

Science and Operation of the Advanced Technology Solar Telescope

Stephen Keil, Thomas Rimmele (National Solar Observatory), Jeff Kuhn (University of Hawaii), Phil Goode (New Jersey Institute of Technology), Robert Rosner (University of Chicago), Michael Knoelker (High Altitude Observatory), Thomas Berger (Lockheed Martin)

1. INTRODUCTION

The Advanced Technology Solar Telescope (ATST) is an identified project in the NSF MREFC program and construction began in 2010. The NSF provided \$7 M in FY09 and \$13M in FY2010 MREFC funds. In addition Congress provided \$146M in American Recovery and Reinvestment Act (ARRA or stimulus) funding. The ATST represents the culmination of the solar community's desire going back over several decades to have a solar telescope capable of resolving fundamental scales and processes on the photosphere and to finally be able to measure the "dark energy" magnetic fields that dominate the solar corona. The 2000 Astronomy and Astrophysics Decadal Survey¹ stated that "The first scientific goal for advancing the current understanding of solar magnetism is to measure the structure and dynamics of the magnetic field at the solar surface down to its fundamental length scale – ATST is designed to achieve this angular resolution." The 2003 NSF/NASA Solar and Space Physics Decadal Survey² recognized the high priority of the ATST and its synergism with space missions as essential for solving the questions surrounding solar magnetism and solar activity. With its completion in 2017, strong NSF support will be needed to operate ATST and to exploit its scientific capabilities.

2. KEY SCIENTIFIC GOALS

Magnetic fields control the inconstant Sun. The key to understanding solar variability rests with understanding all aspects of these magnetic fields. The majority of magnetic energy, predicted by models and sophisticated simulations to exist on very small spatial scales ($< 0''1$) and often with weak field strength, cannot be sensed with current telescopes. Up until now it is only from photospheric and chromospheric observations that we have direct measurements of these magnetic fields. As the world's largest solar telescope and coronagraph the photon collecting power of the ATST's 4m aperture is essential to make progress. For the first time we will have the capability to measure solar magnetism from the photosphere to far into the corona, where the solar wind is accelerated and CME's are launched. But even in the lower atmospheric layers, the magnetic fields change so rapidly that current telescopes can not resolve many important aspects of the field before it has evolved and the bulk of the field may exist on scales that have not been resolved. In higher atmospheric layers our current ability to accurately measure the magnetic field is rudimentary at best. ATST observations are not incremental improvements in our understanding of the Sun, but paradigm changing visions.

The photosphere is a crucial region where energy is readily transformed from convective motion into thermal and magnetic energy, and electromagnetic radiation. The energy stored in magnetic fields is eventually dissipated at higher layers of the solar atmosphere, sometimes in the form of

violent flares and coronal mass ejections (CMEs) that ultimately affect the Earth and drive space weather. The photosphere, the chromosphere, transition region, and the corona are connected through the magnetic field and therefore have to be treated as one system, rather than as individual layers. The ATST with high performance adaptive optics and state-of-the-art instrumentation is a crucial tool to understand this complex, interconnected physical system. Some of the scientific problems the ATST will address include the origin and generation of magnetic fields, magnetic activity and instability, chromospheric and coronal structure and heating, and sources of solar irradiance variability³.

2.1. FLUX TUBES, THE BUILDING BLOCKS OF STELLAR MAGNETIC FIELDS

Observations have established that the photospheric magnetic field is organized in small fibrils or flux tubes. This small scale flux may be the dominate form taken by the magnetic field and could be a major contributor to the energy balance of the atmosphere, in particular heating of the outer atmospheric layers and a source of energy for the solar wind. Magnetic structures are mostly unresolved by current telescopes. Flux tubes are the most likely channels for transporting 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.

