Project Documentation



Science Goals of the ATST



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1. OVERVIEW

The astronomical object most relevant to humanity and life on earth is the Sun. Amongst the many reasons for the intense, continuing interest in observing the Sun are:

- The Sun sustains life on Earth; it controls our environment and impacts our technological civilization. Understanding and predicting the influences of the Sun on the Earth's climate and on space weather in the near-Earth environment is a major challenge for science. Understanding the Sun and Sun-Earth connection is crucial for understanding planetary systems (solar and extrasolar) in general.
- The Sun is the nearest and most readily studied astronomical object. Many physical processes that form the foundations of our current understanding of the universe are most accurately observed on the Sun.
- The Sun is a unique plasma physics laboratory. Its magnetic field configurations and environment provide conditions unattainable in terrestrial laboratories and are close enough to study with precision.
- The Sun presents us with many important unsolved mysteries and unexplored domains that challenge science.

Nowhere in the universe is there a better place to explore and understand how magnetism directs astrophysical and terrestrial change. The ATST is the first telescope the astronomical community has designed in all its aspects as a tool for magnetic remote sensing. Its collecting area, diffraction limit, wavelength performance and integral instrumentation are all targeted for understanding how magnetic fields affect the dynamics of the Sun and the solar-terrestrial environment. ATST will replace the aging national facilities (built in the 50s and 60s) that are now beginning to lose their competitive edge to moderately sized new solar telescope such as the 1m New Swedish Solar Telescope. The 4m aperture ATST will be the largest solar telescope ever built and with its unique and unprecedented capabilities will be at the forefront of international solar research and astronomy.

The Sun sustains life on Earth and is our main source of energy. Although we are confident that the Sun's total radiative output will not change over times relevant to human society, it is the subtle variation in the spectral composition of this output that profoundly influences Earth climate and our more and more technology driven society that we have to worry about. These variations occur on much shorter time scales and are modulated by the evolution of the magnetic field in the solar interior in ways we do not yet understand, but need to be able to predict. The detailed study of the structure and dynamics of the solar magnetic field on all its relevant scales, which is required to develop such predictive capabilities, is the main objective for building the ATST. ATST is not only a telescope of unique design but also provides a set of state-of-the-art instruments that in many cases will be operated simultaneously to obtain the maximum amount of information about the dynamic solar atmosphere.

Our vantage point on Earth allows us to study the Sun in more detail than any other star. We would never have been able to extract the physical intricacies of all the processes we see on its surface if we had to go by the spatially averaged light we receive from other stars. Although, with the prospect of 30-100 m telescopes resolving distant stars will become feasible and the observations of the sun that ATST will deliver will be essential for the correct interpretation of the data coming from the giant aperture telescopes. Currently, we are not yet able to observe these processes at their natural scale, even in the case of the Sun. With ATST we will have the ability to zoom in on these scales and finally gain an understanding of the role magnetic field and its interaction with the embedding plasma plays in the Sun and many other astrophysical objects. With the new spatial scales that ATST will allow us to resolve, and

the new spectral windows it will make available to us we will also have new opportunities for discoveries of processes we had no idea existed.

To achieve the goals we have set for ATST we require an instrument with a large aperture, not only to reach sufficient spatial resolution, but also to collect enough photons for accurate polarimetry. We also require the ability to observe the Sun at many wavelengths simultaneously, including in the near ultraviolet and in the infrared, to resolve the three-dimensional structure of the solar atmosphere, and at high temporal resolution to resolve the highly dynamic nature of the atmosphere. With these requirements the ATST will be the ideal tool for magnetic remote sensing.

Much progress in our understanding of the behavior of the solar magnetic field and its direct influence on the near Earth environment has been made with space missions like Yohkoh, SoHO, TRACE, and most recently RHESSI. These missions have reinforced our perception that the Sun's atmosphere is highly dynamic and changes in its magnetic field lead to strong variations in its UV and X-ray, and particle flux. Changes in the solar magnetic field produce solar flares, coronal mass ejections, and cause variations the solar wind. All of these processes have profound impacts on human society, driving terrestrial climate, determining the state of the Earth's atmosphere and magnetosphere, affecting communication, power transmission and other activities on the Earth's surface, and presenting hazards to humans in space. Unfortunately, our understanding of these phenomena is still very limited. We do not know how the highly intermittent magnetic fields observed at the solar surface are generated by dynamo processes and how are they dissipated. We do not know what magnetic configurations and evolutionary paths lead to flares and coronal mass ejections, or which mechanisms are responsible for variations in the spectral and total irradiance of the Sun and solar-type stars.

Over the last two decades a remarkable change has taken place in solar physics. The increasing power of numerical simulations, both in hardware performance and through development of new techniques, has transformed the field from a more phenomenological science, describing the appearance of the wide variety of magnetic phenomena, to a real physical science that investigates their nature and connections between them. Unfortunately, the spatial, spectral, and temporal resolution of solar observations has not been able to keep up with the predictions the simulations produce. As a result, many simple questions remain unanswered. The ATST is needed to constrain and guide the modeling efforts to the point where we not only understand the behavior of the solar magnetic field and plasma, but also are able to predict its behavior.

There is a great incentive for ATST to work at infrared wavelengths. Maximum sensitivity to magnetic field is achieved with infrared lines. Earth's sky is also darker in the infrared than the visible, resulting in much reduced background levels and improved signal-to-noise levels. For accurate determination of the magnetic field parameters from the photosphere to the corona, ATST will provide access to infrared wavelengths at high spatial resolution in a way that cannot be achieved economically from space due to the required large telescope aperture. The unique ability of ATST to measure coronal magnetic fields using infrared lines is needed to solve the mystery of flares and coronal mass ejections (CME). No existing instrument can provide these crucial measurements. Coronal magnetic field observations are starved for photons. ATST constitutes an improvement in sensitivity by nearly a factor of 50 from one of the worlds' current largest coronagraphs (0.4m). This sensitivity improvement will allow fields as low as the equi-partition field strength to be measured for the first time. This is a unique capability, which ATST provides because, except for occasional point-like observations of background radio sources, we have never had the capability to detect and measure such coronal magnetic fields.

It should be emphasized that exploration of the Sun at infrared wavelength is a relatively new field and is an area with the potential for new discoveries. The history of science is full of examples where measurements of the Sun, stimulated by basic questions and using new observational capabilities (often first applied to the Sun), led to revolutions in our deepest understanding of nature. A recent example is the neutrino problem (Bahcall et al. 2000), i.e., the disagreement between the measured and predicted solar neutrino fluxes. Helioseismology has proven the standard solar model to an accuracy of better than 0.1%. The conclusion from this is that the origin of the problem was an incomplete understanding of neutrinos – a result recently confirmed by experiments far more expensive than the ATST. The ATST is such a large qualitative and quantitative step forward that it offers a good chance of continuing this tradition of revolutionary discoveries with impacts far beyond solar physics. Based on the history of major solar telescopes, we emphasize that a main scientific contribution of the ATST is likely to be one or more discoveries that we cannot foresee.

The 0.022 arcsec (at 430nm, g-band, 16km on the surface of the Sun) diffraction limited resolution of ATST will finally allow detailed comparison with models of physical processes on their natural scales. The ATST will easily resolve the fundamental scale of the photon mean free path in the photosphere, which probably restricts the spatial extent of thermal variations. ATST will be the only solar telescope that can resolve these fundamental scales at near infrared wavelengths such as 1.6 microns, which have become an indispensable diagnostics tool for magnetic field measurements. ATST will be the only solar telescope that can resolve these fundamental scales in the corresponding important parts of the spectrum. ATST's large aperture is also needed to achieve a high photon flux for accurate measurement of physical parameters like magnetic strength and direction, temperature and velocity through polarimetry and spectroscopy at high spectral and temporal resolution. A large field of view is needed to study the evolution of magnetic active regions, the prime manifestation of solar magnetic fields on larger scales. The flexible post-focus instrument package of the ATST will allow the observer to optimize the relevant observing parameters such as spatial and spectral resolution and polarimetric sensitivity and accuracy to a specific problem. Such optimization is hardly ever possible for space missions.

During the past decade, solar astronomers have presented strong scientific arguments for a large-aperture solar telescope. These arguments are presented in the latest NSF/NASA Astronomy & Astrophysics Survey Committee (AASC) Decadal Survey (2000) and the NAS/NRC report on "Ground-Based Solar Research: An Assessment and Strategy for the Future" (1999). The close synergism between ATST and NASA's "Living with a Star" program and its space missions such as the Solar Dynamic Observatory (SDO) was stressed by the Solar and Space Physics Decadal Survey (Lanzerotti, 2003). Combining the individual strengths of the ground-based ATST and space missions will lead to the desired scientific breakthroughs. These reports make a strong and persuasive case that high-resolution studies of the Sun's magnetic fields will lead to a better understanding of cosmic magnetic fields and the fundamental processes responsible for solar activity and variability. The latest Decadal Survey of Astronomy has given the ATST a high ranking within the Nation's astronomy program. The ATST is a community-wide program. The recent NAS/NRC panel study on Ground-Based Solar Research and its recommendation that the ATST be the next major solar project, as well as the broad participation of university and other national and international partners, reflect the community's support.

Some of the major scientific questions addressed by the ATST, and the requirements these science goals place on the telescope and its instrumentation, are outlined in detail below.

ATST will allow us to study the fundamental physical processes underlying solar magnetic activity at the spatial and temporal scales at which they naturally occur. Relating these measurements to the global magnetic variability of the Sun is a critical component of the science that the ATST will enable. The Sun's magnetic machine involves the processes of flux generation, transport, dissipation, instability and ejection; the ATST is critical for our understanding of all of these. For example, in Section 2.1 we discuss how ATST observations of the small-scale processes at the solar surface may play a critical role in understanding the overall dynamo process – the generation of the magnetic fields themselves and their cyclic behavior. This leads naturally to Section 2.1.3, a discussion of "flux tubes," which are generally

believed to be the fundamental building blocks of magnetic structure in the atmosphere and the progenitors of solar activity. The ATST will for the first time reveal the nature of solar magnetic flux concentrations. With the ATST we'll be able to observe the interaction of the magnetic field with convective motions and waves (Section 2.1.4) and determine how energy is transferred to the magnetic field. By exploiting the broad spectral coverage planned for the ATST, especially the IR spectrum, we can observe these processes with height and measure their role in determining the structure, dynamics, and heating of the chromosphere and the corona (Section 2.3). The unique IR capabilities of the ATST will be used to measure the cool chromospheric component and provide critically needed measurements of coronal magnetic fields. The dynamics and heating of these outer layers of the solar atmosphere in turn results in the violent flux expulsions we see as flares and mass ejections (Section 2.2.1) and variations in the solar radiative output (Section 2.4). All of these processes are tied together by the behavior of magnetic flux in the dynamic plasma at the solar surface. In Section 3 we discuss the significant impact of the ATST on other areas of astrophysics, space science, and plasma physics and how the results from the ATST will be crucial for building and refining space weather models. The synergism between the ATST and other ground- and space-based assets and the crucial interplay of ATST observations and models and simulations are described in the same section. ATST's large photon collecting area, high angular resolution, infrared sensitivity, low scattered light and high polarimetric sensitivity and accuracy provide the tools we need to trace the origin, transport and evolution, and dissipation of magnetic fields in the Sun. This new ability to observe the life-cycle of magnetic flux is essential to resolve many longstanding solar problems.

The science focus of ATST will undoubtedly evolve with time as the results from ATST observations and joint ATST-space mission observations drive the field of solar physics. ATST has been designed in a way that will allow it to adapt to new scientific frontiers.

2. ATST SCIENCE OBJECTIVES

The sections that follow cover a broad field. For the readers' benefit, references are limited to review articles and workshop proceedings that summarize the current status of the field or a few examples of recent work.

In addition to the discussion of the ATST science goals below we refer the reader to the detailed description of specific ATST science goals and experiments listed in the ATST Science Requirements Document (SRD).

2.1 ORIGIN AND GENERATION OF MAGNETIC FIELDS

2.1.1 Magnetic Field Generation and the Solar Cycle

To understand solar activity and solar variability we need to understand how magnetic fields are generated and how they are destroyed. The 11-year sunspot cycle and the corresponding 22-year magnetic cycle are still shrouded in mystery. A small fraction (10^{-5}) of the energy produced in the thermonuclear core of the Sun is transformed to magnetic fields, which in turn produce nearly all the dynamic phenomena observed in the solar atmosphere. The dynamo process in the Sun and stars is not yet well understood.

Global dynamo models attempt to explain large-scale solar magnetic fields based on mean field theories. Turbulent convection is believed to stretch and amplify the magnetic field and shear due to meridional circulation or at the base of the convection zone is believed to organize the large-scale solar magnetic field of several 100 kgauss. This field intermittently rises up to the surface and emerges as active regions. However, the properties, such as diffusion and helicity, that have to be assumed in these models are produced by small- scale turbulent processes and have not yet been measured for the Sun. The ATST is

needed to observe the turbulent vorticity and the diffusion of small-scale magnetic fields to measure these properties and how they evolve with the solar cycle.



Figure 2.1. Small-scale dynamo. Mixed polarity fields are "generated" in intergranular lanes. A movie showing the evolution of these fields (http://flash.uchicago.edu/~mhd) demonstrates how field lines get twisted and tangled by vortex motions. This important detail (left) is lost when the resolution is reduced to what can currently be achieved with the best high resolution telescopes and adaptive optics (courtesy of F. Cattaneo).

Any three-dimensional turbulent flow with sufficiently high Reynolds number is a dynamo (Fig. 2.1, Cattaneo 1999). Each scale of turbulent motion will produce its own "magnetic scale" and magnetic fields should be observed virtually everywhere on the Sun. It is possible, if not likely, that several dynamos are at work on the Sun and other stars. Local dynamo action near the surface may produce the magnetic flux, organized as a "magnetic carpet," observed to cover the entire Sun, which continually renews itself on a time scale of a few days at most and whose flux may be comparable to that in active regions (Schrijver et al. 1997; Title et al. 1998).

This hierarchy of scale posses many questions: How do strong fields and weak fields interact? Does the weak-field component have a large-scale structure? What is the small-scale structure of the global component? How are both generated? How do they disappear? How do they contribute to chromospheric/coronal magnetism and heating?

The ATST will address these questions by resolving individual magnetic flux concentrations and observing their emergence and dynamics. It will measure distribution functions of field strength, field direction and "flux tube" sizes and compare these with theoretical models. The ATST will observe plasma motions and relate them to the magnetic field dynamics.

Infrared observations are particularly useful here because they can measure weaker magnetic fields. Important examples of magnetically-sensitive infrared lines are the Fe I Zeeman triplet at 1.565 μ m (low photosphere), and the high-Rydberg transitions of Mg I at 12 μ m (upper photosphere). Using the Mg I lines fields down to 100 gauss can be measured directly from their Zeeman splitting. With explicit radiative transfer modeling, even lower field strengths can be observed, making these lines excellently suited to map the weak inter-network magnetic fields.

