simultaneity. Neither the Stokes I nor the Stokes II instrument accomplished such observation, but the more limited spectral resolution of the University of Hawaii Stokes polarimeter (now using the HAO Stokes II Reticon detector) permits routine observations of the Fe I lines at 630.15 and 630.25 nm. Lites and Skumanich are collaborating with Donald Mickey (University of Hawaii) in analyzing measurements of this multiplet. The advanced Stokes polarimeter will provide superior data in this respect.

Final analysis of the suitability of the NSO/Sac Peak Tower telescope as a site for the advanced Stokes polarimeter was completed by David Elmore and Laurence November (NSO). They concluded that one can obtain and correct Stokes profiles using the tower as an image-forming device and correct for the polarization introduced by the tower to the order of one part in 1,000. Tests by Skumanich and Lites with synthetic data subjected to such noise indicate that the magnetic field parameters are recovered with an acceptable uncertainty for almost every circumstance. The inference of thermodynamic parameters is more sensitive in some circumstances, but generally it is felt

that entirely satisfactory scientific research could be achieved using the tower as a feed. Simulations and theoretical studies such as those discussed above have led to a continuing refinement of the analysis of Stokes measurements and have been invaluable in the definition of the new polarimeter.

With the issue of a suitable feed telescope answered, Elmore and Fisher undertook a design effort to identify the systems necessary for an addition to the tower so that solar Stokes data could be collected and processed. An 18-element observing system is now seen as necessary, and this design is being studied so that specific system components may be purchased and fabrication begun. This design was recently considered by a joint NSO/HAO group meeting at Sacramento Peak Observatory. A tentative division of the labor required to fabricate the advanced Stokes polarimeter was agreed upon, and specific technical items were identified for further study. The NSO will provide the vacuum tower telescope, the imaging mirror, the fast (Image Motion Compensator) mirror, the prism assembly, and the spot tracker required to form a stable and seeing-compensated image at the spectrograph slit. HAO will build and install a calibration fixture and a polarization modulator to complete the prespectrograph optical system. The NSO, as part of the tower upgrade program, will (in any event) build and install a set of spectrograph feed optics and an image scanning mirror system as well as a spectrograph. To allow the observer to view the location of the slit, HAO will build and install a field-of-view camera system using a set of filters having bandpass characteristics satisfactory for the identification of both photospheric and chromospheric features. To achieve a satisfactory image scale for the experiment, HAO will provide a specific objective for the spectrograph system. Finally, the data system for the polarimeter and the associated control and display systems will be constructed and integrated into the solar tower by HAO. The required systems include the spectrograph charge-coupled-device cameras, the digital demodular system, the data preview processor, and the control computer, along with user storage and display devices necessary for the large volumes of data expected.

Following this general and informal agreement, a development plan for the HAO design and fabrication effort was devised. A review is presently scheduled for 8 March 1988, and specific items will be purchased following the review.

Solar/Stellar Activity Analogs

As a consequence of the perspective gained from solar/stellar studies of dwarf flare stars, Skumanich, in collaboration with Harrison and Gillian Pearce (University of Birmingham, England), explored different solar active regions with regard to their being analogs of flare stars, i.e., they explored the relationship between flaring rates, mean flare power loss, and quiescent X-ray (coronal) background power for different active regions. They found that both the flare X-ray power loss and mean flare X-ray yield (mean energy per flare) varied

inversely with flare rate in similar fashion to the case for flare stars. This supports the suggestion that the flare mechanism is universal in magnetically active dwarf stars and that a "build-up" process is at work whereby the more frequent the flaring the less the amount of energy available for each flare.

The extraction of a quiescent X-ray background proved to be possible for only a few active regions. For these, a possible inverse relationship was suggested between mean flare loss and quiescent X-ray background, i.e., brighter active regions are sources of weaker mean flare power loss. This result is opposite to the correlation in flare stars where both variables rose together and indicated a common magnetic driver. Solar active regions appear to represent a "leaky" situation where energy cannot build up efficiently for flaring. If the background in active regions relates to coronal heating processes, then their preliminary result suggests no coupling between flaring and coronal heating. Owing to the paucity of data, the issue must be pursued further.

Analysis of the chromospheric activity of the rapidly rotating dwarf M star Gliese 890 was completed by Skumanich, MacGregor, Arthur Young (visitor, San Diego State University), and Scott Temple (graduate student, San Diego State University). This star has the shortest known period of rotation (10 h 30 min) among the magnetically active dwarfs, and its luminosity shows star spot modulation (the BY Draconis syndrome). The data were the result of a successful program that measured simultaneously the time-resolved broad-band spot-induced photometric variations (Laguna Observatory, Temple), as well as chromospheric Hα spectroscopy (Kitt Peak National Observatory, Young and Skumanich), and ultraviolet chromospheric Mg II hk lines as well as transition region C IV emission lines (International Ultraviolet Explorer or IUE, MacGregor). It was found that the activity in all tracers varied on the order of a few rotation periods. Surprisingly, the overall level of activity was not in proportion to the degree of rotation excess over slower rotating stars, suggesting a saturation of activity. Further, the active regions and associated spots are required to be at remarkably high latitudes, in excess of 60°, to fit the Doppler velocity data. This raises the issue of whether the extreme angular velocity (60 times solar) confines such activity to the polar latitudes, or merely permits it to migrate to such latitudes.