Addressing the issue of small scale magnetic fields requires simultaneous vector magnetometry in multiple layers of the solar atmosphere and drives the spatial ($0.03''$ at 500nm and $0.08''$ at 1.6 microns) and temporal (periods as short as a second or less) resolution requirements. At this resolution ATST will provide the required spectroscopy and polarimetry at an angular resolution to explore the enigmatic flux tube structures on time scales compatible with their lifetimes. For the first time, ATST will achieve the resolution and photon flux required to investigate the role of flux annihilation and MHD wave modes in generating and transporting energy to the outer solar atmosphere. 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 high-resolution solar telescopes. The ATST will provide spectroscopic observations of sufficient resolution to study the formation, internal structure, interactions with convection and disappearance of flux tubes and what role they play in the heating of the outer atmosphere

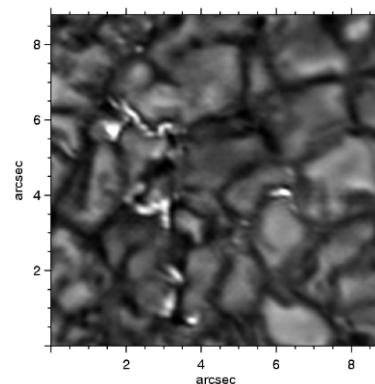


Fig 1. Solar granules and bright magnetic flux regions observed in the g-band of CN with the Dunn Solar Telescope. Measuring the vector magnetic field associated with the rapidly changing bright points needs a larger aperture.

2.2. MAGNETIC FIELD GENERATION AND LOCAL DYNAMOS

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. There are two types of dynamo. The large scale or *mean field dynamo* generates magnetic fields at scales larger than the energy-containing scale of

the turbulence, whereas *the small-scale dynamo* amplifies magnetic fluctuation energy below the energy-containing scale of the turbulence. The small-scale dynamo is usually a much faster process than the mean-field dynamo, and the large-scale field produced by the latter can be treated as approximately constant on the timescale of the small-scale dynamo. However, the mean-field dynamo also gives rise to small-scale magnetic fluctuations because of the turbulent shredding of the larger scale magnetic field, i.e., the large scale and small scale dynamos interact and some solar cycle dependence of the small scale fields might be expected.

The Sun's magnetic machine involves the processes of flux generation, transport, dissipation, instability and ejection. The 11-year sunspot cycle and the 22-year magnetic cycle are still shrouded in mystery. Global dynamo models attempt to explain large-scale solar magnetic fields are based on theories involving large averages. Turbulent convection is believed to stretch and amplify the magnetic field while differential rotation, meridional circulation, and the tachocline shear layer 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 on scales of active regions down to intergranular lanes. However, properties such as diffusion and helicity, that must be assumed in these models are produced by small-scale turbulent processes and have not yet been measured. High spatial, temporal, and spectral resolution 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.

In addition, local dynamos may produce the majority of small-scale magnetic flux elements recently observed to cover the entire Sun^{4,5}. This "magnetic carpet" continually renews itself on a time scale of a few days at most and its flux may be comparable to that in active regions. The ATST will make it possible to directly observe such local dynamo action at the surface of the Sun.

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 Alfvén waves will require a computation of electric currents inside individual "flux tubes" -- a task well outside the scope of existing ground-based telescopes or existing and future space instruments. 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

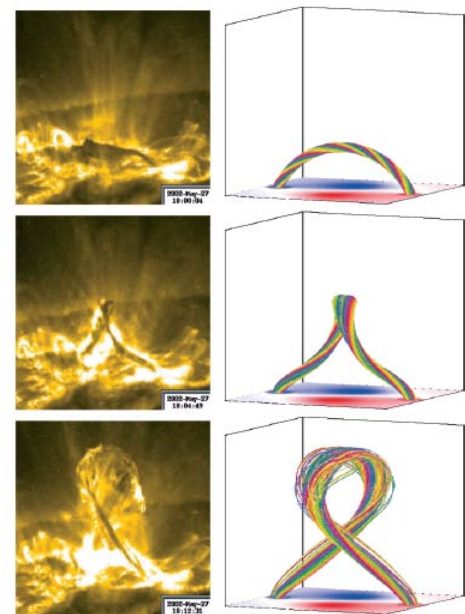


Fig 2. Filament eruption: Trace image sequence (left), model of magnetic field (right.) Actual measurements of the coronal field are missing. What coronal field configurations lead to CMEs and what are the trigger mechanisms?