Using the 1.565-micron lines, ATST will be able to measure weak magnetic fields with unprecedented spatial resolution (0".1), sensitivity, and temporal resolution, allowing the study of their evolution. By combining magnetic field measurements from the Fe I 1.565- μ m and the MgI 12- μ m lines, for example,

we can measure the run of magnetic field strength with height in the important regime where the field becomes de-coupled from gas motion.



Figure 2.2. Stokes polarimertry of "granular" magnetic fields observed at 1.56 microns, showing that the "quiet" Sun is covered with both weak and strong magnetic fields. These data taken at the Dunn Solar Telescope represent the state-of-the-art and have a spatial and temporal resolution of 1 arsec and 5 min, respectively, which is insufficient to resolve the mixed polarity fields and study their evolution (courtesy of H. Lin).

2.1.2 Magnetic and Current Helicity and its Relevance to the Dynamo Problem

Helicity plays a fundamental role in evolution and topology of solar magnetic fields on different spatial and temporal scales (Brown, Canfield, and Pevtsov 1999; Buchner and Pevtsov 2003). Helicity is essential for the effective operation of a dynamo. On the other hand, excessive helicity may suppress the dynamo action. To ensure efficient operation of the dynamo, helicity has to be removed from the dynamo region and transported to the corona. On their way to the surface, magnetic fields can accumulate additional helicity by interacting with turbulence in the convection zone. Since coronal fields can store only a limited amount of helicity it needs to be removed from the sun via CMEs.

Is active region helicity primarily due to interaction with convection or produced by the dynamo? What is the contribution of surface horizontal flows? The propagation of twist to the corona depends on the emergence of twisted fields, surface flows and Alfven waves and can provide information on the origin of magnetic helicity. Detailed modeling combined with high-resolution vector magnetograms of large number of active regions will allow us to separate dynamo and turbulence contribution to the helicity.

ATST's high time-cadence, high spatial resolution vector magnetograms will provide crucial information about evolution of magnetic field twist during flux emergence. To detect helicity "pumping" by Alfven waves will require a computation of electric currents inside individual "flux tubes" -- a task well outside the scope of existing ground-based telescopes or near-future space instruments (SOLAR-B, SDO).

Small-scale weak field may be generated by local dynamo action. A local surface dynamo would explain the lack of solar cycle variations in magnetic flux on the quiet sun, and it is consistent with the short, ~ 40 hours life-time of network flux. The large-scale subphotospheric dynamo operates on time-scales comparable to the period of solar rotation. The Coriolis force will affect the dynamo flows and result in hemisphere-dependent helicity, i.e., hemispheric helicity rule. In contrast, the small-scale photospheric flows that drive the surface dynamo will not be affected by the solar rotation. The magnetic helicity generated by these flows is expected to be hemisphere independent (Pevtsov & Longcope 2001; Ossendrijver 2003). On the other hand, if the local dynamo simply recycles magnetic flux generated by a subphotospheric dynamo, the hemispheric helicity rule should also be present. Observations of magnetic helicity in quiet sun areas are necessary to understand the role, if any, of a local dynamo. These observations will require observations of vector magnetic fields with spatial resolution better than 0.1 arcsec.

ATST will provide ultra-high resolution vector magnetograms allowing direct observational test of the hypothesized local dynamo. In addition, the high resolution and high time-cadence white-light images will allow direct comparison of kinetic helicity of local dynamo flows and helicity of magnetic fields generated by these flows.

2.1.3 Small-Scale Magnetic Flux Concentrations

Observations have established that the photospheric magnetic field is organized in small fibrils or "flux tubes". They account for a significant, possibly dominant, fraction of the magnetic flux outside of sunspots. These structures are mostly unresolved by current telescopes. Large-scale active regions decay through flow field dispersal of flux into smaller scales and the subsequent transport of these magnetic field concentrations is a key mechanism in the 22-year global magnetic cycle of the Sun. Magnetic field lines are the most likely channels for transporting convective energy into the upper atmosphere, which is the source of UV and X-ray radiation from the Sun, which in turn affects the Earth's atmosphere. Detailed observations of these fundamental building blocks of stellar magnetic fields are crucial for our understanding not only of the activity and heating of the outer atmospheres of late-type stars, but also of other astrophysical situations such as the accretion disks of compact objects, or proto-planetary environments. Current solar telescopes cannot provide the required spectroscopy and polarimetry at an angular resolution to explore the enigmatic "flux tube" structures.



Figure 2.3. Observation of plasma flows associated with small flux concentrations (from Rimmele 2003, ApJ, submitted). These data were recorded at the Dunn Solar Telescope using the newly developed high-order adaptive optics system. Tick marks are 0."5. FOV: 8.6" x 12.6". Right image: Intensity in the wing of the iron line FeI 5434. The bright points mark the location of magnetic flux concentrations. Left image: Corresponding (bisector-) velocity map. Dark is downflow; bright is upflow. Strong narrow downflows are located at the edge of most flux concentrations. This observation provides the first direct confirmation of strong downflows at the edge of fluxtubes driven by radiative losses into the evacuated magnetic structure. Such downflow jets were predicted by MHD simulations (see Figure 2.4).

Theoretical calculations and numerical simulations suggest that small-scale flux concentrations are formed by convective intensification by the photospheric flow field: flux is continually swept to the intergranular downflow regions where it is concentrated, twisted by local vorticity in the intergranular downflows, and radiatively cooled to form coherent flux bundles. A "surface dynamo" mechanism for field generation may exist, which has major implications for the surface magnetic flux budget of the Sun. The flux concentrations are highly dynamic, undergoing constant merging, shearing, fragmentation and reformation leading to substructures predicted to be on the order of a few tens of kilometers in scale. Interaction of the flux concentrations with convection buffets, bends, and twists the magnetic field, which changes the magnetic topology in and heats the upper atmosphere via magnetohydrodynamic (MHD)



Figure 2.4. Dynamics of magnetic flux elements. Numerical simulations predict how magnetic flux tubes dynamically interact with convection to produce, e.g., MHD waves and shocks that are likely to contribute to the heating of the upper atmosphere. Physical quantities such as temperature (color coded), magnetic field strength and the flow field (arrows) can be computed. Through radiative transfer calculations, the temporal evolution of observable quantities can also be modeled. An example is shown on the right: Evolution of Stokes I and V during the transit of an upward propagating shock. Time progresses upwards (courtesy of O. Steiner et al.). With ATST we will be able to verify these model predictions.

waves and intertwining of magnetic lines leading to magnetic reconnection and ohmic sdissipation of currents (Parker 1972; Parker 1983)

In spite of the significant progress that has been made with the development of adaptive optics (Figure 2.3) current magnetogram observations lack the spatial and temporal resolution necessary to verify these theoretical predictions of small-scale flux formation and flow-field interactions. Indirect methods using flux-associated bright points have observed constant splitting and merging of flux concentrations, occurring on time scales of tens of seconds to minutes in response to granular flows similar to the turbulent 3D simulations. However, confirming ob servations of the formation and decay mechanisms of flux concentrations, or of the expected vorticity within flux elements, are lacking. Such observations require vector magnetic field measurements on spatial scales of a few tens of km combined with a temporal resolution on the order of 10 seconds.

Investigating the role of small-scale flux dynamics in powering the Sun's outer atmosphere also requires new levels of spatial and temporal resolution. The TRACE mission (Handy et al. 1999; Schrijver et al. 1999) has shown that coronal fine structure exists on arcsecond scales and very likely below this level as well (Fig. 2.5). Chromospheric and transition region motions observed with TRACE at 10-second cadence are still not fully resolved in time, in agreement with theoretical predictions that the flow-field motions of flux concentrations in the photosphere are "amplified" by the sweeping of field lines in the higher layers. Indeed the magnetic topology above the photosphere remains completely unclear. For example, a comparison of TRACE observations to ground-based photospheric and chromospheric data shows that transition region emissions from hot coronal loop foot points correlate only on the large scales to magnetic field sites in the lower atmosphere (Berger et al. 1999). At smaller scales, transition region emissions do not directly overlie Ca II K-line chromospheric bright points or G-band bright points in the photosphere. Thus coronal loops do not appear to be vertically anchored to the flux concentrations in the photosphere that must ultimately be their source regions. Are magnetic field lines entangled by motions as they rise through the atmosphere? Or are the transition region emissions (and perhaps coronal loop heating sources) located at the interface regions of expanding magnetic field lines from the photosphere?

What is the relationship between bright coronal plasma and the magnetic field? Can we correlate magnetic flux motions in the photosphere with impulsive events in higher layers of the atmosphere such as spicules and transition region explosive events and ultimately with episodic heating of coronal loops?

Addressing these issues requires simultaneous vector magnetometry in multiple layers of the solar atmosphere and drives the temporal resolution requirement even lower, perhaps to one second time scales or less. Only ATST will achieve the resolution and photon flux requirements and will also allow investigations of the role of MHD wave modes in energy transport to the outer atmosphere, addressing such issues as the source of the fast solar wind in open-field regions.

ATST will provide direct measurements of magnetic flux cancellation rates in the quiet sun from magnetograms that have 16 times better resolution (pixel area) or 30 times better sensitivity (or a compromise between the two) with the 4m ATST than with the current largest solar telescopes. By keeping the same pixel resolution we have now, but using the 4m ATST at lower resolution, we can obtain a sensitivity of 0.1 G (or better) for the line-of-sight component of the magnetic field. Alternatively, we can go for maximal spatial resolution of 0.03" at 630nm. Either way, we will be able to detect more intranetwork fields and their interaction with network fields. For the quiet Sun the flux cancellation rate is a good representation of the reconnection rate. Therefore, we will be able to accurately measure the energy released during the reconnection of the quiet Sun fields. This will enable us to estimate the energy and mass flow of solar wind, and understand the sources of coronal heating.

Finally, small-scale magnetic flux plays a large role in the total irradiance budget of the Sun. An accurate physical model of flux concentrations, however, is still lacking. Fully resolved measurements of small-scale flux irradiance as a function of disk position are needed in order to complete a realistic physical model of the temperature, density, and internal flow fields of these elements. Large fields of view are also required in order to capture entire active regions as they transit the disk, observing in detail the potential



Figure 2.5: Left: TRACE image of coronal loops (courtesy of A. Title). Right: Field extrapolation from photospheric field measurements (courtesy of Meudon Observatory).

interplay between sunspot, pore, and plage region irradiance. Establishing an accurate physical model of small-scale flux is also crucial for testing the results of numerical simulations addressing flux formation and dynamics.

To do so, individual flux concentrations have to be resolved and gas motion, magnetic field, and temperature variations within and around the "flux tube" have to be accurately measured and compared to model predictions.

The ATST will also allow us to derive the distribution of field strengths as a function of element size in quiet and active regions. We will be able to measure the spatial profile of vector magnetic field across a typical element. The ATST will enable us to investigate where the magnetic flux is located relative to surrounding convective flows and search for evidence of vertical mass flows within "flux tubes".

MHD waves propagating along magnetic fibrils are a likely candidate for transporting energy to the upper atmosphere. In many cases, detailed model predictions, including detailed simulations of observable quantities, such as spectral line profiles or Stokes profiles, are available. The spatial resolution in these models is of the order of a few tens of kilometers. These predictions have to be verified through observations.

The ATST will provide the required spectroscopic observations of sufficient resolution. Thus we will be able to study the formation, internal structure, interactions with convection and disappearance of these flux tubes and what role they play in the heating of the outer atmosphere.

2.1.4 Magnetoconvection and Flux Transport

Our understanding of the nature of stellar convection has changed considerably during the last two decades. The conventional picture based on the simple mixing length theory, used in modeling stellar evolution, provides an inadequate description of the dynamics of convection. Modern numerical simulations (Rast et al. 1993; Nordlund et al. 1997; Stein et al. 1999) provide a very different picture in which convection is driven by radiative cooling of material that becomes optically thin upon its arrival at the surface of the Sun. The simulations predict that this cold plasma forms narrow, turbulent downdraft plumes. However, observational evidence for these small-scale (significantly smaller than 0."1) vortex flows within the intergranular lanes has yet to be found. The ATST is needed to resolve the small-scale structures and dynamics of convection and verify (or falsify) the predictions of the models.

Vortical plasma motions, such as those that occur in the downdrafts, will stretch and amplify any seed magnetic fields, producing a small-scale dynamo. The downdrafts may also pump the small-scale magnetic flux produced down towards the base of the convection zone. Convective flows may be important in breaking up the magnetic "flux tubes" into smaller elements and in merging individual "flux



Figure 2.6. Diffraction-limited images of flux tubes (bright points) in the vicinity of a magnetic pore. In this example the diffraction limit (0".16) was reached by combining adaptive optics and post-facto image reconstruction (phase diversity). From images like these one can infer that most flux tubes have sizes below the diffraction limit of the Dunn Solar Telescope. A time sequence of such images was recorded in an attempt to study flux tube dynamics (Courtesy of Keller, Paxman et al.).

tubes" into larger structures. They also may shuffle around the atmospheric magnetic loop foot points and launch MHD waves that propagate into the upper atmosphere. The ATST is essential to observe the dynamics of the individual flux concentrations.

The ability to resolve and track individual "flux tubes" is needed to understand how magnetic field is organized into larger scale patterns such as meso- and supergranular scales. For example, there is a controversy about the relation of magnetic fields and supergranulation. Does the supergranular scale diverging flow advect magnetic field to the network at the supergranule boundaries? Or, is it the magnetic field that produces the observed supergranulation pattern?

Another example of how a magnetoconvective process that occurs on very small scales (<100 km) causes a global phenomena are the solar p-mode oscillations. Helioseismology, based on observations of the 5-minute p-mode oscillations, is now one of our most important tools for studying the internal structure and dynamics of the Sun. For some time it was assumed that the convective excitation of solar oscillations

was due primarily to the deceleration of the updrafts in granules, acting as pistons to drive the oscillations. But then numerical simulations of granulation showed the presence of strong, narrow, supersonic downflows in the intergranular lanes. These downflows, which are much stronger than the broader, slower upflows, generate acoustic noise. It has been suggested that this noise is the principal exciter of the p-modes. Recent observations were able to suggest a connection between acoustic sources observed in the photosphere and strong downflows in intergranular lanes (Strous et al. 2000).

Numerical simulations also provide detailed predictions on how convective energy is converted into acoustic energy (Stein et al. 2000). These acoustic events may also contribute to the heating of the lower chromosphere through the formation of shock waves. While the spatial and temporal resolution of current facilities is sufficient to verify the existence of acoustic events, they are unable to study the underlying physical mechanisms and to



Figure 2.7. G-band image of sunspot observed simultaneously with the DLSP (fig. 2.8) and high order AO. Dark penumbral filament cores recently reported in observations from the new Swedish 1m telescope on La Palma are visible in this image.

verify model predictions. Surface cooling producing low entropy fluid is part of the process, but according to model predictions, turbulence below the surface appears to be actually the more important driver. One of the remaining challenges is to understand quantitatively the origin of the oscillation mode line asymmetries. This is part of the bigger challenge of understanding the dynamical interaction of oscillations with convection.