The Large Earth-Based Solar Telescope

The prospect of U.S. participation in a major new ground-based facility for solar observations has prompted HAO to organize a committee to evaluate the scientific merit of the LEST program. The committee (Athay, Bogdan, Fisher, Lites, Pizzo, and Skumanich) found that the LEST holds considerable promise to advance our observational understanding of physical processes in the solar atmosphere, particularly with regard to the observation of vector magnetic fields. Indeed, the LEST represents the next step in a logical progression of Stokes polarimetry. (Note that the

advanced Stokes polarimeter was considered from the outset as an effort intermediate between Stokes II and the LEST.) It is, therefore, important to the long-range goals of HAO that the observatory have a visible participation in the LEST program. The committee also identified several areas of concern regarding the performance of LEST. The greatest concerns lie in the realization of extremely high spatial resolution. The success of ongoing programs to select an excellent site, and to develop adaptive wavefront correction schemes, will weigh heavily in the overall success of the LEST program. In particular, implementation of adaptive optics on the LEST will be crucial to polarimetry at high spatial resolution. HAO intends to continue its support of the LEST initiative with the expectation that it will become a facility that is accessible to the national solar physics community. The scientific staff of HAO will work with a wider U.S. community to help resolve the present concerns regarding the LEST performance.

Solar Interior Section

The Solar Interior Section is concerned primarily with understanding the processes determining the structure and dynamics of the sun below the photosphere. This effort emphasizes the observation and interpretation of solar parameters (including the solar diameter, statistics of activity, and various properties that can be determined using the solar pressure modes, usually called p-modes), combined with theoretical modeling of the convection zone, the solar dynamo, and other aspects of the sun's internal magnetic field. It also includes efforts to observe the oscillations and activity of other stars, with the aim of using the variation of these parameters over a range of stellar types to clarify the basic processes of stellar structure. All of these studies help the group's scientists understand the fundamental origins of the variability of the sun's output of radiation, particles, and fields.

Fourier Tachometer Observations of
Solar Acoustic Oscillations

Timothy Brown and Cherilynn Morrow (HAO graduate student, University of Colorado) completed an analysis of the frequency splitting of solar p-modes caused by the sun's differential rotation. These frequency splittings carry information about the variation of the sun's angular velocity with both depth and latitude. Brown and Morrow, in collaboration with a number of others (visitors Jorgen Christensen-Dalsgaard, Aarhus University, Denmark; Wojciech Dziembowski, Copernicus Institute, Warsaw, Poland; Philip Goode, New Jersey Institute of Technology; and Douglas Gough, Cambridge University, England) have performed several forward and inverse calculations using the splitting data in order to infer this angular velocity variation. These calculations suggest that the sun's rotation within the convection zone is almost independent of depth, and that its latitudinal variation is similar to that observed at the surface. This picture conflicts with the most commonly accepted theoretical one, namely, that the angular velocity within

the convection zone should be constant on cylindrical surfaces aligned with the rotation axis. Moreover, the observations indicate that the deep interior of the sun probably rotates much like a solid body, at a rate intermediate between the surface equatorial and polar rates, but that the latitudinal variation of the rotation persists well below the bottom of the convection zone.

Morrow has been working to distill the rotationally induced shifts in frequency of solar acoustic modes contained in high-resolution data obtained by Brown and William Jeffrey (visitor, Harvard University) using the Fourier tachometer. Such frequency splittings will yield information about how the sun's internal angular velocity varies with depth in the upper part of the convection zone. The analysis of these data is novel. The power spectrum of these waves was accomplished using a three-dimensional fast Fourier transform ($x, y, t > k_x, k_y, \nu$, where x corresponds to solar longitude and y to latitude). The splittings are obtained from the power spectrum by considering a wave number plane ($k_x - k_y$) at each frequency and fitting the rings of power that appear there. The power along these rings (affectionately known as k-space cookies) represents waves traveling in all directions with respect to the sun's axis of rotation. If there were no solar rotation the rings would be concentric. But the sun's angular velocity in the convection zone introduces shifts, dependent on the rings' radii, that may be measured and converted to frequency shifts. Morrow has been fitting these rings using a new technique derived from Bayesian statistics and will do a forward analysis of the resulting frequency splittings as part of her doctoral thesis at the University of Colorado. Jeffrey will implement a novel inverse analysis on these data as part of his doctoral thesis at Harvard.

During FY 87, Brown used the HAO/NSO Fourier tachometer to take two lengthy series of full disk observations of the solar p-modes, one six weeks in October-November 1986 and the other for a similar period in May-June 1987. These data are now being archived and reduced in Boulder. They hold the promise of substantially improved measurements of rotational frequency splittings, and, because they are part of a relatively homogeneous observation set spanning almost three years, of giving the best available estimates of changes in p-mode properties during the solar cycle.

Near the end of the year, the Fourier tachometer was upgraded by the addition of a continuous calibration using a Zeeman-stabilized laser as a standard wavelength source. Brown anticipates that this improvement will allow the observation of flows with smaller amplitudes and larger spatial scales than can now be recorded. At the same time, an additional detector channel was added, which observes the full solar disk using a single photomultiplier. This gives the equivalent of the disk-integrated observations provided by atomic resonance instruments; it is hoped that this facility will allow observations of solar oscillations with degrees between zero and three.

Implications from Oscillations Measurements for Solar Angular Momentum and the Solar Dynamo

The implications of this newly proposed picture of the sun's internal rotation for the distributon and transport of angular momentum and for the solar dynamo are being studied by Gilman, Morrow, and Edward DeLuca (University of Chicago). In particular, these results affect our understanding of how angular momentum is cycled in the sun and provide clues as to how and where the solar dynamo is driven. The data imply that the only significant radial gradient of angular velocity exists in a transitional region between the bottom of the convection zone and the top of the rigidly rotating deep interior. Moreover, this radial gradient must change sign at the latitude where the angular velocity of the interior matches that of the surface. These results suggest that the cycle of angular momentum that produces the observed latitudinal differential rotation in the convection zone may be coupled to layers of the interior beneath the convection zone. In particular, they support the idea of a time-averaged balance of torques in the transitional zone such that the torques caused by some physical source of stress at low latitudes balance the torques exerted in the opposite direction at high latitudes. The candidates for causing this stress include turbulent viscosity, meridional circulation, and/or magnetic fields. The favored candidate is magnetic stress because the results from the data also strengthen the case for the solar dynamo's being in an overshoot layer beneath the convection zone where radial gradients of angular velocity and fluid motions with the correct sign of helicity exist to induce magnetic fields in a manner consistent with observations of sunspot migration. A simple model, with an eddy viscosity and a transition layer depth that are constant with latitude, uses the differences in angular velocity across the region that are given by Morrow's forward analysis of the data to demonstrate the feasibility of the balance of torques. A simple Cartesian model of a dynamo in the transitional region uses these same velocity differences to demonstrate the plausibility of operating a dynamo there. DeLuca and Gilman are currently working to construct a model of this dynamo in spherical geometry.