2.3. INTERACTION OF MAGNETIC FIELDS AND MASS FLOWS

Sunspots are the ideal objects for testing magneto-hydrodynamic theory under astrophysical conditions. In sunspots, the total magnetic field is large enough to completely dominate the hydrodynamic behavior of the local gas, a regime very different from that of the rest of the solar photosphere. Numerical simulations and theoretical models predict dynamical phenomena, such as oscillatory convection in the strong-field regions of sunspot umbrae, flows at the speed of sound along penumbral filaments and oscillations and wave phenomena. To verify the predictions of numerical simulations of sunspots and ultimately answer such fundamental

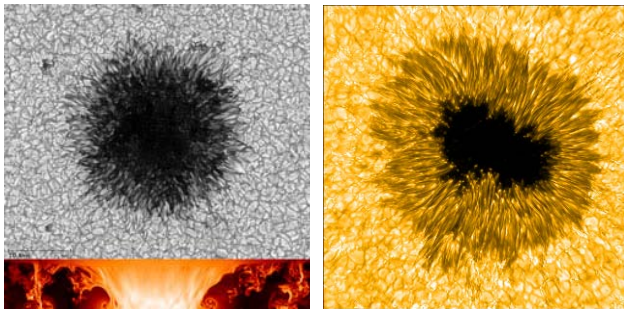


Figure 3. (right) A high resolution sunspot image using adaptive optics and the Dunn Solar Telescope. (left) A state-of-the-art MHD simulation of a sunspot penumbra (Rempel, HAO).

questions as “Why do sunspots exist?” requires an extremely capable instrument. High-resolution (<0.1 arcsec) vector polarimetry combined with high sensitivity (high photon flux) and low-scattering optics are required.

The ATST will be the first telescope able to collect precision polarimetric data 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 $1.6 \mu\text{m}$), where scattered light is less of a problem and much more accurate magnetic field fine-structure determination is possible.

2.4. FLARES AND MASS EJECTIONS

An important goal for the ATST will be to study origins and mechanisms of solar activity such as the small-scale and rapid processes in solar flares and configurations leading to flares and CMEs⁶. It is commonly believed that solar flares 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. 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 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.

Coronal mass ejections (CMEs) 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. 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. 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 or models in which small-scale photospheric reconnection events inject helicity into the corona. These hypothesized reconnection events occur when small (0.1'') photospheric flux elements cancel along the active region's magnetic neutral line. This model 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.

2.5. INHOMOGENEOUS STELLAR UPPER ATMOSPHERES

Measurements of CO absorption spectra near 4.7 μm show surprisingly cool clouds that appear to occupy much of the low chromosphere⁷. 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 observed spectra can be explained by a new class of dynamic models of the solar atmosphere. However, the numerical simulations indicate that the temperature structures occur on spatial scales that cannot be resolved with current solar infrared telescopes. A test of the recent models requires a large-aperture solar telescope that provides access to the thermal infrared. Spicules, the forest of hot jets that penetrate from the photosphere into the chromosphere, are clearly a MHD phenomenon that is not understood nor adequately modeled. Their role in the mass balance of the atmosphere is uncertain. Combined with UV observations from space, the ATST will allow us to resolve their nature.