The ultra high spatial resolution along with excellent temporal resolution is required to verify the exciting results of numerical simulations. Also needed are measurements of spectral line profiles with sufficient spectral resolution so that the information contained in the details of line profiles can be revealed. Such data will be provided by ATST and will greatly advance our understanding of the nature of stellar convection.

2.1.5 Sunspots: An Example of Magnetoconvection

Sunspots are the ideal objects for testing magnetohydrodynamic theory under astrophysical conditions. In a sunspot there is a strong interplay between magnetic and hydrodynamic forces. The interaction of magnetic fields with mass flows is an important general phenomenon in astrophysical situations over a vast range of length scales, and including intense "flux tubes" and sunspots on the Sun, spots on other stars, planetary magnetospheres, star-forming regions, planetary nebulae, supernovae remnants, galaxies, and clusters of galaxies. Sunspots allow us to subject theories of such phenomena to comparisons with detailed observations (Thomas et al. 1992).

Sunspots present us with a considerable challenge. For example, we still do not understand completely how sunspots manage to hold together for a few months. Whether the small (<0."1), bright umbral dots are a manifestation of magneto convection in a diffuse magnetic field or channels of hot, field-free gas



Figure 2.8. Intensity, linear and circular polarization maps obtained with the Diffraction Limited Spectro-Polarimeter on Oct. 24, 2003 at the DST. The map is obtained using 660 slit positions with step size of 0.09". It took us about 50~minutes to complete the map. High order adaptive optics was used to produce a scan of consistent and high image quality. These data contain information about the magnetic field at spatial scales near the diffraction limit of the DST (0."2 at 630nm) and thus represent an improvement of a factor 2-3 over what was previously achieved with the ASP (Fig. 2.9). The data is neither flat-fielded nor corrected for instrumental polarization.

penetrating the magnetic field from below, is still unclear. This question is part of the larger questions concerning the subsurface structure of a sunspot and the stability and breakup of sunspots.

Sunspots exhibit a range of interesting oscillatory motions, including umbral oscillations and flashes, running penumbral waves, and five-minute oscillations. The nature of these oscillations and the relationships among them are still not completely understood. Once the nature of the wave modes is well understood, these oscillations can provide valuable information about the structure of the sunspot. In particular, studies of the interaction of the solar p-modes with a sunspot ("sunspot seismology") can serve as a probe of the structure of a sunspot below the visible surface of the Sun.

The two recent review articles by Solanki (2003) and by Thomas and Weiss (2003) summarize the progress and remaining challenges in our quest to understand the physics of sunspots and the underlying MHD processes. Some fundamental unanswered questions include:



Figure 2.10. Diffraction limited magnetogram (left) and corresponding narrow-band filtergram (630 nm) of a small sunspot observed at disk center with the help of the adaptive optics system at the DST. The correlation between small (<0."2) bright points in the vicinity of the sunspot and magnetic flux is clearly visible. In order to achieve excellent signal-to-noise an effective exposure time of 20 sec was chosen. In spite of the long exposure diffraction limited resolution was achieved demonstrating the effectiveness of the adaptive optics correction. ATST will provide similar observations of active regions but with more than 5 times better resolution thus resolving the sunspot fine-structure and the internal structure of individual "flux tubes" – the basic building blocks of solar magnetism. (Rimmele 2003)

- How do sunspots form and how do they decay?
- What do sunspots tell us about the large scale dynamo?
- What is the subsurface structure of sunspots?
- Why do sunspots have a penumbra? What causes their rapid formation?
- What determines the intrinsic brightness of umbrae and penumbrae?
- What is the nature and origin of umbral dots?
- What is the true small-scale (magnetic) structure of penumbrae?
- What drives the Evershed flow?
- Why do more active stars seemingly have larger spots.
- What fraction of the heat flux blocked by sunspots is stored in the convection zone?

Some of these questions are elaborated on in the following subsections.

To develop valid theoretical models of sunspots, it is essential to perform high-resolution vector polarimetry of sunspots throughout the solar atmosphere. The precise measurements of the magnetic Stokes vectors needed to accurately map out the full vector magnetic field in a sunspot is a fundamental goal for the ATST. Competing models of the filamentary structure of the penumbra and the Evershed effect exist. However, verification of model predictions requires imaging and polarimetric/spectroscopic observations at the highest spatial, temporal and spectral resolution, which only large aperture telescopes like the ATST will be able to achieve. The state-of-the art observation of the sunspot vector field shown

in Figure 2.8 took 50 minutes to complete. However, the sunspot fine structure evolves on time scales much faster than that.

Only with the ATST will we be able to collect precision polarimetric data as shown in Figure 2.8 but with a temporal cadence necessary to capture the evolution of sunspot fine structure and finally understand its physical origin.

In sunspot umbrae and penumbrae, optical observations are plagued by contamination of scattered light from the bright surrounding photosphere. The ATST is carefully designed to allow observations of high resolution and low scattered light. In addition, the 4-m aperture will allow high-resolution observations in the infrared (e.g., 0.08 arcsec at 1.6 μ m), where scattered light is less of a problem and much more accurate magnetic field fine-structure determination is possible. For the first time we will have magnetic field strength measurements directly from a fully split Zeeman line at this very high spatial resolution.

Formation of Sunspots: An active region begins with the emergence at the solar surface of large, magnetic flux (Zwaan 1992), that is initially fragmented into small, intense "flux tubes," which then accumulate between granules and mesogranules to form small pores. Some pores fade away, while others accumulate to form sunspots. A sunspot differs from a pore by having a penumbra. Recent observations with the 1m Swedish Solar Telescope reveal a gradual development of penumbra from pores to spots. Tracing the development of a sunspot from the coalescence of magnetic elements and pores, from sub-arcsecond scales to large, mature spot, requires observations with high spatial, spectral, temporal, and polarimetric resolution.

The ATST will provide detailed observations of pores as they emerge and evolve into sunspots. With ATST, we will observe the structures of pores and sunspots over a range of heights from the deepest observable layers of lower photosphere to the chromospheric layers with a spatial resolution of 50-100 km. With the capability of continuous high quality seeing stabilized by adaptive optics, ATST will provide the necessary tools for monitoring the magnetic and dynamic structure of these elements. Our current knowledge of the underlying structure of sunspot magnetic fields is primitive.

Filamentary Structure of Sunspot The filamentary structure of **Penumbrae:** sunspot penumbrae holds considerable clues as to how the magnetic field connects outwards from the dark umbral cores. It also has a bearing on the stability and lifetime of sunspots. Recent observations have revealed the "fluted" structure of the penumbral magnetic field, with radial spokes of inclined field separated by regions of nearly horizontal field. This structure is intimately connected with the outward Evershed flow in the penumbra, which is concentrated in narrow (<0."1) channels in the regions of nearly horizontal magnetic field and which in many of these channels dives down below the solar surface near the outer penumbral boundary. The structure and dynamics of penumbral filaments is an enigma, particularly because their size is below the reach of current telescopes (Solanki 2003). Recently, Thomas



Figure 2.11. High resolution sunspot image taken at the German VTT on Tenerife using the low-order NSO adaptive optics system. This image was recorded using a g-band filter (430.6nm). Courtesy O. v.d. Luehe, M. Sailer, T. Rimmele



Figure 2.12. Recent high resolution observations from the new 1 m aperture New Swedish Solar Telescope on La Palma. Tick marks are 1000km. A moderate increase in aperture size has already led to the discovery of a number of previously unobserved fine structure such as dark penumbral filament cores (small image, Images: courtesy G. Scharmer). Many of these features are likely due to convective patterns highly modified by the strong magnetic field. The ATST will deliver substantially increased resolution (by a factor of 4 in linear resolution) and is expected to reveal a variety of previously unobserved phenomena on the surface of the sun.

et al. (2002) have proposed that the filamentary nature of the penumbra and its interlocking-comb magnetic field are due to a convective fluting instability of the outer edge of the flux bundle, followed by downward flux pumping of the more horizontal fields in the granulation layer surrounding the sunspot. This model may also explain the fact that the smallest sunspots are smaller than the biggest pores, and the behavior of the moving magnetic features observed in the moat surrounding the spot.

With high polarimetric precision and high spatial and spectral resolution, ATST will be able to identify the physics of penumbra to its smallest fundamental scales. This will help verify and falsify penumbral models (Montesinos and Thomas (1997), Schlichenmaier 1998, Hurlburt et al. 1996, Thomas et al. 2002).

Radiative Flux balance in sunspots: A consequence of magnetic fields dominating convective forces in strong field regimes, such as sunspots, is the suppression or radiation. For example, umbrae of sunspots carry about 20% and the penumbrae about 80% of the heat flux of the quiet sun. At wavelengths below 500 nm, bright rings around sunspots have been seen (Bray and Loughead 1974). In turn, these structures must have some consequences for the solar radiative output, at least when a significant portion of the sun is covered with sunspots, such as at solar maximum.

ATST will provide unprecedented high spatial resolution (16km at 430nm) measurements over individual "flux tubes" to probe the radiation emitted or suppressed by these individual structures at very high spectral resolution. With the advantage of high spectral and spatial resolution coupled with sustained temporal coverage, ATST will provide the necessary tools to begin modeling of the coupled radiation-hydromagnetic structure of sunspots (Rast et al. 2001).

A physical understanding of the radiation balance due to the dominance of magnetic energy over convective energy is important to understanding of the nature of solar variability and the observed 0.2% over the solar cycle. Such observations would also help us to understand circumstances under which existing sunspot models are applicable. Sunspot models include the Schluter-Temesvary (1958; IAU Symp. 6, 263) models, Pizzo (1986), Return-Flux Models (Oscerovich and Garcia 1989), Jahn and Schmidt (1994) and Force-Free Models (Martens et al 1996).

2.2 MAGNETIC ACTIVITY & INSTABILITY

2.2.1 Flux Expulsion: Flares and Mass Ejections



Figure 2.13. H-alpha image of a flare observed at the Dunn Solar Telescope using high-order adaptive optics. The small sunspot observed here close to the limb on Oct. 24-2003 was part of the big active region that produced the X17.2 flare on Oct. 28-2003. The footpoints of the loops as well as some loop tops become bright during the flare. Tick marks are 1 arcsec. Structure on spatial scales of 0".2 arcsec is visible in this image showing that flares are structured on such small scales.

Coronal mass ejections (CMEs) constitute a failure to confine a magnetic flux rope. On the order of 10¹⁵⁻¹⁶ g of mass are expelled per event into the interplanetary space. Although up to 1-3 events per day can occur this still implies an insignificant mass loss rate relative to the solar wind. However, besides being a major factor for space weather CMEs take magnetic flux and magnetic helicity out of the corona, thus playing a fundamental role in the reversal of the global magnetic field of the corona (Low 2003).

Coronal mass ejections (CMEs) (Crooker et al. 1997) originate in large-scale magnetic arcades known as helmet streamers. These structures are known to contain twisted magnetic fields. According to the prevailing view, the arcade becomes dynamically unstable when its fields are twisted beyond some critical point (Amari et al. 1996) Field line footpoint motions in the photosphere have long been considered efficient ways to supply (or drain) magnetic shear and energy into (from) the coronal field. Observations have hinted at a correlation between the field line footpoint shearing motion and eruptive phenomena such as flares or coronal mass ejections in the active region. MHD simulations have identified critical magnetic shear conditions above which the arcade field will form current sheets, and magnetic reconnection processes will occur to cause active phenomena such as flares, CMEs, and prominence formation and eruption. It is thus important to measure field line footpoint motions and, if possible, the magnetic shear in active regions as well. Although measurements of the footpoint motion (in particular the horizontal plasma flow velocity) have improved considerably, the ATST will offer unprecedented high spatial and temporal resolution in measuring the field line footpoint motion.

More recently this view has been challenged by models in which the arcade emerges as a twisted flux rope (Low et al. 1995) or models in which small-scale photospheric reconnection events inject helicity into the corona (Martens et al. 1990) These hypothesized reconnection events occur when small (0."1) photospheric flux elements cancel along the active region's magnetic neutral line. It has been shown empirically that the onset of a CME is strongly correlated with nearby flux emergence (Feynman et al. 1995). While the cause of this relationship remains uncertain, it seems to contradict those models in which CMEs result from excessive twist in the arcade. Detailed observations of the flux emergence can reveal whether the emerging flux is introducing magnetic twist into the arcade, or changing the arcade's topology through footpoint cancellation.

Only with higher spatial resolution vector measurements and good temporal resolution as will be provided by the ATST, however, can it be established, for example, that the rate and orientation of these cancellations is consistent with an observed change in the twist of the overlying arcade. Such observations are critical to distinguishing between competing models.

It is commonly believed that solar flares (Gaizauskas et al. 1993) represent a process of rapid transformation of the magnetic energy of active regions into the kinetic energy of energetic particles and plasma flows and heat. Detection of variations of magnetic field associated with solar flares has been one of the most important problems of solar physics for many years. Such detection would provide direct evidence of magnetic energy release in the flares. The observational results, however, are controversial. It is established that the flares occur in the regions of strong magnetic shear, which is gradually built up before the flares. There is little unambiguous evidence, however, for changes in the magnetic field during a flare. One of the reasons for this situation can be that the magnetic field is measured at the photospheric level, but most of the energy release occurs in the upper chromosphere and corona. Nevertheless, one

would expect some magnetic response to the flares at the photospheric level. Recently rapid irreversible changes of the photospheric magnetic field in the form of magnetic flux cancellation during an X-class flare were detected using the Michelson Doppler Imager (MDI) instrument on SoHO (Kosovichev et al. 1999). The amplitude of these variations is about 100 G; the characteristic time 1–10 min; the spatial scale $\sim 5 - 20$ Mm. Obviously, such rapid changes should involve processes of magnetic dissipation on much smaller scale, 10 - 100 km, which are not resolved by the MDI instrument.

An important goal for the ATST will be to study the small-scale processes in solar flares. The ATST will also provide a new set of tools, in particular in the infrared, to measure magnetic fields at higher layers of the atmosphere. There is limited observational evidence that the distribution of electric currents and current helicity



Figure 2.14. Flare observed with TRACE (courtesy of A. Title).

inside an active region varies with flares. Highly uniform sequences of high-resolution vector magnetograms of an active region before and after a flare are required to address this important issue.