Sunspot Tomography

Recent observations have shown that sunspots appear to absorb (or convert to other forms) a substantial fraction of the p-mode energy that is incident upon them. Brown, Bogdan, and Lites are investigating ways of using this interaction between spots and oscillations to learn something of the subsurface structure of the spots. Brown has made progress this year in developing techniques to analyze the sunspot data obtained with the Fourier tachometer in June 1986, while Lites (in collaboration with John Thomas, University of Rochester) made an attempt to obtain higher-resolution observations using the NSO/Sunspot Tower telescope. The latter attempt was frustrated by clouds and lack of solar activity, but methods for performing the observation were successfully explored.

Bogdan and Brown have been proceeding with methods for inverting the p-mode absorption and scattering data to infer the active region structure. Two techniques are under investigation, one involving a parameterization of the sunspot as a collection of point scatterers, and the other using an approximate solution to the acoustic scattering problem, which is valid in the limit of low oscillation frequencies. This work is still in progress, but early indications are that it will be possible to learn something about the subsurface morphology of active regions, while detailed information about physical conditions will be much more difficult to derive.

Bogdan and Fausto Cattaneo (University of Colorado) are investigating the propagation of compressive waves through a gas of cylindrical vortices. This problem is intended to illuminate the interaction between p-modes and convective flows. The technique they employ is to first calculate the scattering of a plane wave from a region of constant vorticity embedded in a fluid at rest. This determines the so-called T-matrix of the vortex. Armed with the T-matrix, they apply the theory of multiple scattering to determine the propagator in a close-packed array of vortices. It is hoped that investigation of this problem may lead to estimates of the lifetimes and amplitudes of solar p-modes, as well as corrections to their computed frequencies.

Sunspot Size Measurements

An important and poorly understood aspect of the solar activity cycle is the mechanism by which sunspots are formed. In an effort to gain some information about this process, Bogdan, Gilman, Robert Howard (National Solar Observatory), and Ian Lerche (University of South Carolina) have analyzed an extensive set of sunspot umbral area measurements. These measurements are derived from the Mt. Wilson white light plate collection, covering several solar cycles. The measurements show that the size distribution of sunspot umbrae is lognormal and does not vary between solar cycles or with phase within a solar cycle. One possible interpretation of this result is that the magnetic flux concentrations responsible for sunspots arise from successive fragmentation of larger structures. Bogdan and his colleagues are currently working to determine the lifetimes of sunspots as a function of their size. Using these lifetimes and the size distribution, they hope to estimate the distribution of sizes of magnetic features within the solar convective envelope.

Stellar Acoustic Oscillations

Since the knowledge gained from observing acoustic oscillations on the sun has been so great, it is likely that observing such oscillations on other stars would be similarly informative. The difficulties involved in doing so are severe, however, since the expected oscillation amplitudes are exceedingly small (tens of centimeters per second in the Doppler shift, or several parts per million in the intensity). Fortunately, recent technology has brought these levels of precision within reach. In FY 87, Brown and Gilliland made significant progress toward

the goal of detecting solar-type oscillations on solar-type stars, using two different observational approaches.

Although the broad-band intensity variations expected from oscillating solar-like stars are quite small, the photometric methods now available have the potential for great precision. The limits of these methods (and the limiting processes) are not well understood, however, since the techniques themselves are rather new. To better understand these limits, Gilliland and Brown obtained in April 1987 test observations of stars in M67, a solar-age cluster of stars. Via simultaneous charge-coupled-device photometric measurements on a large ensemble of stars they were able to eliminate some sources of error inherent to classical photometry. Gilliland and Brown demonstrated that, with an observational cadence of one frame per 1.3 min, they could obtain differential photometry over more than nine hours per night with a root-mean-square scatter of less than 1.3 millimagnitudes (0.13%) for at least 25 stars in M67. Such observations, if they were extended over ten to 12 nights on a 1-m telescope, could allow detection of oscillations at amplitudes approaching ten times the solar amplitude. The stars observed are expected to have amplitudes of several times that of the sun, so this precision may suffice for many purposes. Preparations are under way (in collaboration with Nick Suntzeff, Cerro Tololo Inter-American Observatory, La Serena, Chile; Robert Rosner, University of Chicago; and Jeffrey) to obtain observations from several sites simultaneously in an aggressive observing campaign aimed at the detection of solar-type oscillations in other stars.

Brown and Gilliland have also attempted to detect stellar oscillations using high-resolution spectroscopic observations. In January 1987 they obtained four nights of spectroscopic observations of the bright F5 subgiant α CMI (Procyon), using the coudeé spectrograph and coudeé feed at Kitt Peak National Observatory. In May, they observed α Centauri for four more nights with the 1.5-m telescope and 4-m fiber-fed echelle spectrograph at the Cerro Tololo International Observatory (CTIO). The Procyon observations proved to be of limited utility because of the relatively poor stability of the Kitt Peak coudeé spectrograph. Fortunately, the fiber-fed echelle was surprisingly stable, allowing Doppler measurements to be made with about five meter per second root-mean-square precision in a 60-second observing interval, providing that slow instrumental drifts were first removed. Analysis of these observations is proceeding. Although it now seems unlikely that oscillations will be detected in this particular data run, Brown and Gilliland have set a new upper limit on the oscillation amplitude that can be present: about 80 cm/s for single oscillation modes, or about four times the solar oscillation amplitude.