2.6. MAGNETIC FIELDS AND STELLAR CORONAE

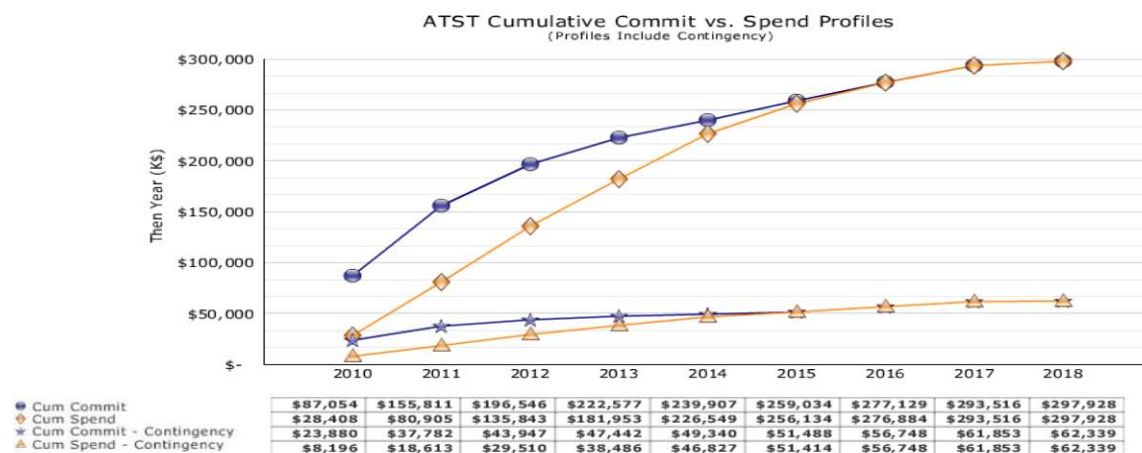
The origin and heating of the solar corona are still mysteries. Most of the proposed scenarios are based on dynamic magnetic fields rooted at the 0.1-arcsec scale in the photosphere. However, none of the processes has been clearly identified by observations or theory. EUV and X-ray

observations have gained in importance, but ground-based observations are still critical, not only to determine the forcing of the coronal fields by photospheric motions, but also for the measurement of the coronal magnetic field strength itself. This is important for developing and testing models of flares and coronal mass ejections, which propel magnetic field and plasma into inter-planetary space and induce geomagnetic disturbances. In particular, precise measurements of the coronal magnetic field strength and topology are needed in order to distinguish between different theoretical models. The ATST with its large aperture, low scattered light characteristics, and the capability to exploit the solar infrared spectrum will provide these critical measurements.

The ATST will also address many other problems in chromospheric and coronal structure and heating. The ATST will have an unprecedented multi-spectral imaging capability with which true three-dimensional 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. Its coronal capability will allow it to map coronal fields and plasma properties of coronal loops and structures

3. COST AND STATUS

The costs for the ATST construction phase are based on the Work Breakdown Structure (WBS) down to eight levels of detail, depending upon the complexity and availability of comparable existing systems. The construction phase will cover eight fiscal years, beginning in FY 2010 and ending in FY 2017. The vast majority of the work will be subcontracted competitively to industry and to qualified partners with unique expertise. ATST personnel manage all activities centrally.



Current planning, based on an FY 2010 construction start, has calendar year 2017 targeted for obtaining the first scientific data with an ATST instrument. During the first two years of construction, site work, manufacture of the primary mirror blank and completion of the final fabrication designs are primary objectives of the project. Construction of main components such as the enclosure and telescope structure should also be well underway during this period.

Operational costs for ATST have been estimated based from a bottoms-up exercise looking at the task that must be performed for operations, maintenance, and ongoing instrument development. The increased cost of living on Maui was factored into the costs. The payroll to maintain a staff of approximately 40 on Maui is estimated at ~\$7.6M. Non-payroll costs are estimated at \$4.2M. An addition \$2M per year for instrumentation and telescope upgrades would be required, giving a total estimate of ~\$13.8M. This is roughly 5% of the capitol cost.

Funding to support the use of ATST by the solar community will be critical. NSF needs to establish a strong grants program that will permit investigators to propose for funding that will permit them to work with ATST data. NSO plans to make all ATST data available to the community similar to data from the HINODE and SDO missions.

4. SUMMARY

High-resolution studies of the Sun's magnetic fields are needed for a better understanding of the fundamental processes responsible for solar variability. The generation of magnetic fields through dynamo processes, the amplification of fields through the interaction with plasma flows, and the destruction of fields are poorly understood. There is incomplete insight into physical mechanisms responsible for chromospheric and coronal structure and heating, causes of variations in the radiative output of the Sun, and mechanisms that trigger flares and coronal mass ejections. Progress in answering these critical questions requires study of the interaction of the magnetic field and convection with a resolution sufficient to observe scale fundamental to these processes. The 4-m aperture ATST will be a unique scientific tool, with excellent angular resolution, a large wavelength range, and low scattered light. Scientific operation and exploitation of the ATST will require strong NSF support starting during the period covered by this decadal survey.

5. REFERENCES

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