2.2.2 High Resolution, High Cadence Studies of Solar Flares

With observations of unprecedented resolution as will be provided by ATST we will make significant progress in our understanding of solar flares, which would otherwise be beyond our reach. High cadence X-ray and microwave observations have revealed a temporal (sub-second) fine structure in solar flares,

called elementary flare bursts (see the review paper by Sturrock, 1989). These may be attributed to the fine structure in coronal magnetic fields, which are related to the aggregation of photospheric magnetic fields into ``magnetic knots". Very recently, the BBSO group has experimented with high cadence flare observations (Wang et al. 2000; Qiu et al. 2002), probing the far blue wing of H α with a cadence between 10ms to 33ms and an image scale of 0.5". Wang et al. (2000) identified the H α source of sub-second hard X-ray bursts. Qiu et al. (2002) studied the footpoint shifts of flare kernels and derived the DC electric current as a function of time. This current was found to be coincident with the hard X-ray temporal profile, and therefore, clearly revealed the flare acceleration mechanism.

ATST will obtain high resolution, high cadence images of flares in wavelengths such as He D^3 and offband Ha. These observations will provide details of electron precipitation on fine temporal and spatial scales. By combining high cadence optical imaging with hard X-ray imaging from missions (such as a possible future mission replacing the Ramaty High Energy Solar Spectroscopic Imager (RHESSI)) and future high energy space missions, as well as with high resolution magnetograms, we expect to learn if



Figure 2.15. Left: a line-of-sight magnetogram of November 24, 2000 obtained at BBSO.The white rectangle encloses a magnetic channel structure (characterized by the striations). The field-of-view is 150" x180". Right: H α image of the X2 flare at 21:53UT, in the same field of view as the magnetogram. An erupting flux rope is denoted by F, and the black contours show Yohkoh hard X-ray kernels. Courtesy of H. Wang.

and how, the individual sub-second peaks in the hard X-ray and microwave time profiles correspond with the rapid precipitation along various flux loops. Since the ATST will provide a spatial resolution of 20 km at visible wavelengths (500nm), we will be able to determine the true spatial scale of moving flare kernels. Currently our resolution is only about 150km under excellent seeing conditions using adaptive optics (Fig. 2.13) or about 750km for the TRACE observations (Fig. 2.14).

2.2.3 Structure and Evolution of Magnetic Fields Associated with Flares and CMEs

It is generally accepted that the energy released in solar flares is stored in stressed magnetic fields. So, the study of magnetic fields is a crucial component of flare science. This concept of energy release has motivated many attempts to detect flare-induced changes in the magnetic fields of active regions. So far, no one has detected, in any consistent way, the changes in magnetic fields associated with solar flares. The inconsistency of the results is due to observational limitations. We cannot get high temporal and spatial resolution, as well as high polarization accuracy at the same time, with existing telescopes/instruments.



Figure 2.16. Sigmoidal coronal structures of AR7790 (a, b) and AR7792 (c,d) before eruption and their associated geomagnetic storms. Left panel: Yohkoh SXT images (a), (c), and Kitt Peak photospheric magnetograms (b), (d). White corresponds to positive polarity magnetic flux, black to negative. Right panel: geomagnetic Ap-index. Vertical dashed lines indicate approximate time of eruptions. The orientation of the magnetic field (northward/southward) specified in this figure is determined using the coronal flux rope model and Kitt Peak magnetograms (courtesy of A. Pevtsov).

ATST will provide reliable and high quality measurements of vector magnetic fields at high cadence. Existing ambiguities discussed above will be resolved with the new higher resolution, higher cadence data. In addition to the temporal and spatial resolution mentioned earlier, the accuracy and precision of the polarimetry of ATST will be on the order of 10^{-4} . With the improved accuracy of vector magnetograph system, studies of more examples of evolving magnetic fields, and active regions, and changes due to flares will provide the evidence needed to lead us to understanding the process of flare energy release, triggering of CMEs, and the role of photospheric magnetic fields therein. Figure 2.15 shows an example of the complex magnetic structure associated with the core of a flare. ATST is needed to really understand these structures.

ATST will be able to answer the following questions: (a) What is the role of the evolution of the photospheric magnetic field in triggering solar flares, and what is the relationship between the magnetic configuration and the properties of flares? (b) How do electric currents evolve, and what is their relationship to particle precipitation?

In order to clearly discriminate between existing models and develop a sound understanding of magnetic configurations that lead to CMEs, ATST will provide accurate magnetic field measurements in the chromosphere and corona. In particular, ATST will perform prominence magnetic field measurements and measurements of magnetic fields in the coronal helmets.

The goal is to determine pre- and post CME field configurations as well as the field configuration of preand post flare loop systems. The large aperture of ATST will allow us to study the dynamics of the coronal field and give new insight into coronal heating mechanisms.

2.2.4 CMEs: The need for prominence studies

Prominences are cold and dense structures suspended in the hot and tenuous solar corona. Prominences can be observed either at the solar limb, in emission, or as dark filaments against the solar disk. Although being significant contributors to the mass and energy budget of the whole (cool & hot) solar corona and indeed, a subject of study by itself, prominences are also known to be strongly related (>60%) to coronal

mass ejections i.e., those large scale energetic events which may significantly affect sun-earth relationships (e.g., Subramanian & Dere 2001).



Figure 2.17. Left: CME observed with LASCO C3. Right: model magnetic field configuration for a CME event (courtesy B.C. Low). ATST will answer important questions such as: Is the predicted fall off in magnetic pressure the same as the observed? Do we see changes in magnetic field configuration during CME eruption? What are the pre-eruption conditions? What is the magnetic field configuration of prominences? What is the relation to CMEs of normal vs. inverse prominences?

The magnetic field of the prominence (Fig. 2.18) controls the channeling of plasma motions and the thermal conduction. The magnetic field also provides the necessary support for the cold material against gravity. It is therefore a key-parameter responsible for the support, the structuring and, finally, the eruption and disappearance of prominences into the heliosphere. It is therefore crucial to obtain quantitative and systematic measurements of the prominence magnetic field.

MHD models schematically fall into two major classes: twisted flux rope (TFR) and sheared magnetic arcade models (SMA). Both of these models can reproduce the main features of the magnetic field relatively well. However, the observations that the models are compared to were performed in the 70s and in the mid-80s (Paletou & Aulanier 2003).

It is important to test, validate and discriminate between existing MHD models. This can only be achieved by providing new observational constraints. The observational input to models and the expected improvement and evolution of prominence models is crucial to further our understanding of the magnetic topologies pre-existing the CME.

Among the many outstanding questions are:

- What is the degree of twist of the prominences field lines? And how homogeneous (or "coherent") is that twist across the prominence body? Indeed, TFR models always appear to generate highly twisted field lines, quite homogeneously (in space) unlike SMA models (Karpen et al. 2003).
- Is an inverse polarity pattern always seen across the prominence body, or can mixtures of inverse and normal polarities be observed? Unlike TFR models, SMA models can produce mixtures (e.g., where inverse polarity is predominate but where normal polarities can happen, for instance, at the top and edges of the prominence).
- Can we get direct observational evidences for the presence of magnetic dips? Those dips are most often invoked for bringing support to the cool plasma forming the prominence body against

gravity, but whose necessity is still contested by several authors though (e.g., Karpen et al. 2001); such a detailed study would require high-angular resolution mapping of the magnetic field.

- What is the magnetic topology at the prominence feet? It would put more constraints on the MHD models and help in clarifying our knowledge upon how prominences are anchored to the photosphere (as well as how they may DETACH from it and turn into eruptive structures); little is known about the low-lying parts of prominences just because the majority of the observations were made with coronagraphs limiting the lower radial distance observable above the solar surface.
- What is the relationship between the horizontal mean magnetic field and the observed vertical fine structure? Since Leroy's et al. contributions (mainly in the 80s) using the Hanle effect as a new diagnosis tool for astrophysical magnetic fields, it is a well-recognized fact that the mean magnetic field in quiescent (i.e., long-living) prominences is mostly horizontal. However, high-resolution imaging of solar prominences has already revealed a sub-arcsecond fine structure, mostly vertical, and with lifetimes in the order of ~ 10 mn.

High-angular resolution mapping the magnetic field across a over a FOV of the order of a few arcmin² (say $3'\times3'$ typically) is therefore required. Such observations should be done not only for limb prominences but also for filaments passing on the disk for which observations [a] were obviously not possible with coronagraphs, and [b] observations at HeI D³ are not suitable but rather at H α and/or He at 1083 nm wavelengths. Not only the spatial distribution of the magnetic field across a prominence should be investigated, but also its temporal variations in order to be able to put in evidence the kind of MHD instabilities leading to the triggering of CMEs, since the energy that drives CMEs is contained in stressed magnetic field lines.

ATST will provide the required precision spectropolarimetry in the visible (e.g., D^3 at 587.6 nm and/or Ha at 656.3 nm) and up to the near-infrared (e.g., He I at 1083 nm), with the advantage of a lowscattered light, and with a large photon collection area. The large photon collection area of ATST is needed since polarization signals of the order of a few percent or less are also expected (e.g., Paletou et al. 2001; Lin et al., 1998; Trujillo Bueno et al. 2002). With existing telescopes we are unable to detect any signal above the noise level for resolutions better than 2-3 arcsec and with a temporal resolution of the order of 2-3 seconds. ATST with its high photon flux will provide the required sub-arcsec spatial resolution while at the same time allowing us to achieve the necessary sensitivity in polarimetry. Finally, ATST will also provide a unique opportunity to combine prominence (cool) and (surrounding) hot coronal magnetic field measurements using, for instance, Fe XIII at 1074 and 1079 nm (Lin et al. 2000).

2.2.5 Magnetic Flux Emergence

Active regions are the manifestation of a strong magnetic field generated by solar dynamo at the base of the convection zone (DeLuca et al. 1991). Observed properties of active-region magnetic fields might therefore be used to infer properties of the solar dynamo once proper account is made of processes affecting the field during and after its emergence. To the initial imprint of the solar dynamo will be added distortions from turbulent plasma in the convection zone and from surface motions after the field emerges. Once these additional affects are understood and removed, it will be possible to observationally constrain models of the solar dynamo.



Figure 2.18. New prominence magnetic field observations have been carried out by Casini, Lopez Ariste, Tomczyk and Lites using the ASP at the Dunn Solar Telescope. They obtained the full spectro-polarimetric maps of 20 prominences in the magnetically sensitive lines of He I D³, and Na I D¹ and D². The two Na I lines were also used with the same equipment in order to study the "second solar spectrum" of sodium in quiet regions of the solar limb. This is the first time in prominence magnetic-field investigations where prominences were observed simultaneously in all four Stokes parameters, with a spectral range of 20 Angstrom encompassing three magnetic sensitive lines with coverage all the way down to the solar limb. This figure shows a 3D image of that prominence, in which you can see the HeD³ intensity image and over it a mesh of arrows representing the magnetic field vector. The geometry of the arrows is given respect to the line-of-sight, represented by the white arrow on the forefront. The length of the arrows is proportional to the field strength, which is also coded in the color of the arrows: purple goes for 10G fields, dark blue for 20G, light blue for 30-40 and green for >40G roughly. Yellow arrows are for 80+G but these values are somewhat uncertain.

The relative importance of dynamo and convection zone contributions remains controversial. Simulations have shown that many observed properties of twist such as a hemispheric sign asymmetry and the large variance around the mean value agree well with theoretical prediction, which implies that all of the observed twist in active region fields is due to the convection zone and not to the dynamo itself (Longcope et al. 1998). On the other hand, a number of theoretical models indicate that to maintain its integrity a "flux tube" must be twisted even before it rises (Emonet et al. 1998). Newly emerging flux seems to have a roughly constant twist throughout its emergence, implying that the twist was present prior to emergence. To better understand both active region magnetic fields and the underlying solar dynamo, it is important to resolve this apparent discrepancy.

The solar photosphere forms a boundary separating two very different plasma regimes. Below the photosphere, the magnetic field is controlled by plasma motions, while above it the magnetic field dominates the dynamics. As an active region emerges through the photosphere, its magnetic field must change from subphotospheric to coronal conditions. This mixture of dynamical conditions and the transition between them makes flux emergence one of the most difficult topics of study both theoretically (Shibata et al. 1990; DeLuca et al. 1997) and observationally (Lites et al. 1998; Strous et al. 1999).

If below the photosphere an active region's magnetic field is organized into isolated "flux tubes" that consist of twisted field, they must carry an electric current inside the tube and an opposite return current in a very thin shell at the tube's surface. According to the same theories, this return current will not cross into the magnetically dominant corona, but instead will join the current layer at the magnetic canopy just below the so-called merging height. Observational support for this picture is lacking, since no evidence of return currents has been found at the photosphere (Wheatland 2000). It is likely that the measurements

made so far lack the spatial resolution to detect a return current. ATST will furnish the required spatial resolution to test the model.

Mass will drain from the active-region flux as it rises into the corona. In the case of a twisted field, the draining mass will carry with it magnetic helicity. According to theoretical models, this leaves a torque imbalance, between the coronal and subphotospheric fields, which drives vortical flows in the photosphere. Understanding this aspect of active region emergence is of utmost importance in understanding the activity of the solar corona. Only direct vector magnetograms will bring the final understanding of evolution of magnetic helicity during emergence of active region through the photosphere.

An observational test of the model will require the highest possible spatial resolution and high cadence vector magnetograms that will only be provided by the ATST.

While the flux emergence problem has occupied solar observers for decades, the opposite process, flux submergence, has been studied far less. Flux submergence may play an important role in the solar dynamo and in the creation of filaments (van Ballegooijen et al. 1990). Nevertheless, direct observational evidence for the submergence of magnetic flux remains scant. It is well documented that active regions emerge as a single entity and then gradually break apart when their flux disperses into the plage and quiet Sun as smaller elements. If this flux is ever to submerge, it must do so through the piecewise cancellation of these much smaller flux elements. High spatial and temporal resolution is therefore even more critical to study submergence than it is to study emergence.

Observations to study the flux emergence and disappearance require high spatial (<0.1 arcsec) and temporal resolution. To study the evolution of active regions requires, in addition, a large field of view (several arcminutes), a large period in time (hours to days), and a combination of a number of different diagnostic tools.

The science problems discussed above are best addressed by a combination of instruments in space and on the ground. Space observations that will become available from SOLAR-B and the Solar Dynamics Observatory, for example, offer good temporal and spatial coverage, while the ATST with its unprecedented aperture and adaptive optics offers superior spatial resolution (within the isoplanatic patch), large wavelength coverage, and the flexibility to combine different instrument. Post-facto image reconstruction techniques can and have been used successfully to achieve diffraction-limited observations over large field of views.