Most of the noise remaining in the α Cen observations comes from mechanical instability in the spectrograph. One can overcome this problem in a fiber-fed spectrograph by providing a reference fiber, carrying a beam from a standard wavelength source, which can be observed simultaneously with the light from the star. Brown is supervising a program to fabricate such a standard source, which will incorporate a stabilized Fabry-Perot interferometer. It is anticipated that this source will allow Doppler observations to be made with a precision approaching 1 m/s, making solar-type oscillations fairly easily visible. Observing time to use this device on several large telescopes has been allocated during the first half of 1988.

Trajectories of Flux Tubes Rising through the Convection Zone

Gilman and Arnab Choudhuri (visitor, University of Chicago) have continued their collaboration on the problem of the trajectories through the convection zone that rising flux tubes would follow. Earlier results obtained for toroidal tubes that are axisymmetric about the axis of rotation indicated that for a field strength of 10^5 gauss or less at the base of the convection zone, the tubes would rise on a track parallel to the rotation axis and, therefore, would reach the solar surface at latitudes higher than sunspots are observed.

During 1987 Gilman and Choudhuri generalized their model calculations, relaxing the assumption of axisymmetry. The new calculations are for flux tubes that have periodic wave structure in longitude, so that it is possible for the lower part of the tube to remain anchored at the convection zone base while the upper part rises to the surface. They find that in this case the rising parts of the flux ring still move mostly parallel to the rotation axis and, therefore, reach the solar surface at latitudes too high to be responsible for sunspots. It was expected that with nonaxisymmetric flux tubes, drainage of material from the upper part of the tube to the lower part could occur and, therefore, keep the upper part from expanding so much as the tube rises. But in the examples studied so far, drainage, if it occurs at all, is a minor effect. Gilman and Choudhuri are planning to generalize these calculations still further to allow for the rise of a single loop of flux in a limited region of the sun. In this model, the loop remains anchored to a much longer tube that circumscribes the rotation axis at the base of the convection zone. Substantially more drainage may occur in that case.

Solar Diameter Measurements

Solar diameter measurements have been continued through the sixth year under the supervision of Gilliland. The continued observations will allow time coverage through most of a solar cycle, and the resulting long overlap with solar luminosity measurements from the active cavity radiometer irradiance monitor (ACRIM) will be exploited to set limits on related global changes.

Solar-Stellar Spectrophotometry Project

Over FY 87, considerable progress was made on the solar-stellar spectrophotometry program, whose scientific goals are to expand spectroscopic diagnosis of solar-type activity to new spectral bands and to extend knowledge of solar-type variability to cooler stars.

Collaborators in the project included Mihalas, Richard Radick (Air Force Geophysics Laboratory or AFGL), Lawrence Ramsey (Pennsylvania State University), Wesley Lockwood (Lowell Observatory), Fisher, and Gilliland. Scientific questions to be addressed are as follows: How does the dynamo process depend on the existence of a radiative-convective interface? What differences in solar-type activity are there between older disk stars and halo stars? How do differences in chemical abundance influence the dynamo process? What is the nature and mechanism of the process producing a magnetic activity cycle in subgiant stars? How do orbital considerations, in those serendipitous binaries to be found in the study population, interact with convection and magnetic activity? Finally, what relationships exist in the sample stellar population between surface activity (flares) and stellar parameters such as age, composition, and angular momentum?

Development of the instrument system was driven by the selection of a 43-inch (about 109-cm) telescope at Lowell Observatory as the feed for the spectrograph. Approximately 500 field stars not likely to be farther than 25 parsecs from the sun were identified and cataloged to form a sample population extending from the late subgiants to early M-type stars. This catalog was incorporated into the control computer and serves as the source for targets of the observing program. The data will be subjected to a reduction and storage protocol that has been specified and partially written.

Final mechanical and optical assembly of the spectrograph has been completed. The solar feed, a system used to inject the sun's light into the stellar spectrograph, is complete and installed at the HAO facility; its performance has been adequately tested. A calibration light source, containing a variety of line and continuum sources, has been integrated into the observing system and tested. The fibers used to feed the spectrograph with the solar source, the calibration facility, and the focal plane assembly are now in use. Final camera electronics are being manufactured. System testing and end-to-end tests are under way in Boulder, in preparation for shipping the equipment to Lowell.

Neutrinos, WIMPs, Hypercharge, and the
Solar Interior and the Solar Interior

An outstanding problem of astrophysics is the discrepancy between models of the sun based upon standard input physics and their prediction of the high-energy neutrino flux, which is higher than observations by a factor of 3. Gilliland, in earlier collaborations, has produced solar models that include the effects of energy transport by recently hypothesized weakly interacting massive particles (WIMPs). Such models are consistent with a low detected high-energy neutrino flux by virtue of suppressed core temperatures induced by the WIMPs' efficient energy transport. With Werner Däppen (visitor, University of Cambridge, England), Gilliland has analyzed the oscillation properties of solar models containing a small mass fraction (order 10^{-10})

of WIMPs. The parameter space of reasonable WIMP models was explored to delineate the domain allowed by the combined neutrino flux and oscillation observations. The slightly altered sound speed distribution leads to oscillation frequencies for the low-degree, high radial order p-modes in better agreement with observations than are the results from standard solar models. The models also yield a prediction for g-mode frequencies (yet to be observed unambiguously) that is quite different from the prediction by standard input physics, holding out the hope that future observations can effectively probe the core structure changes that would be induced by WIMPs.