2.2.6 Hanle Effect and UV-Polarimetry – A Tool for Highly Sensitive Magnetic Field Measurements

The term Hanle effect represents the totality of ways in which the scattering polarization can be modified by magnetic fields. The Zeeman and Hanle effects (Fig. 2.19) are highly complementary to each other because they respond to magnetic fields in very different parameter regimes. While the magnitude of the Zeeman-effect polarization depends on the ratio between the Zeeman splitting and the Doppler line width, the Hanle effect depends on the ratio between the Zeeman splitting and the damping width (or inverse life time) of the relevant atomic levels. The Hanle effect can relate to atomic polarization of the upper or the lower level of a transition. For upper-level Hanle effect the magnetic-field sensitivity range is typically 1-100 G, while for lower-level Hanle effect it is 2--3 orders of magnitude smaller (in the milligauss regime).

As the Hanle and Zeeman effects have different symmetry properties, cancellation effects that occur for the Zeeman effect may not occur for the Hanle effect. For instance, a spatially unresolved turbulent magnetic field with an isotropic distribution of field vectors is invisible to the Zeeman effect due to cancellation of the opposite polarity contributions, while these contributions do not cancel for the Hanle effect. The Hanle effect has therefore in the past enabled the detection of the existence of such a turbulent solar field.

Most of the early use (in the 1970s) of the Hanle effect was for the diagnostics of magnetic fields in prominences with the He I D^3 line, which had the advantage of large polarization signals (a few percent), and a well defined incident radiation field on an optically thin scattering medium, removing the need for complex radiative transfer to interpret the observations. Off-limb observations of prominences and the solar chromosphere will remain important applications of the Hanle effect in the ATST era, but the on-disk observations offer a much richer variety in the possible observational uses of the Hanle effect. The Hanle effect provides a unique and highly sensitive diagnostics tool to explore the spatial structuring and temporal variability of the weak and turbulent magnetic fields at different heights in the solar atmosphere. It also allows accurate determinations of the horizontal component of chromospheric magnetic fields.

For the diagnostic use of the Hanle effect, the solar UV is the spectral region of choice, for two main reasons:



Figure 2.19. Hanle effect in the core of the Ca I 4226.740 A line, recorded at NSO/Kitt Peak with the UV-sensitive version of ZIMPOL on March 9, 2002. The spectrograph slit was placed parallel to and 20 arcsec inside the west limb of the Sun in a weakly magnetized region. The strong 4227 A line of calcium exhibits pronounced scattering polarization in Stokes Q and U, while the surrounding lines show signatures of the transverse Zeeman effect in Q and U and of the longitudinal Zeeman effect in Stokes V. The spatial variation of the scattering polarization in the core of the 4227 A line is due to the Hanle effect from weak and largely horizontal magnetic fields in the lower chromosphere. Although this example refers to a solar region near the limb, such Hanle effect polarization can be observed all over the solar disk, also at disk center. (Stenflo 2003)

- 1. Since the limb darkening increases steeply with decreasing wavelength, the amplitudes of the scattering polarization increase correspondingly, such that the effects appear amplified.
- 2. The UV is much richer in resonance lines suitable for Hanle diagnostics than higherwavelength regions.

To resolve ambiguities in the complex interpretations of Hanle observations, one needs to combine observations in a set of well-chosen lines with different sensitivities to the Hanle effect but with otherwise similar formation properties. The UV offers much better choices. High-sensitivity imaging Stokes polarimetry in the UV has recently been successfully implemented, allowing us to explore the Hanle effect down to the atmospheric cut-off near 300 nm.

ATST will deliver high-sensitivity imaging spectro-polarimetry down to the atmospheric cut-off (300nm). The relative polarimetric sensitivity will only be limited by photon statistics down to a level of at least 10^{-5}

Ic. With the large aperture of ATST we will achieve the required photon statistics at good spatial and temporal resolutions. Current telescope provide this sensitivity only at a highly compromised spatial (~10") and temporal (5min) resolution. For off-limb observations of prominences and the chromosphere the ATST will provide the critical low scattered light observations.

2.3 CHROMOSPHERIC AND CORONAL STRUCTURE AND HEATING

2.3.1 Three-Dimensional Mapping of the Solar Atmosphere

The conventional layers of the solar atmosphere - the photosphere, chromosphere and corona - each have distinct physical properties but are also strongly coupled through heat flow, magnetic energy and material motion. Because of this interconnection, the atmosphere must be regarded as a single three-dimensional system (Fig. 2.20). Information on the physical conditions at different heights is obtained by observing a given two-dimensional area of the solar surface in different parts of the spectrum



Figure 2.20. A sunspot region observed at several heights in the solar atmosphere representing different temperatures ranging from 5000 deg. to 2 million deg.. Sequence starting from the bottom: g-band –CaK - Ha - soft xray. Credits: Stack-plot courtesy Bart De Pontieu, Swedish Solar Observatory, Yohkoh/SXT

each originating from its own specific layer. Ideally one would like to be able to observe at many wavelengths simultaneously so that a coherent picture of the three-dimensional structure of the atmosphere can be inferred.

The ATST will have an unprecedented multi-spectral imaging capability with which true threedimensional mapping will become routine. Simultaneous observations will regularly be conducted at more than one wavelength in the whole range of near-ultraviolet, visible and infrared. Because the optical path in the ATST is fully reflective it is the first big telescope that will be able to observe at all these wavelengths.

On the solar disk, a combination of images at several wavelengths will track the structure of matter and magnetic fields as a function of height. Continuum images will sample a range of heights in the photosphere, from the deepest layers observed at 1.6 microns to middle photospheric heights observed at visible and infrared wavelengths. Spectral lines of atoms and molecules will sample a variety of higher layers and provide information on material flows and magnetic fields through measurement of Doppler motions and polarization. For example, in a single observation instruments on the ATST might image the photosphere in Ni I at 676.8 nm while also imaging the upper photosphere in CO at 4.7 microns and the chromosphere in He I at 1083.0 nm.

Zeeman lines in the visible and infrared will be used to map the three-dimensional structure of magnetic fields throughout the atmosphere. Synchronized observations of Fe I and Mg I lines at 1.56 and 12.3 microns have demonstrated that fields near the bottom and top the photosphere can be measured simultaneously (Moran et al. 2000). The difficult but pivotal measurement of field strengths in the corona

has recently been demonstrated to be feasible in the Fe XIII line at 1074.7 nm (Lin et al. 2000) and may possibly be extended to the coronal lines at 3 and 4 microns (Judge et al. 2002).

It should be noted that the ATST will also excel in the temporal domain. With its large aperture and high image resolution, together with its suite of very fast cameras and spectrometers, the ATST will allow us to follow the evolution of matter and magnetic structure on time scales as short as seconds. This will be necessary to resolve changes in the features with sizes less than 0.1 arcsecond.

2.3.2 Structure and Dynamics of the Chromosphere

The chromosphere is a complicated, dynamic region where radiative equilibrium does not exist, where rates are so slow that populations do not reach their equilibrium values, where compressible waves steepen and form shocks, and where the Lorentz force begins to dominate pressure forces. Observationally the challenge is to achieve sufficient temporal and spatial resolution to record the dynamic changes and to obtain direct measurements of a magnetic field topology, which is changing rapidly with height. Theoretically the challenge is to model the non-linear dynamics consistently with non-equilibrium chemistry and radiation. In particular, we are not yet able to reproduce the thermal structure of the chromosphere nor do we understand the sources of its heating.

Measurements of CO absorption spectra near 4.7 µm show surprisingly cool clouds that appear to occupy much of the low chromosphere (Figs. 2.21, 2.22). Only a small fraction of the volume apparently is filled with hot gas, contrary to classical static models that exhibit a sharp temperature rise in those layers. The dark cores of infrared CO vibration-rotation lines observed close to the solar limb, which indicate the persistent presence of material with temperatures as low as 3700 K in the solar atmosphere are among the most puzzling features found in the solar spectrum. Any model intended to represent the physical conditions in a cool stellar atmosphere should be able to simultaneously reproduce the CO lines, and the optical and UV line diagnostics (like the resonance lines of ionized calcium and magnesium) with which they seem to be in conflict.

An important goal of the ATST is to determine the structure and energetics of the solar atmosphere in particular and cool stellar atmospheres in general. To do so, it will be essential to obtain high spatial and spectral resolution observations of the solar surface in the infrared; such observations are only possible with a large-aperture all-reflective telescope.

Distinct advantages of observations in the infrared are the following. At long wavelengths the Planck function is approximately linear with temperature. While emission at optical and UV diagnostics in inhomogeneous media is strongly weighted towards the hot fraction, infrared diagnostics are equally sensitive to hot and cold material. In addition, infrared intensity contrasts can be determined much more reliably due to strongly reduced instrumental and telluric atmosphere scattering. Also, the observable part of the solar infrared spectrum contains a large number of molecular vibration-rotation lines. The source function of these lines is close to LTE so that their emergent intensities closely reflect the actual temperatures of material at the depth of formation.



Figure 2.21. Left: Bottom panels show the intensity in a CO line as calculated from a theoretical granulation model, and the intensity in the neighboring continuum (left-most panel). It illustrates the reversal granular contrast that is observed in the CO line cores and it emphasizes the sensitivity of these lines to the intricate details of solar atmospheric structure. The upper panels show the calculated spectrum at different locations. Right: Corresponding observations are severely limited in resolution by the small aperture of existing telescopes (courtesy of H. Uitenbroek).

The spatial grid of current state-of-the-art granulation simulations is now fine enough to provide an almost perfect match between observed and calculated spatially averaged profiles of photospheric iron lines. A much coarser resolution gives appreciably less reliable results. This suggests that much better spatial resolution is needed in observations in order to verify theoretical predictions. Spatially averaged molecular line profiles do not seem to fit nearly as well as the atomic and ionic iron lines. A possible source of that discrepancy could be a non-equilibrium CO concentration (Uitenbroek 2000, Asensio

Ramos 2003). Indeed, a better agreement with observed limb extensions is achieved when explicit treatment of chemical reaction rates is included in the transfer calculations. If proven, this would have important implications, not only for the temperature stratifications that we determine from observed spectra, but also for the determination of abundances of elements C, N and O in cool stars, for which molecular lines of C², CH, CN, and OH are used. Obviously, before we understand how the inhomogeneities and temporal variations that are introduced in the stellar atmosphere by convection affect the star's emergent spectrum, we cannot hope to use that spectrum to accurately measure that atmosphere's physical quantities. Unfortunately, even the world's largest infrared-capable solar telescope, the NSO 1.5-m McMath-Pierce telescope at Kitt Peak, lacks the spatial resolution to verify the dynamical numerical models on the required spatial scale.



Figure 2.22. Limb spectrum of solar CO lines. Near the limb the CO lines change from absorption lines on the disk to emission just beyond the continuum limb. The extent of this emission is an important measure of the amount of cool CO in the chromosphere. The dark absorption line at wavenumber 2142.3 is a telluric line. These kind of data have led to the discovery of cool (~3700K) gas in the lower chromosphere. The chromosphere is now believed to be spatially and temporally intermittent where acoustic shock waves light up K2_V grains in the internetwork regions but on average the lower chromosphere is cool, not hot! (e.g. Ayres 2002).

Radiation-hydrodynamic simulations of chromospheric dynamics show that dissipation of acoustic shock waves does not provide sufficient heating in the chromosphere to explain the observed omnipresent emission in UV lines in internetwork regions. These are regions between the magnetic network that are characterized by low values of photospheric magnetic flux. It is possible that the unaccounted heating component is associated with the magnetic field at locations where it expands with height in the atmosphere and fills what was traditionally considered the region above the magnetic canopy. From magneto-convection simulations, and high-resolution spectro-polarimetry we know that magnetic fields in the solar atmosphere are extensively tangled, so that a simple canopy surface may not exist if the magnetic complexity extends to the upper chromosphere. Rather, the region of interest is the surface where gas pressure equals magnetic pressure (i.e., $\beta = 1$). At this surface, acoustic waves are very efficiently converted into magneto-acoustic modes, which transport energy and can be dissipated to provide additional chromospheric heating.

With ATST we will be able to confirm the theoretical predictions of chromospheric structure and dynamics by providing high spatial resolution observations of the three-dimensional structure of the magnetic field, for instance by combining vector magnetograms of photospheric lines with chromospheric lines like the calcium 854.2 nm line and hydrogen Ha at high spatial resolution and high cadence. The Accurate absolute pointing capabilities of ATST will allow comparison with simultaneous co-spatial observations of UV line emission from spacecraft like SOLAR-B and SDO. To unravel the inhomogeneous, dynamic chromospheric properties, high spatial, temporal and spectral resolution observations of the contrast in the infrared are needed—a task which can only be achieved economically from the ground with an instrument like the proposed ATST. It is important to emphasize that in a region like the chromosphere it is essential to collect enough photons to achieve excellent temporal as well as spatial and spectral resolution, because one cannot diagnose structures that change dynamically unless they are also resolved in time.

2.3.3 The Thermal Structure of Coronal Loops

The enormously successful space experiments aboard Yohkoh, SoHO and TRACE have repeatedly shown us how dramatic coronal events like flares and coronal mass ejections (CMEs) have a direct influence on the near Earth environment. Often such events coincide with a rearrangement of magnetic loops in the corona, but we currently lack the fundamental understanding of the physical processes that link these processes together. If we want to be able to understand coronal structure, and eventually desire to predict the occurrence of violent events like flares and eruptions, we have to acquire a sound understanding of the physics of coronal loops and their interactions with each other and their environment (Golub and Pasachoff 1997). The corona is organized into loop like structures, which are regions of enhanced plasma density embedded in a volume filling structure.

The relationship of these "plasma loops" and the magnetic field is not known and its determination is an important goal of ATST. Only after addressing this fundamental question can other issues be addressed.

Why is a coronal loop nearly one-thousand times hotter than the surface of the Sun? What is the magnetic field, the temperature, the density and the plasma velocity inside a coronal loop? Why do some loops dramatically change while others lead more stable lives? These are some of the same questions that the earliest coronal investigators asked nearly a century ago.

While some progress has been made (and more can be expected) from space-based instruments, some of these questions have are more likely to be answered with a large area ground-based coronagraph. The ATST will be a coronagraph with almost 100 times the collecting area of the largest coronagraph ever built, and in the first few years of observing (assuming only a fraction of the ATST observing time is used

to study the corona) the ATST will collect more coronal photons than all previous ground and spacebased coronagraphs combined.

Significant theoretical progress has been made recently in identifying the most likely mechanisms that drive coronal structure and dynamics (Metcalf et al. 1994; Fisher et al. 1998). Scaling properties of non-radiative heating processes were constrained in a study parametrizing the coronal heating flux as function of base field strength, loop length, and foot point velocity, and using known dependencies of stellar coronal structure on magnetic cycle and rotation period (Schrijver & Aschwanden 2002). This led to identification of current layer dissipation and dissipation of turbulence as the most likely candidates for coronal Three-dimensional heating. numerical simulations of coronal MHD seem to confirm this identification (Gudiksen & Nordlund 2002). These simulations were able to reproduce the temperature structure of the corona, including the appearance and evolution of slender hot coronal loops similar to those observed with TRACE, by modeling the evolution of an active region as it is driven by photospheric convective flows.