Terrestrial Interactions Section

Studies of the response of the earth's environment to the variable nature of the sun encompass a wide range of topics, ranging from solar wind/magnetosphere coupling to the modulation of the middle and upper atmosphere by solar radiation. Understanding the chain of events involved in the coupling of solar energy to the terrestrial environment is a major goal of the Terrestrial Interactions Section.

Raymond Roble is the section head and Arthur Richmond and Holzer are full- and half-time scientists in the section, respectively. These scientists along with Robert Dickinson (Climate and Global Dynamics Division or CGD) were selected as a team in late FY 86 to participate in the NASA solar-terrestrial theory program. The management and scientific use of the NCAR incoherent-scatter radar data base also occurs within the section.

Thermospheric Dynamics

The NCAR thermospheric general circulation model (TGCM) has been developed as a collaborative effort by Roble, Cicely Ridley, and Dickinson. The model is evolving continuously with the addition of new physical, chemical, and radiational processes. During the past year several major changes have been made in the basic model structure that has been used for earlier studies (TGCM-3). Building on studies made with the globally averaged structure model of the thermosphere and ionosphere, the scientists have devised a self-consistent aeronomic scheme that allows the TGCM to calculate total neutral gas temperature instead of perturbation temperature, about some global mean reference temperature profile that was obtained from an empirical model such as the mass spectrometer/incoherent scatter model (MSIS-83). The heat sources for TGCM-4 now include heating from photoelectrons; free oxygen (O_2) absorption in the Schumann-Runge continuum and bands; excess energy from exothermic ion-neutral and neutral-neutral chemical reactions; thermal electron, ion, and neutral collisions; ozone (O_3) absorption in the Hartley bands; atomic oxygen recombination; and Joule and auroral particle heating. Cooling processes that are included in the model are molecular and eddy thermal conduction and infrared cooling from the 5.3μm emission from

nitric oxide (NO), 15-μm emission from carbon dioxide (CO$_2$) and 63-μm emission from O(^{3}P). The TGCM-calculated total neutral gas temperature is in reasonable agreement with temperatures obtained from global empirical models such as MSIS-86 and also with various ground-based and satellite measurements. A more detailed evaluation of the model's overall performance will be made during the next year.

The TGCM has also been modified to include transport of minor species such as N(^{2}D), N(^{4}S), and NO. These species are important for establishing and controlling the overall structure of the thermosphere and ionosphere. The exothermic neutral-neutral chemical reaction heating from these species is the dominant heat source in the thermosphere between 150 and 225 km. These chemical species are produced by nitrogen (N$_2$) photodissociation by solar extreme ultraviolet (EUV) radiation, auroral particle bombardment, and complex ion-neutral and neutral-neutral chemical reactions. The 5.3-μm emission from NO is an important cooling process especially during solar cycle maximum and geomagnetic storms. These complex physical, chemical, and radiational processes have been included in TGCM-4, and their interactions with global dynamics are now calculated self-consistently. The TGCM results show complex global distributions for all of the species. N(^{2}D) is generally in photochemical equilibrium through most of the thermosphere, and its distribution is strongly influenced by solar and auroral production. The NO distribution depends upon O$_2$, oxygen (O), N$_2$, and neutral temperature distributions, and it shows a latitudinal gradient with maximum densities in the auroral zones in general agreement with measurements made by the *Stratosphere-Mesosphere Explorer* satellite. The TGCM-calculated N(^{4}S) distributions are also in reasonable agreement with the N(^{4}S) distributions in the MSIS-86 empirical model. The overall magnitude of the calculated N(^{4}S), however, is somewhat smaller than that predicted by MSIS-86, suggesting a higher quenching rate for N(^{2}D) by O than that used in the model. TGCM-4 will be used in future years for various satellite studies (*Dynamics Explorer, Stratosphere-Mesosphere Explorer*) and for analyzing data obtained during various CEDAR campaigns.

TGCM-3 has been used by Geoffrey Crowley (visitor, University of Leicester, England) to study a major geomagnetic storm that occurred during the Equinox Transition Study, 17–24 September 1984. Time-dependent auroral and magnetospheric convection pattern forcings for this storm have been derived from satellite and ground-based data. These prescribed forcings were introduced into the TGCM, and the model calculated the time-dependent global circulation, temperature, and compositional variations during the period. The results have been analyzed in detail, and TGCM predictions have been compared with measurements obtained globally during this observational period. The TGCM successfully reproduced many of the observed features of the storm. There are, however, a number of discrepancies at individual station sites that suggest that certain physical processes

occurring during the storm period are not currently included in the TGCM inputs, such as the penetration of auroral-zone electric fields to midlatitudes. The TGCM, used in combination with a global ionospheric model, did successfully predict a negative F-region storm effect in the ionosphere that was in general agreement with observations obtained by the global ionosonde network. Detailed studies of this type are important for evaluating TGCM performance, identifying missing physical processes, and suggesting critical measurements that are needed to improve our overall understanding of global dynamic processes that are operating in the thermosphere and ionosphere. The model will be used extensively in various CEDAR campaigns.

The TGCM has been used by John Meriwether, Timothy Killeen, and Gonzolo Hernandez (University of Michigan), Robert Sica (Utah State University), Vincent Wickwar and Roberta Johnson (SRI), Joe Salah and Maura Hagen (Massachusetts Institute of Technology), and Jeffrey Forbes (Boston University) to interpret thermospheric dynamics measurements made from various ground-based observing stations. It has been used to examine the effect of the interplanetary magnetic field *By* component in altering high-latitude neutral dynamics through its control of the magnetospheric convection pattern, the effect of magnetospheric convection in the throat region in accelerating wind at high latitudes, the neutral dynamic response caused by the penetration of auroral zone electric fields to midlatitude, and the influence of upward propagating tides on dynamics at ionospheric F-region altitudes.