The current layer dissipation, caused by convective displacement of the photospheric foot points of the magnetic field, is



Figure 2.23. The top figure shows two cusped loops observed by SXT/Yohkoh. The figure shows that the pressure and inertial forces dominate over the magnetic forces at the cusp and distend the field outward. This implies $\beta \ge 1$ at these heights [see figure to the left, plasma β over an active region; (Gary 2001)]. These figures demonstrate the need and importance to understand the coronal plasma beta, i.e., determining the coronal magnetic field and pressure in order to model the coronal eruptions correctly. ATST will provide coronal magnetic field measurements in the range from r=1.05 to r=1.5.

sufficient to heat the corona in the simulations to the observed temperatures, but accurate determination of the three-dimensional structure of the magnetic field structure at its lower boundary, the chromosphere, is needed for detailed confirmation.

With the large collecting area and unique multi-spectral capabilities of ATST, we will be able to accurately determine the vector magnetic field in the photosphere and chromosphere, for instance through polarimetry in the Ca II infrared triplet lines or the hydrogen H α line, needed to provide complete boundary condition for the MHD simulations of the evolution of the coronal loops. ATST will provide accurate vector magnetograms of unprecedented resolution and at a high cadence.

Only with accurate values for the fields at the coronal foot points will we be able to assess the need for additional heating mechanisms. By understanding the mechanism that heats the solar corona we also gain a better understanding of coronae of cool stars with different levels of activity than the Sun's.

Observations from TRACE, SOHO, and Yohkoh have revealed details of coronal loops that, even with the improved insight provided by recent simulations, are still poorly understood. One big puzzle concerns the loop density. Hot (> 2 MK) loops observed by Yohkoh tend to be under dense compared to the predictions of equilibrium theory, while warm (1 MK) loops observed by TRACE and EIT tend to be

over dense. The possibility that observed loops are comprised of large numbers of unresolved strands that are heated impulsively and randomly by nanoflares has been discussed (Warren et al. 2002), given the fact that TRACE instrumentation shows that loop structures are spatially unresolved at even at 1 arcsec. The loops appear quasi-steady even though the individual sub-strands may be highly time dependent. When the strands are hot, they cool primarily by thermal conduction and are underdense, but when they are warm, they cool primarily by radiation and are over dense. Predictions from the recent stranded-loop models are more difficult to test [Warren et al 2002], as they strain not only the spatial resolution of space-based instruments, but also the limits imposed by the photon flux collected by spectrographs in space with relatively small apertures.

With a 4m primary mirror, the ATST will produce spectral scans across coronal loops using nearinfrared emission lines of Fe XIII with high signal to noise ratios, capable of measuring plasma flows with amplitudes less than 100 m s⁻¹ and capable of measuring electron densities in the corona with a precision of about 10^5 electrons cm⁻³. These new low noise levels are revolutionary and will allow direct testing of predictions from recent stranded-loop time evolution models.

2.3.4 The Magnetic Field of Coronal Loops

This routine measurement the magnetic field in coronal loops would have a far-reaching impact in the study of the Sun. There are dozens of coronal loop models, which predict the magnetic field in a loop. There are perhaps hundreds of extrapolations of the photospheric magnetic field into the corona, which have been made to predict the morphology of the corona. However, only a handful of observations have been made that could constrain these models. Any disappointment borne from the delicacy and intermittency of space experiments has been heightened by their success and the fact that the solar research community has not experienced comparable developments in ground-based coronal observing



Figure 2.24. Coronal magnetic field observations are starved for photons. This figure shows how the limiting sensitivity in a 5 min observation improves by nearly a factor of 50 from one of the worlds' current largest coronagraphs (0.4m) to the proposed ATST with an aperture of 4m. This sensitivity improvement will allow fields as low as the equipartition field strength to be measured for the first time. Based on extrapolation of radio frequency Faraday rotation data, the quiet region coronal magnetic field should be visible out to one solar radius from the limb. If the magnetic field in streamers or active regions is as large as the Lin et al. Zeeman measurements suggest then the ATST should be able to explore the Sun's magnetic field several radii out into the corona, where wind acceleration, coronal heating, and CME acceleration physics can be directly studied. This is a unique capability, which ATST provides because, except for occasional point-like observations of background radio sources, we have never had the capability to detect and measure such coronal magnetic fields.

capabilities. Continued progress still depends on ground-based experiments. "Snapshot" measurements from eclipse experiments play an important role in advancing our understanding of the static coronal plasma. Long-term experiments, like the High Altitude Observatory (HAO)/Mauna Loa K-coronameter or the NSO/Sac Peak green-line programs, are also clearly essential—our conceptual understanding of coronal mass ejections or the corona's solar cycle evolution would be rudimentary without these data. Ground experiments are important because they enable large-aperture, high- (spectral and temporal) resolution measurements, and the possibility of complex, exploratory instrument development. In addition, routine measurements from the ground can be competitive or superior in the IR, where many of the advantages of satellite experiments are less important than at shorter wavelengths.

The ultimate observable discriminant for nearly any coronal physics problem is the magnetic field. The ability to detect the twist in the field of a coronal loop, or even just the projected polarity changes in a helmet streamer, will effectively clinch many long-standing questions. For example, the detection of a sufficiently twisted magnetic field loop topology would apparently solve the problem of how a large wave energy flux from the photosphere can propagate up to, and deposit energy in, the corona (Litwin et al. 1998).

Mean magnetic field strengths at 0.1 solar radii are only about 10 G (Dulk et al. 1978). Potential field extrapolations of photospheric measurements yield a similar magnitude, except near active regions and measuring such fields is obviously a difficult observational problem (Hoeksema et al. 1986). Microwave (gyrosynchrotron) observations provide some information on the field strength above active regions (Bastian 1995) and Faraday rotation measurements at longer radio wavelengths are occasionally used to infer averaged magnetic fields at large solar-limb distances (Patzold et al. 1987). Optical measurements of coronal magnetic fields are, so far, also unproven.

There are several Zeeman splitting measurements of prominence magnetic fields (Lin et al. 1998), but the coronal problem is significantly harder. Because the Zeeman splitting-to-Doppler width ratio of an emission line increases with wavelength, the magnetic sensitivity from splitting measurements also increases with wavelength. The magnetic sensitivity of the IR lines is an important motivation for exploring the IR coronal spectrum (Fig. 2.24). For example, the Fe XIII line at 1.075 µm has just recently



Figure 2.25. Measurement of coronal magnetic fields. The box in the SOHO/EIT FeIX 171 Å image (left) shows the region observed with the Evans Solar Facility at Sacramento Peak. Images on the right show the averaged Stokes Q and V spectra measured in the 10747 Å line. In spite of the 40-minute exposure and spatial averaging, the signal-to-noise is poor. Nevertheless, the weak Stokes-V detection is obvious. The field strength derived from this averaged spectrum is 33 gauss. The ATST will provide the sensitivity to measure the coronal field with much better resolution (courtesy of H. Lin).

been used for direct measurements of coronal magnetic fields (Fig. 2.25, Lin et al. 2000, Figure 2.24).

The observational problem of making such a measurement is extreme, since the magnetic field is thought to be weak, and the induced Zeeman shift in a polarized emission line profile is but a tiny fraction of the temperature broadened width of that line. Two important physical arguments suggest that the easiest way to approach this measurement lies with a ground-based instrument. First, there is an advantage in Zeeman resolution (splitting divided by thermal width) gained by using longer wavelengths, and secondly very high signal to noise ratio spectra must be used to detect such meager line shifts. Twisted coronal features are important signatures for predicting solar eruptive events, and are not yet clearly understood.

ATST will be a crucial tool for determining the complex, non-potential coronal magnetic field configurations of active regions at high resolution by measuring the full vector magnetic field in the photosphere and chromosphere thus providing the lower boundary conditions for the coronal magnetic field.

Extensive efforts have been carried out in relating the vector magnetograms to flare theories. The ATST will be extremely useful in the research of describing the non-potential nature of active regions by exploring and defining the photospheric and chromospheric electric currents and the coronal magnetic field characteristics (Fig. 2.26). The non-potentiality is related to the understanding of the vertical electric current density, j_z , and horizontal electric currents, j_h , as derived from vector magnetograms. The overall goal is to define the free-energy available via defining three dimensional electric current morphology. Furthermore, the changes in the photospheric vertical currents are slow (with time scale on several hours) while faster changes (with time scale on minutes) occur in the structure of the chromosphere.



Figure 2.26. The magnetic field and vertical electric current distribution is shown for AR 6659 on 1991 June 9. (a) The observed magnetic field obtained form the MSFC vector magnetograph showing the longitudinal field as contours and the transverse field as line arrows. (b) The potential field transverse field as derived from the observed longitudinal component. (c) The vertical electric current density using the potential comparison method. (d) The vertical electric current density using the pseudo-electric-current method. The gray scale for the electric current is such that positive (negative) currents is white (black) with contours levels at ± 2.5 , 10, and 50 mA m⁻². The electric currents are the key to understanding the free energy that drives the eruptive solar phenomena (Gary et al. 1995).

The accuracy of detailed observations of how the electric current in the chromosphere and the photosphere change will be critically improved by the high resolution and large light-collection attributes of ATST.

The question of the path of the electric currents can also be addressed, e.g., how much of the electric current returns across field lines in the temperature minimum layer. Measuring the electric currents, which are thought to flow through active region coronal loops, will provide important clues about the physics of coronal loops. The rough derivation of the distribution of normal vertical electric current in active regions began over 30 years ago. Obtaining this current from observations remains a formidable

task (Leka et al. 1993; Metcalf et al. 1994; Gary and Démoulin 1995). The current $j_z(x,y)$ is obtained by taking partial derivatives of the transverse field components. These calculations are not straightforward since one must resolve the 180° ambiguity. However recent improved techniques are now available and are being refined to resolve the ambiguity (e.g, Metcalf 1994). Furthermore with the higher spatial resolution of the field, the measurement problems of aliasing (not having continuous values) are ameliorated.

The ATST vector magnetic field observations at extremely high resolution (below 0.1 arcsec) will characterize the electric current systems down to the level of the poloidal current sheets which are expected to sheath individual magnetic fibrils. Such progress will allow a complete characterization of the electric currents associated with solar activity and why flux loops seem to have nearly constant cross-section along their loops (Bellan 2003). These fine scale electric currents may be important in heating the lower transition region (Rabin and Moore 1984). These studies will help to describe the subphotospheric origins of electric currents and magnetic helicity flux and hence help determine the mechanism of magnetic field ejection into the solar wind as coronal mass ejections and magnetic clouds.

2.3.5 Seismology of coronal loops

Oscillations that have been observed in the intensity and position of coronal loops have opened the new field of coronal seismology. Although periodic or quasi-periodic oscillations have been recorded from coronal radio emission since several decades, a breakthrough came only when the first spatial displacements of oscillating loops were discovered with high-resolution movies from TRACE, which were interpreted as fast kink-mode oscillations (Aschwanden et al. 1999). In the meantime SUMER/SoHO discovered longitudinal slow acoustic oscillations in hot postflare loops (Wang et al. 2002). In optical wavelengths there have been reports of long periods (~1-5 min) by Koutchmy et al. (1983) in the Fe XIV green line, and in H α by Jain & Tripathy (1998) during eclipse observations. Fast periods in optical wavelengths have been detected with marginal significance earlier (Pasachoff & Landman 1984; Pasachoff & Ladd 1987), but have now been detected with higher significance (Williams et al. 2000, 2001, Pasachoff et al. 2002).

Future work will undoubtedly lead to an unambiguous identification of various oscillations modes (fast kink, fast sausage, slow acoustic modes) and their characteristics (eigen-modes, harmonics, impulsively generated propagating modes), which will open up a new branch of diagnostic for the coronal magnetic field strength, plasma damping mechanisms, plasma resistivity, Reynolds number, Lundquist number, etc.

Under coronal conditions and with the nominal instrumental scattered light the ATST should provide a S/N of 1000 in 2A band pass images with 1 arcsecond pixels during a 1 second exposure after background subtraction in regions of relatively bright (40 millionths) coronal emission in the 1075nm Fe XIII line. The expected intensity variations in the coronal emission line images is a few percent for intensity fluctuations (Murawski et al. 1989), so an integration time of only order 10 milliseconds is required for a 3-sigma detection of a 3% intensity oscillation.

For transverse oscillations of loops (fast kink mode), movements in the position of TRACE loops show amplitudes of $\sim 3''$, which damp out during a decay time of $t_d \sim 10$ min. With 1" pixels at a S/N of 1000 over a 1 second exposure ATST will be able to sample these motions with better resolution than previous studies in optical and EUV.

2.3.6 Plasmoids in and around Coronal Loops

Coronal models predict the size of small packets of coronal plasma, "plasmoids" to be near 250 km and suggest they play a major role in the mass flux of the solar wind (Mullan 1990). Observations during the 1991 eclipse using the 3.6m CFH telescope observed a plasmoid feature with a size of about 1500 km and

internal structure at the 400km seeing limit of the data (Delannee et al.1998, Zhukov et al. 2000). The feature was seen during the short 210 seconds of totality as it moved across the corona at a mean height of $1.13R_{sun}$. The feature was observed in white light but thought to have a cool temperature near 10^4 K.

For a 1 second exposure with 1x1 arcsec pixels the ATST is expected to achieve a S/N ratio of 1070 in the 2A wide Fe XIII emission line where the line has a brightness of 40 millionths of the disk center brightness. Reducing this spatial scale to 0".1 pixels decreases the flux by a factor of 100. Further, making the exposure time 10 milliseconds to freeze the seeing now reduces the flux by a total factor of 10⁴. This reduces the S/N ratio to 11; if a coronal plasmoid is bright in Fe XIII then direct imaging in this line with ATST with high spatial dispersion with short exposures should reveal coronal plasmoids. The 3 sigma limit is reached at an Fe XIII brightness of 3 millionths; if coronal plasmoids are at least this bright then ATST direct imaging (with simultaneous continuum subtraction) should also reveal plasmoids. However, since previous observations suggest plasmoids are cool, another option is to use the He I 1083nm emission line. This line is much brighter than the coronal Fe XIII emission as the transition is not a forbidden transition, and the 1083nm emission is often seen at levels of several thousand millionths of the disk center intensity in prominences off the limb. As the line is also about a factor of 10 narrower than the Fe XIII line, the 3 sigma limit detection limit in He I would be about 10 millionths disk center intensity.

If coronal plasmoids are faint in emission lines a different detection technique is required which could employ broadband polarization imaging without a spectrograph. Assuming 40% transmission through the polarizing element, and a plasmoid brightness of 0.1 millionths, and integrating over a 50nm filter pass band near 1 micron with a background brightness of 50 millionths results in a 2.4 sigma detection of the plasmoid.