The TGCM and TGCM diagnostic package have also been used by Killeen and Allen Burns (University of Michigan) to investigate the physical processes that control the global distribution of the major constituents of the thermosphere. They examined the magnitude of each of the various terms in the major composition equation of the TGCM and found that the major compositional changes at high latitudes are determined by a balance between vertical motions and molecular diffusion. Local horizontal species transport is important at high latitudes where wind speeds are large but become less important at low and midlatitudes. The compositional variations during geomagnetic storms have been shown to have an important effect on the structure of the ionosphere, especially in describing negative ionospheric F-region storms.

Cassandra Fesen (University of Colorado) and Roble continue to use the TGCM to study the upward propagation of tides from the lower atmosphere into the thermosphere. The amplitude and phase of the TGCM 2-2, 2-3, 2-4, and 2-5 tidal components have been adjusted from previous studies to obtain agreement with new tidal data from the Chatanika incoherent scatter radar provided by Johnson and Wickwar. Fesen and Roble have also studied the effect of high-latitude auroral processes in altering the basic tidal structure propagating upward from the middle atmosphere. They found that high-latitude auroral processes have a

significant influence on the dynamic structure of the tides. This suggests that auroral variability may be an important additional source of the variability in the tidal structure observed at thermospheric heights.

The TGCM continues to be used to calculate global thermospheric dynamics for times when measurements from a satellite in the solar wind, and ionospheric drifts and neutral thermospheric winds measurements from the *Dynamics Explorer* satellite are both available. *Dynamics Explorer* measurements of ion drift and neutral wind have recently been sorted by Killeen and Gerald McCormac (University of Michigan) into bins representing magnetic latitude and magnetic local time and also according to the *By* component of the interplanetary magnetic field for both the Northern and Southern Hemisphere. The results show a significant variation in both the ion drift and neutral wind patterns depending upon whether *By* is positive or negative. An empirical ion drift model has been developed by Rodney Heelis (University of Texas, Dallas) and used in the TGCM to investigate the role of ion drag forcing in altering thermospheric dynamics at high latitudes. Within the ion drift model, the TGCM-calculated wind patterns also show a significant variation, depending upon the sign of the *By* component, that is in excellent agreement with the *Dynamics Explorer* wind data. The TGCM continues to serve the upper atmosphere community by providing simulations for the interpretation of measurements, testing various proposed forcing mechanisms, and providing insight into the various dynamic, physical, chemical, and radiational processes that are operating in the thermosphere/ionosphere system.

Global Mean Thermospheric Structure

A self-consistent, one-dimensional global average column model has been developed and used to examine the mean structure of the thermosphere and ionosphere above 97 km. The purpose of the model is not only to examine the global mean structure of the thermosphere and its response to solar EUV and UV output over a solar cycle, but also to develop rapid parameterizations of physical processes for eventual incorporation into a self-consistent TGCM.

The global mean thermospheric structure model has been used, with a model of the solar EUV and UV flux, to calculate thermospheric and ionospheric variations over the 3.5 years from 1 July 1977 to 31 December 1980. The period covers the rising portion of solar cycle 21. The model of solar EUV and UV fluxes is based upon the measurements of full disk irradiances from 5 to 200 nm made by the *Atmosphere Explorer* satellite. The solar EUV flux measurements were grouped into 37 EUV wavelength intervals to represent the entire EUV spectrum. Daily variations of this spectrum, with linear interpolation between daily solar flux values to accommodate the model's one-hour time step, were used in the global mean model to calculate the variation of the thermosphere and ionosphere structure over the period. The calculated globally averaged temperature

and composition profiles were compared with similar profiles obtained from the MSIS-86 empirical model. The empirical model is driven by the daily and 81-day mean solar $F_{10.7}$ cm flux values. The results show that the calculated overall global mean temperature structure is similar to that predicted by the empirical model, suggesting that the overall solar EUV flux variations are similar to the solar $F_{10.7}$ cm flux variation and that the self-consistent aeronomic model can reasonably account for the solar cycle variation. The major difference between the two models, however, is in their ability to predict short-term (daily) variations of thermospheric properties. It is known that the short-term behavior of various solar EUV emissions and that of the solar $F_{10.7}$ cm flux are distinctly different and these differences are reflected in differences between satellite-measured and empirical model-predicted densities. It is not possible to determine which of the two model approaches yields a better representation of thermospheric density variations. There is a serious need for new and improved measurements of the solar EUV spectral irradiance for future aeronomical studies and for the calculation of global thermosphere and ionosphere dynamics. This need is driven by the requirement for improved predictions of satellite drag and for improved calculations of thermospheric and ionospheric properties during various CEDAR campaigns.

Lower Thermosphere-Mesosphere Interactions

The globally averaged one-dimensional column model of the thermosphere, described in the previous section, has been extended 60 km into the mesosphere. The number of minor species in the model have been extended to include water vapor (H_2O), hydrogen (H and H_2), methane (CH_4), carbon monoxide (CO), and CO_2 with appropriate photochemistry and transport, and O_3, nitrogen dioxide (NO_2), hydroxyl (OH), H_2O, and hydroperoxyl (HO_2) in photochemical equilibrium with the above. The model also includes heating by ozone absorption and both local-thermodynamic-equilibrium (LTE) and non-LTE CO_2 radiational cooling. The model has been used to calculate the global mean structure for conditions appropriate to solar minimum and solar maximum. The solar EUV and UV flux measurements obtained by the *Atmosphere Explorer* satellite during July 1976 (solar $F_{10.7}$ cm flux of approximaely 70) are used to represent the solar flux during minimum, and the same measurements obtained on 19 February 1979 (solar $F_{10.7}$ cm flux of approximately 240) are used for solar maximum. Variations over a solar cycle were also prescribed for solar X-ray and solar UV (wavelengths greater than 200 nm). The model uses these solar flux values and the auroral particle precipitation and Joule heating rates, determined from a previous study of the global mean structure of the thermosphere, to calculate the global mean structure of the upper atmosphere above 60 km. It was found that chemical heating in the mesosphere is an important heat source for the region near 85 km. In order to bring the calculated temperature profile into agreement with the temperature profile predicted by the U.S. Standard

Atmosphere, it is necessary to consider a CO_2 cooling rate enhanced by collisions with atomic oxygen above 90 km and significant eddy cooling at 80–90 km. There is also a significant solar cycle variation in the upper mesosphere with temperature and the number of most minor constituents increasing from solar minimum to maximum.

Venus and Mars Thermospheric Dynamics

Stephen Bougher (University of Arizona), Dickinson, Ridley, and Roble have modified the NCAR TGCM to investigate the global thermospheric circulation, temperature, and compositional structure of Venus (VTGCM) and Mars (MTGCM). The Venus TGCM predicts a general subsolar-to-antisolar circulation modified by superrotational forcing from the lower atmosphere. To achieve a reasonable agreement between VTGCM predictions and measurements made by the *Pioneer* Venus spacecraft it was necessary to introduce into the model a parameterization for wave drag on the winds flowing across the terminator. This wave drag slowed the mean flow across the terminator, from the day-to-night side of the planet, sufficiently to allow a cold nightside (about 200 K) to develop and also to produce a compositional distribution that is consistent with *Pioneer* Venus observations.

Minor constituent transport for helium and odd nitrogen—$N(^2D)$, $N(^4S)$, and NO—have also been included in the model, and the calculated global structure of these constituents is in reasonable agreement with observations indicating that the VTGCM reasonably reproduces the global circulation, temperature, and composition structure of Venus.

Since CO_2 is also the main neutral atmospheric constituent on Mars, the VTGCM was appropriately modified and used to calculate the global circulation, temperature, and compositional structure for Mars (MTGCM). Initial MTGCM calculations indicate a strong in-situ solar-driven semidiurnal circulation that is comparable in magnitude with the diurnal circulation. The calculated thermal structure appears to be in reasonable agreement with the few available measurements, but considerable development is still required (especially with respect to the inclusion of upward propagating tides from the lower atmosphere) before a reasonable prediction of the Mars thermospheric circulation can be made.

Global mean column models, developed for the Earth, Mars, and Venus, have been used to calculate the global mean structure of these planets and their response to solar EUV and UV output over a solar cycle. The results show that the Earth has the largest solar cycle response, with the exospheric temperature varying by 500 K. Mars has the next largest variability with about 150 K, and Venus, because of strong CO_2 damping, has the smallest variation at about 50 K.

Ionospheric Electrodynamics Mapping

A new technique was developed for mapping high-latitude electric fields and currents and their associated magnetic variations from sets of localized observational data. The technique generalizes earlier ones that were designed to deduce these electrodynamic features from ground-based magnetometer data alone. In the new technique, many different types of measurements can potentially be used: electric fields from radars and satellites, electric currents from radars, and magnetic perturbations at the ground and at satellite heights. The technique also makes use of available statistical information about averages and variances of the electrodynamic fields. One of its advantages over earlier techniques is that it quantifies the errors inherent in the mapped fields, taking into account the distribution of available data, their errors, and the statistical variances of the fields. A related application of the procedure is used for estimating the distributions of high-latitude ionospheric conductances, using available direct and indirect measurements.

The technique was used to estimate the large-scale electric potential patterns, describing ionospheric convection for northern high latitudes during 18–19 January 1984 from combined incoherent-scatter radar and ground magnetometer observations. The pattern was usually found to be a characteristic dominant two-cell convection, although the intensities, orientations, and shapes of the cells change considerably with time. Often evident during substorm expansive phases is a "tongue" of low electric potential extending toward the east along the low-latitude edge of the high-potential cell at night. Time-series plots of the maximum and minimum electric potentials show that they can respond rapidly to changes in the interplanetary magnetic field B_z component. Total estimated potential drops for this two-day period ranged from about 15 kV to 108 kV.

The influence of the different types of observations on the resultant estimated electric potential patterns was also analyzed. Where available, the direct electric field observations by the radars primarily control the characteristics of the estimated potential patterns, while the magnetometer data have their greatest influence in regions where direct electric field measurements are unavailable. It was found that the ionospheric electrical conductance observations from the Sondrestrom and European Incoherent Scatter Radar Organization radars, together with a global statistical conductance model, could be used to yield conductance distributions suitable for interrelating the electric fields, currents, and magnetic perturbations. Analysis of the statistical uncertainty in the estimated large-scale electric field patterns showed it to exceed 50% in the polar cap and subauroral regions and to be less than 20% only in the vicinity of the radar electric field observations. This work was carried out by Richmond in collaboration with Y. Kamide (Kyoto Sangyo University, Japan), Byung-Ho Ahn (Kyungpook National University, Korea; University of Colorado/NOAA), S.-I. Akasofu (University of Alaska), Denis Alcayde' (CESR/CNRS/UPS, France), Michel Blanc (CNET/CRPE, France), Odile de la *Beaujardi*ère (SRI International), David Evans (NOAA), John Foster (MIT Haystack Observatory), E.

Friis-Christensen (Meteorological Institute, Denmark), Timothy Fuller-Rowell (University College, London, England), John Holt (MIT Haystack Observatory), Delores Knipp (University of California, Los Angeles), H.W. Kroehl (NOAA), R.P. Lepping (NASA Goddard Space Flight Center), R.J. Pellinen (Finnish Meteorological Institute,), C. Senior (CNET/CRPE, France) and A.N. Zaitzev (IZMIRAN, USSR).