The source of these plasmoids is unknown; they may be related to spicules or macrospicules. For this reason plasmoid observations should be made in conjunction with limb spicule observations. If these plasmoids are common and observable, they will help to trace out the solar wind velocity and acceleration properties at limb heights below the $2R_{sun}$ limit of current space-based results (Lewis and Simnett, 2002).

With short exposure, high signal to noise, high spatial resolution imaging, the ATST will be able to determine properties of coronal plasmoids, something that no other coronagraph (nor any future planned coronagraphs) has been able to do.

2.3.7 New Spectral Diagnostics for Coronal Loops

There are few working coronagraphs in the world and none of them allows observations longward of about 1.8 μ m. It is not surprising that, until recently, the IR coronal spectrum beyond about 1 μ m was largely unknown. In dramatic contrast with the visible, the 3.3-4.1 μ m atmospheric "window" yields a strongly reduced sky brightness, which is several times fainter than the coronal surface brightness. The availability of sensitive infrared array detectors has stimulated significant growth in our knowledge of the corona in this "low background" spectral region. Many research opportunities were described in the proceedings of a meeting largely devoted to this topic (Kuhn et al. 1994). The possibility of new plasma emission-line diagnostics is a notable deficiency in our knowledge of the corona. While the IR FeXIII lines near 1 μ m are well studied as an excellent coronal density probe, we are essentially blind to the diagnostic opportunities from lines longward of this. This is particularly annoying given the potential observational advantages of the IR because of the dark sky conditions. Relative to the sky, the brightest predicted emission line is from Si IX at 3.93 μ m. During the 1998 eclipse, tentative evidence of this line was obtained from an aircraft experiment. The Si IX line was also spectroscopically detected at the McMath-Pierce solar telescope, but the high scattered-light background at this facility increase the signal to noise level in the line and preclude scientific studies beyond the detection of the line.

The ATST will be a unique telescope facility that complements and extends the temporal and wavelength coverage of the space experiments by utilizing the new infrared detector and optical component fabrication technology now available. The ATST facility will allow coronal observations that have not yet been realized, even from space, and provide a long-term coronal observing platform that dramatically extends the intermittent space observations.

2.3.8 Wide-Field Coronal Photometry

Aside from SoHO/LASCO and dark-sky eclipse experiments, probably the best empirical description of the K-coronal electron density distribution comes from observations of the polarized continuum Thomson scattered light using the High Altitude Observatory Mark III K-coronameter.

The ATST will allow direct (i.e., non-polarized) measurements of the K-corona out to at least 1 solar radius from the limb. The ATST does this by dramatically reducing the net background intensity (with respect to the solar K-corona) by approximately two orders of magnitude from all other instruments. Such a reduction will allow polarized light detection of the K-corona in an MkIII-style detector system out to beyond 6 solar radii from the limb. This objective depends on minimizing the instrumental and atmospheric scattered light in the 3-to-4-micron wavelength regime.

2.4 THE SUN AND EARTH CLIMATE

2.4.1 Solar Irradiance Variability

A fundamental discovery of 20th-century observational solar physics has been the variation of the total brightness of the Sun by one or two parts in a thousand in step with the 11-year sunspot cycle. Observations of other solar-type stars have now demonstrated this variation to be a widespread property of normal, late-type stars.

Understanding the solar irradiance variability is a special topic amongst scientific research problems. Seldom in astrophysics can our scientific work have such an important bearing on social, cultural, or economic well-being. The case for the Sun is dramatic. Evidence for Sun-induced climate change as one of the driving forces in the development and evolution of civilization is compelling. For example, European climate in the late 17th century was brutally cold for several decades when the solar cycle mysteriously vanished for nearly half a century during the Maunder minimum. Conversely the unusual warm period during the Viking colonization of coastal Greenland occurred during a time when the solar cycle was probably only somewhat more vigorous than it is now. The correlative relationship between climate fluctuations and the Sun is by now well established even though the causal mechanism that connects 0.1%- scale solar bolometric luminosity changes to terrestrial effects is unaccounted for. Understanding solar irradiance variability is the key to refining our knowledge of climate change on Earth. Solar variability is the major natural forcing input to Global Circulation Model (GCM) calculations used to understand the relative importance of anthropogenic and natural sources of climate change. Recent studies have shown that solar variations must be taken into account in order to fully model the surface temperature increase seen over the past century.

We live near a star that we don't yet understand. NASA has accepted part of the challenge to deduce what we can about our critical solar-terrestrial relations through the Living With a Star (LWS) program. Unfortunately, some problems, like the irradiance or luminosity variability, are long-term activities that will outlive any directed series of space experiments. For example, NASA's currently operational SORCE experiment to measure solar variability from EUV to visible wavelengths, and the planned LWS SDO experiment will only provide ``snapshots'' compared to the 50 year lifespan of ATST solar irradiance studies.

For 20 years we have debated the physical mechanisms responsible for solar irradiance changes. Many believe these changes are due primarily to magnetic faculae and sunspots. Others see evidence of additional components to the net solar irradiance variability originating deep in the convection zone. Coincidently, for more than 20 years, the relevant observational limits have been set by the seeing and the small apertures of our telescopes.

The ATST, with its 4m aperture, adaptive optics, and exquisite control of scattered light, opens new opportunities to explore solar photometric variability. The photosphere holds faint and shadowy clues to how magnetic fields carry and redirect the energy from the deep solar radiative zone. These clues are buried in the random convective noise at the top of the photosphere but accessible from sensitive high resolution photometry the ATST will deliver. High spatial resolution observations, as those that will be provided by the ATST, are required to determine the temperature stratification of small-scale magnetic elements and the evolution of their structure. The ATST, with its broad wavelength sensitivity and ability to spatially resolve irradiance contributions down to the flux tube limit, is the breakthrough instrument we've been waiting for. Only in this way can the roles of the facular contribution and its center-to-limb variation be properly understood within the context of the total and spectral irradiance variability of the Sun. It is only through the construction of accurate models, based on actual observations of the structural components that contribute to solar variability, that predictive capability can be developed.



Figure 2.27. Solar active region 10377 on 6-June-2003 seen near the East limb of the Sun through the New Swedish 1-meter Solar Telescope (NSST) on La Palma in 430 nm light. The tickmarks are 1000 km apart and the blue circle shows the relative size of the Earth. The spatial resolution is approximately 70 km. Active region faculae are the bright structures surrounding the central sunspot in a large network pattern. The black box is shown enlarged on the right. Courtesy T. Berger.

Figure 2.27, one of the current highest resolution photometric solar observations, shows contributions to the solar irradiance at the smallest angular resolution yet achieved. The tiny brightness contributions to the Sun's output energy budget shown here are the faculae. Zooming into this image reveals that the convective granulation cells that make up most of the photosphere are complex structures that resemble desert mesas with elevated central regions and steep walls plunging into the intergranular lanes. In addition, the bright faculae are seen to be regions of these walls that are heated by their proximity to the magnetic elements and are facing Earth. This discovery may implicate granular convection dynamics in

facular brightening and lead to new ways of understanding the effect of magnetic fields on solar radiative properties. We are, however, unable to determine whether they account for the brighter and hotter Sun we see near times of sunspot maxima. More importantly we have yet to understand why the Sun organizes its surface magnetic features into sometimes bright and sometimes dark surface elements, but we need these answers before we can understand or predict how the total solar irradiance can vary.

ATST is designed to eliminate most of the scattered light, which typically corrupts telescopic photometry of extended objects. Its angular resolution will also be nearly an order of magnitude greater than the figure above. This combination of photometric fidelity and spatial dynamic range can reveal the energy budget at the photosphere at the fundamental density scale length. At this level we can directly see how magnetic fields regulate or contribute to the emergent solar irradiance and, by integrating over angles and larger regions, we finally account for the total solar luminosity variability."

3. THE ATST IN CONTEXT

While many areas of solar physics—such as helioseismology, measurements of coronal structure, and studies of small-scale surface dynamics and fields—have grown independently, we now understand that the Sun is a highly coupled system. Physical processes that occur on large and small scales, in the interior and at the surface, interact to produce its complex behavior. It is not possible for a single telescope alone to address the broad range of question that must be answered to understand the Sun. Only by combining the data from many instruments, many time scales, and many spatial dimensions, will true progress be made.

When coupled with high-energy and other observations from space (e.g., SOLAR-B, Solar Dynamics Observatory (SDO), Ramaty High Energy Solar Spectroscopic Imager (RHESSI)), with ground-based radio observations (Very Large Array (VLA), Very Large Baseline Array (VLBA), Frequency-Agile Solar Radio (FASR) Telescope), and with long-term synoptic observations (SOLIS, ISOON, GONG, BBSO, Mees, Marshall), which place the current observations in the context of the solar cycle, the ATST optical/infrared observations will enable a complete picture (from interior to interplanetary space) of the Sun to be developed.

Figure 3.1 shows the complementary nature of the ATST and many of the assets that are available now and that will be available in the future.

3.1 SPACE MISSIONS

The ATST is highly complementary to planned space missions, such as SOLAR-B, STEREO, SOLAR ORBITER and the SDO. While these space missions will provide uninterrupted and long-term coverage and are ideally suited to study, for example, active region evolution, the ATST will provide the ultra high-resolution imaging and spectroscopic diagnostics required to gain a physical understanding of many of the observed phenomena. Experience shows that ground-based research benefits greatly from the constant monitoring that is available in real-time from space observatories. Observers at ground-based telescopes regularly check the real-time status of solar activity at the websites of SOHO, TRACE, and RHESSI. Conversely, spacecraft mission goals and day-to-day targeting of events are planned based on knowledge and questions that derive in part from high-resolution ground-based observatories such as ATST. This synergism between ground and space work greatly enhances the relevance and value of both. The contribution of ATST to this cross-fertilization process will advance far beyond present ground capabilities, and will keep pace with the ever-improving capabilities of space instrumentation.



Figure 3.1. ATST compared to other solar assets.

The 50-cm optical telescope on SOLAR-B will achieve a resolution of 0."2 in the visible. As pointed out in the SOLAR-B proposal (SOLAR-B FPIP Science Goals and Observing Requirements) in many cases a resolution better than the 0."2 is required to fully resolve solar structures. The large photon flux provided by the ATST combined with the high image quality achievable with adaptive optics will allow highly accurate measurements of physical parameters such as velocity, magnetic field strength and direction. Such context data will be crucial in interpreting the observations provided by SOLAR-B.

The main proposed mission within NASA's Living With a Star (LWS) initiative is the Solar Dynamics Observatory. The current plans for SDO call for approximately one arcsecond resolution on the solar surface. In order to accomplish many of its science goals, SDO will need coordinated data from the ATST. ATST, which has as its goal 0.05 arcsec resolution, will directly observe the magnetic flux tubes and their dynamics. For example, while SDO will provide observations that will give profound insight into solar variability many of the fundamental physical processes creating changes in the solar output occur on scales well below SDO's spatial resolution. The ATST will be optimized for high-resolution (spatial, spectral, and temporal), vector polarimetery. Without the ATST, SDO will continue the science of TRACE and SoHO, which in itself is important for understanding the Sun, but it will not answer the fundamental questions of the origins of solar activity and irradiance variability. The ATST is complementary to the planned LWS solar missions; both are truly needed to address solar activity and variability and together are vital components in a systems approach to the LWS initiative. SDO has a large field of view (FOV), and will provide connections between surface activity and the outer solar atmosphere and the interplanetary space (and hence the Earth). The ATST has a much smaller FOV, but it will define the physics of how magnetic flux and plasma interact to store energy, destabilize existing

magnetic structures leading to activity, heat the atmosphere to cause irradiance variations, and provide energy to accelerate the solar wind and CMEs. The potential for scientific breakthroughs that will follow from a close synergism of ATST with its unique capability to spatially resolve much of the coronal structure (<1") and sufficient time resolution (seconds) to capture the dynamics of coronal structures and space missions is tremendous. Together, SDO and ATST will provide a more complete picture of solar variability needed to develop predictive capabilities.

The unique opportunity to finally unravel many of the mysteries of our closest star by having the most powerful space-based and ground-based instruments work together was recognized by the recent NAAAC study report:

"The National Solar Observatory's proposed Advanced Technology Solar Telescope (ATST) can provide critical observations not possible with SDO, such as simultaneous measurements of the coronal magnetic fields directly responsible for the heating and activity. The scientific payoff that would be gained from joint observations far exceeds what could be achieved individually. We therefore recommend that NSF and NASA take advantage of this synergism and work to ensure that ATST and SDO are phased together."

The ATST will be a unique scientific tool, with excellent angular resolution, a large wavelength range, and low scattered light. The ATST will also provide access to unique diagnostic tools in the near- and thermal infrared and observing flexibility, both of which are unavailable from space. The ATST also provides the accessible platform needed to develop future space instrumentation. Together, planned space missions and the ATST will provide the complete picture of solar magnetism and solar variability needed to arrive at a physical understanding of the observed phenomena and to develop predictive capabilities.

3.2 GROUND-BASED EXPERIMENTS

Long-term, ground-based, precision observations of solar conditions of the kind now being made by the Global Oscillations Network Group (GONG) and with the Synoptic Optical Long-term Investigations of the Sun (SOLIS) are, like the space mission above, an essential complement to the observations of the ATST. When fully operational, the SOLIS instrument will enable the precision monitoring of daily solar activity with whole-disk vector magnetograms, velocitygrams, and spectroheliograms. In the near future SOLIS will be co-located with the ATST. SOLIS data, as well as data from other solar synoptic programs, will permit the detailed ATST observations of solar magnetic processes occurring in a particular active region to be placed in the context of the global solar magnetic and velocity fields and overall activity pattern. It will also permit linkage of the ATST observations to the longer-term temporal variation of the regions being observed. This additional information will aid tremendously when comparing ATST data to models by furnishing realistic boundary conditions and other constraints on the models. Similarly, helioseismology currently performed by GONG will provide information on the state of the solar interior, subsurface flows, rotation and interior magnetic fields. By linking the fibril magnetic structure observed at the surface with the ATST to subsurface information provided by GONG and other oscillation experiments, the physics of the interaction between local and global dynamo processes can be studied.

While the ATST will measure the magnetic build-up and release of magnetic energy in active regions, it cannot view the more energetic parts of the subsequent activity, which leave their primary signatures at wavelengths longer and shorter than the ATST cutoffs. Microwave and millimeter observations of active regions can be used to measure the more energetic parts of activity. Plans to develop a high-resolution, frequency-agile solar radio telescope (FASR) would greatly enhance this synergism. A FASR would provide unique diagnostics of solar flare plasmas, as well as maps of magnetic fields over surfaces of constant density in active regions. Equally important would be its unique ability to detect and locate the

myriad of microflares, which could then be related to the ATST's observations of magnetic annihilation events fuel models for these atmospheric heating events.