Thermospheric Disturbances

A study by Christine Mazaudier (Center for Research in Environmental Physics, France), Richmond, and Douglas Brinkman (UCLA) compared observations of disturbed neutral and plasma motions above the St. Santin incoherent-scatter radar with a two-dimensional, time-dependent simulation model. They found that the model reproduced the correct order of magnitude of observed effects, lending confidence to the way in which Joule heating by auroral-zone electric currents was parameterized by the geomagnetic Auroral Electrojet index, and to the way in which the model simulates thermospheric circulation in response to this heating. It was recognized that improved agreement can probably only be achieved by using a three-dimensional model like the TGCM.

Symposium and Workshop

The International Symposium on Large-Scale Processes in the Ionospheric-Thermospheric System was hosted by HAO on 2–5 December 1986. Recognizing that the ionosphere and thermosphere are intimately coupled with each other and are strongly linked to the magnetosphere and middle atmosphere, this symposium focused on large-scale coupled processes in the system. More than a hundred papers were presented at the symposium. Most were based on studies that combined different experimental and modeling techniques. This reflects the trend in recent years to coordinate multi-instrument campaigns involving incoherent-scatter radars, other ionospheric and middle-atmospheric radars, ground-based optical instruments, rockets, satellites, and additional measurement techniques and to use global-scale models of the ionosphere, thermosphere, magnetosphere, and middle atmosphere to help interpret these multiple observations.

The Second Annual CEDAR Workshop was hosted by HAO on 29 June–2 July. The 160 participants planned coordinated scientific studies to be carried out in the areas of global thermospheric dynamics, high-latitude plasma structure, lower thermospheric coupling processes, global ionosphere-thermosphere coupling and dynamics, global ionospheric simultaneous measurements of substorms, thermospheric composition, middle atmospheric periodic structured atmospheric radiance, OH climatology, and data-base needs.

Incoherent-Scatter Radar Data Base

Developments to the data base in FY 87 included a substantial addition to the data holdings and an enhancement of the staff. Barbara Emery will be managing the regular operations of the data base in consultation with Richmond. Harsh Passi was hired to help develop and manage the software library, to help in analyzing the data, and to aid users of the data base. Roy Barnes continues to handle the data input and output and to develop analysis tools.

During the summer, Emma Sweetland (HAO summer undergraduate student, Purdue University) worked on a study to correlate ionospheric electrical conductivities measured by the Chatanika radar with magnetic perturbations measured at the nearby college magnetic observatory, in order to have a way of predicting the conductivities from other auroral-zone magnetometers when radar data are unavailable. Another student, Sixto Gonzales (NCAR summer minority undergraduate program), helped develop a way to make use of the electron density continuity equation to correct for an uncertain velocity bias in data from the Arecibo Observatory radar.

During the year, extensive discussions were held on the possibility of expanding the Incoherent-Scatter Radar Data Base into a broader data base serving the needs of the entire CEDAR community. In addition to the incoherent-scatter radar data, the data base would also handle upper atmospheric data from optical instruments and other types of radars, such as Mesosphere-Stratosphere-Troposphere (MST) radars. Plans for this expansion remain under consideration by NSF and the CEDAR community.

Global Atmospheric Electricity

Studies of global atmospheric electricity within HAO have primarily focused on the electrodynamics of the equalization layer of the global electrical circuit. Two main generators operate in the equalization layer: the ionospheric wind dynamo and the magnetospheric dynamo that regulates the coupling of solar wind energy into the ionosphere and thermosphere. A numerical model of the global ionospheric wind dynamo has been developed by Richmond and Roble and used to investigate the global distribution of electric potential and current systems in the ionosphere for solstice and equinox conditions. The dynamo model uses winds calculated by the TGCM for electrodynamic forcing. The calculated ground variations of magnetic perturbations caused by the ionospheric currents are in reasonable agreement with measurements made by the ground-based magnetometer network for equinox and solstice conditions. This model is currently being modified for inclusion in TGCM-4 to provide a model that self-consistently calculates dynamic and electrodynamic interactions between the thermosphere and ionosphere.

III. SCIENTIFIC STAFF

The following scientists (listed with their areas of research interests) were members of the HAO staff in 1987: R. Grant Athay (solar chromosphere, radiative transfer, theoretical astrophysics), Thomas Bogdan

(plasma astrophysics, magnetohydrodynamics, cosmic rays, particle acceleration), Timothy M. Brown (solar oscillations, global structure, image reconstruction, solar low-velocity measurements), Richard R. Fisher (coronal physics, solar activity, astronomical instrumentation), Ronald L. Gilliland (solar global fluid dynamics, solar variations), Peter A. Gilman (solar convection, differential rotation and dynamo theory), Thomas E. Holzer (theoretical models of the solar wind and its interaction with the interstellar medium, physical processes in models of the magnetosphere and polar ionosphere), Lewis L. House (radiative transfer and magnetic fields, atomic physics, coronal emission-line polarization), Arthur J. Hundhausen (physics of interplanetary plasma, solar-terrestrial physics), Bruce Lites (solar and stellar atmospheres, radiative transfer, solar oscillations and magnetic fields), Boon Chye Low (solar hydromagnetics and plasma physics, magnetic fields in interstellar clouds and magnetic stars), Keith B. MacGregor (structure of the solar atmosphere, stellar wind models, heating of solar/stellar chromospheres and coronae), Victor J. Pizzo (theoretical magnetohydrodynamics, application to the corona and solar wind), Gerald W. Pneuman (magnetohydrodynamics, solar corona, solar wind, solar-interplanetary modeling), Arthur D. Richmond (physics of the Earth's upper atmosphere, incoherent scatter radar measurements of the ionosphere, spatial patterns of geomagnetic variations), Raymond G. Roble (solar-terrestrial interactions, terrestrial thermospheric and ionospheric dynamics, planetary thermospheres), David G. Sime (the corona and interplanetary medium), and Andrew Skumanich (radiative transfer coupled to non-LTE excitation and ionization, structure of stellar and solar chromospheres).