3.3 SPACE WEATHER AND CLIMATE CHANGE

As noted before, the Sun's atmosphere is highly variable as it responds to a changing magnetic field, which occurs at the solar surface in a dynamic interactive fibril state that often leads to explosive dissipation of magnetic energy over a wide range of scales and intensities. The dissipation of magnetic energy is the cause of the Sun's supersonic wind, its X-ray emission, coronal mass ejections and the production of flares and solar energetic particles. "Space Weather" (Bothmer 1999; Feynman et al. 2000) refers to conditions on the sun and in the solar wind, magnetosphere, ionosphere, and thermosphere that can influence the performance and reliability of space-borne and ground -based technological systems and can endanger human life or health. Adverse conditions in the space environment can cause disruption of satellite operations, communications, navigation, and electric power distribution grids, leading to a variety of socioeconomic losses. For example, large flares can be accompanied by highly energetic particles that pose hazards ranging from excessive levels of radiation harmful to astronauts to disruption and/or destruction of satellites in space. Coronal mass ejections produce interplanetary blast waves that impact Earth's magnetic field, occasionally so violently that they disrupt electrical power grids on Earth. It appears that the microstructure, i.e., the fibril structure of magnetic fields, plays an essential role in the physics of these large-scale phenomena, so that direct observational study of the microstructure is essential for discovering the source of the Sun's activity. The ATST will play an essential role in understanding and modeling the origins of solar activity and variations in the radiative output of the Sun.

Presently there exist no models of solar active regions that can produce accurate quantitative predictions of when and where activity will occur on the Sun, or predict what the magnitude of the emissions resulting from that activity will be. The accuracy of solar activity predictions is limited by incomplete understanding of the underlying physical processes in the evolving solar atmosphere (Pizzo 2000). The ATST will provide data needed to develop models for the magnetic evolution of active regions, the triggering of magnetic instabilities, and the origins of atmospheric heating events. These models will provide a much better capability for understanding and predicting when and where activity will occur on the Sun and for predicting the level of enhanced emissions expected from these events. These in turn will permit solar-terrestrial models to be refined to include critical solar data instead of the proxies that are used now.

Solar EUV/UV emissions from activity events and increased activity levels directly affect the degree of ionization in the Earth's atmosphere, heating of the thermosphere; they also serve as an input to terrestrial neutral density models. Ionization levels affect communications and surveillance, while thermospheric heating can cause variations in satellite drag, making it more difficult to track satellites and space debris. ATST observations that help us understand the physics of these events will also provide insight into the changes in solar emissions that can be expected from particular magnetic configurations on the Sun.

The evolution of coronal magnetic fields strongly influences the terrestrial environment by modulating the solar wind and producing geomagnetic storms. ATST data combined with space-based coronal EUV and soft X-ray observations will provide data needed to link coronal field evolution to the magnetic fibril structure in the lower atmosphere. This in turn will lead to models for solar wind acceleration and modulation.

Understanding how the build-up and decay of active regions occurs is the first step in building models of the solar output variations that are required in understanding long-term solar irradiance variability and assessing its impact on the Earth's climate. Modelers of the Earth's climate must incorporate solar changes in their models if they are to correctly assess other impacts, such as those caused by human

activity. Knowledge of the sources of variations in the Sun's radiative output across the solar spectrum, especially in the important EUV and XUV bands, will provide information on the range of solar variations that must be included in terrestrial climate models. This will also help in interpreting historical climate data, or conversely, will help solar physicists use historical terrestrial data to understand past solar variability.

3.4 NIGHTTIME OPERATION OF THE ATST

Although nighttime operation of the ATST will be accommodated, if possible, we do not intend to allow this to drive either the telescope design or the cost. That said, the ATST, combined with a stable, highresolution spectrograph, could offer a unique platform for dedicated programs in solar-stellar physics that require synoptic observations—The Solar-Stellar Connection. This active subdiscipline of contemporary astrophysics enables ideas originating in the narrow solar arena to be tested in broader stellar contexts. The stars span a range in physical parameter space including mass, age, rotation, and evolutionary state that is not available with the Sun alone. Solar-stellar studies also offer unique insights into the range of possible behavior of a star like the Sun that solar observations alone are unable to achieve. Some areas in solar-stellar astrophysics that might be appropriate for dedicated nighttime programs at the ATST include:



Figure 3.2: Example for Solar-Stellar Connection: X-ray spectral radiance L_x vs. total unsigned magnetic flux for solar and stellar objects: quiet Sun (QS), X-ray bright points)XBP), solar active regions (ARs), solar disk averages (Sun), G, K, and M dwarfs, and T-Tauri stars. The dashed line represents the power-law approximation $L_x \sim \Phi^{1.15}$ of the combined data set.

Over a great diversity in spatial scales and magnetic flux densities, the X-ray output of coronal plasma is roughly proportional to the unsigned magnetic flux threading the solar or stellar photosphere. The simple, nearly linear relationship suggests a common heating mechanism. The scatter in the distributions suggests that other magnetic parameters, such as the detailed morphology also play an important role (Pevtsov et al. 2003).

• *Asteroseismology.* The study of global oscillations in stars is a promising new technique for measuring the fundamental parameters in stars with significantly higher precision than has previously been possible, allowing quantitative comparison of data with stellar models. Asteroseismology is the classic photon-starved problem. Both high spectral and temporal

resolution are required, along with the highest attainable signal-to-noise ratio per resolution element.

- *Doppler Imaging*. This method employs time-resolved, high-resolution spectroscopy to reveal the actual morphology of magnetic structures on stars. Doppler imaging studies of rapidly rotating stars have already revealed features, such as enormous polar spots, totally unlike any observed on the Sun. Such measurements offer a powerful tool for examining how the surface activity of a star like the Sun evolves as its rotation slows with age.
- *Stellar Convection.* The interaction of convection with magnetic fields lies at the origin of the Sun's magnetic dynamo, luminosity variability and angular momentum evolution. Convection can be studied in other stars through subtle asymmetries in photospheric line profiles. This opens the possibility of exploring the relationship between rotation and convection in other stars to test and refine theories of the Sun's behavior.
- *Magnetic Fields in Late-Type Stars.* Magnetic fields modulate the luminous output of the Sun and stars, and determine their angular momentum evolution. A key observational goal of solar-stellar physics is to determine the magnetic field properties across the H-R diagram along with the variation of these properties on all time scales. In the optical, the Zeeman signature is subtle, though identifiable, in active G-K dwarfs. The signature is more evident in the infrared because of the wavelength dependence of Zeeman splitting.
- *Planets and solar system bodies.* For several years the Dunn Solar Telescope (DST) has been used for spectropolarimetry of planets (e.g., Jupiter/Io system, and Mercury) and solar system bodies (e.g., Hale-Bopp), in efforts to determine magnetic-field properties. The DST was chosen because its well understood and well calibrated instrumentation permit precision polarimetric measurements. Such efforts would benefit significantly from the unique capabilities of the ATST. The increased mirror size alone would be important for observing fainter objects such as planetary satellites and comets. This, combined with the spectropolarimetric capabilities of the ATST, will make the telescope a valuable tool in the extension of polarization measurements to planetary astronomy.

3.5 PLASMA PHYSICS AND LABORATORY ASTROPHYSICS

Combining the results from ATST and a new type of laboratory experiment dedicated to studying the dynamics of magnetic flux tubes will play an important role in furthering our understanding of this key process. The experimentally produced arched, twisted flux tubes are produced by advanced pulse power techniques and are governed by the same magnetohydrodynamic equations as actual solar structures and also by numerical simulations. This method provides the means for making actual scaled experiments of the dynamic magnetic phenomena observed on the Sun and also closely related phenomena associated with astrophysical jets. This experimental program will be undertaken at the California Institute of Technology in a laboratory, which has already produced significant results using this technique. The Caltech group studies the formation of Spheromaks – a self-organized, stable, vortex-like, isolated toroid of plasma. Spheromaks represent a possible plasma confinement configuration for nuclear fusion. Insight into their formation that will result from the laboratory experiments and the close collaboration between the ATST science team and laboratory plasma physicists will help in the design of future magnetic confinement fusion experiments. The laboratory experiments will provide crucial clues to understanding plasma dynamics in the solar corona and other astrophysical problems such as astrophysical jets.

The experiments by the Caltech group have identified the magnetic hoop force due to curvature of a current channel as being the underlying mechanism driving prominence eruption and have shown that this eruption can be inhibited by the imposition of an additional "strapping" potential magnetic field oriented perpendicular to the plane of the arched current channel and having the appropriate polarity. The layout of this experiment is shown schematically in Figure 3.3.



Figure 3.4. Eight arched, plasma-filled flux loops arranged like the legs of a spider.

Figure 3.3 Layout showing basic prominence simulation geometry (insert) and strapping field (green lines), which inhibits eruption.

More recently, merging a pair of simulated prominences having either the same or opposite magnetic helicity, has been used to identify differences between co- and counter-helicity merging, and in particular it has been seen that soft x-ray emission for counter-helicity merging is more than an order of magnitude larger than that of co-helicity merging.

A related experiment having coaxial symmetry (instead of bipole symmetry) initially produces a set of eight arched, plasma-filled flux tubes located about a symmetry axis like the legs of a spider as shown in Figure 3.4.

It is observed, as shown in Figure 3.5, that the inboard portions of the eight arches quickly merge to form an axisymmetric jet, which grows longer until, at a critical length it suddenly develops a dramatic kink instability. These experiments are highly reproducible, easily modified, and it is possible to make movies showing the dynamic evolution. The lab experiments have motivated development of a model proposing an explanation for why coronal loops are axially uniform; this model incorporates aspects of jet physics and shows that driving a current along an initially bulged, arched loop will drive jet-like flows from both footpoints towards the top of the arch where the flows stagnate.

3.6 MODELING AND SIMULATIONS: MAKING THE CONNECTION BETWEEN THEORY AND OBSERVATIONS

The ATST is expected to play a central role in the interplay between theory and observations by providing the fundamental data for testing physical models of solar surface phenomena at hitherto unresolved spatial and temporal scales, along with unprecedented diagnostic capabilities. Therefore, it will be extremely important for the success of the entire ATST project to lay the groundwork as early as possible for establishing the connections between model predictions (Fig.3.6) and the observations and measurements to be performed with the ATST.

This groundwork requires the initiation of a theoretical program, based on both numerical simulations and analytic methods, to quantify the complex interaction between the magnetic field, the radiation field and the partially-ionized plasma near the solar surface. The creation of such a program, whose thrust is specifically on problems related to solar magnetism, as it is constrained by observations of the sort to be

provided by the ATST, has been discussed for some time in the solar community. With the initiation of the ATST program, start-up of a counterpart theory program becomes a crucial next step.

The aims of the coordinated theory program are several. First, we will be exploring a hitherto unknown regime of spatial scales on the solar surface; and a variety of design decisions regarding the instrumentation and telescope will be significantly eased by having the capability to compute expected appearance—both morphologically and spectrally—of the solar surface. For example, radiative transfer as well as the effects of the telescope and instruments and their performance limitations have been taken into consideration during the design phase of ATST. Only in this way were we able to translate specific input from theory/modeling into observational requirements. Second, our present understanding of the physics at these previously unexplored spatial scales is encapsulated by theoretical models and the predictions—based on both numerical simulations and analytical work—that flow from these models.

Once observations get underway, the ATST will then be in a position to validate (or invalidate) our present thinking. This confrontation between our present understanding of the physics at as-yet unresolved scales and the observations is one of the key aspects of the ATST.

At the heart of the theoretical problem lies solution of the induction equation, the evolution equation for the solar magnetic field, coupled with the mass, momentum and energy conservation equations for the compressible and partially ionized solar surface plasma, and with the transport equation for photons. The dimensionless numbers characterizing the ratio of the largest to smallest important spatial scales (the fluid and magnetic Reynolds numbers) are extremely large (typically, in excess of 10^6), so that direct numerical



Figure 3.5. Inner portions of the eight "spider legs" merge to form a jet-like central column (left), the column expands in length (middle), and then at a critical length becomes kink unstable (right).

simulation of these equations cannot be carried out now, nor in the foreseeable future. Theoretical advances will depend on a combination of detailed calculations of physical processes at the smallest spatial scales, combined with modeling of these processes as part of calculations on much larger (observed) scales. Furthermore, the full treatment of non-equilibrium, 3D, radiation transfer must also be simplified to be tractable. Now, as in the case of such modeling carried out in the context of laboratory experiments, comparison of model predictions with observations is essential to developing sensible models. Understanding the complex interaction between dynamics and radiative transfer in nontrivial magnetic field configurations, especially in structures that are barely resolved, require three-dimensional, compressible, radiation-magneto-hydrodynamic codes with realistic equations of state, including partial ionization (which are also equipped with post-processing to compute the Stokes profile diagnostics).

The highly nonlinear nature of the underlying equations describing the interaction of partially ionized fluids, magnetic fields, and photons at the solar surface leads, unsurprisingly, to a comparably rich phenomenology, which is in general entirely unknown in the context of terrestrial laboratory experiments. Calculations to date have illustrated a wealth of such unusual processes, including magnetic flux cancellation, emergence of magnetic flux, convective collapse and magnetic field intensification, and

small-scale (turbulent) dynamo field generation. While many of the underlying ideas have been developed using analytical techniques, it has been generally recognized that a full understanding of these phenomena requires numerical simulations, together with observations targeted specifically to test the validity of the physics included in the calculations.

One of the gratifying consequences of advances in modern massively parallel computations is that the dynamic range of the calculations that can be carried out—while not approaching those characteristic of the solar atmosphere—nevertheless have reached a point at which truly turbulent flows (and their consequences) can be studied. As a consequence, we are now able to carry out calculations that build our physical intuition in parameter regimes that were previously entirely inaccessible (and the consequent physical modeling previously subject to considerable uncertainty).

In addition to being able to solve the underlying equations under much more realistic conditions than before, modern computing capabilities are also beginning to allow us to carry out the next step with considerable fidelity: computing the emergent radiation field, so that we can connect with much more clarity and certainty the theoretical models with actual data.

An important element of the ATST is that, while there is a wide separation between the scales on which magnetic fields are inductively generated and the small scales on which they dissipate by Ohmic action, the resolution of the ATST and its instruments lies between these two scales, in a regime in which radiative transfer effects are extremely important in the interpretation of the emerging photon flux. Thus, numerical simulations are essential to interpret such observations.



Figure 3.6. To illustrate the current state-of-the art in numerical simulations this figure shows the magnetic field lines, vertical component of the magnetic field and the resulting G-band intensity for a snapshot of a 6 x 6 Mm patch of the solar surface with a grid size of 25 km from a simulation of Stein & Nordlund. Magnetic field has been swept to the boundaries of the granules and then to the boundaries of the underlying meso-granules. Horizontal flows in the intergranular lanes produce a few field concentrations of 1-2 kilogauss strength from which mass has drained down and which are in equilibrium with the surrounding gas pressure.



