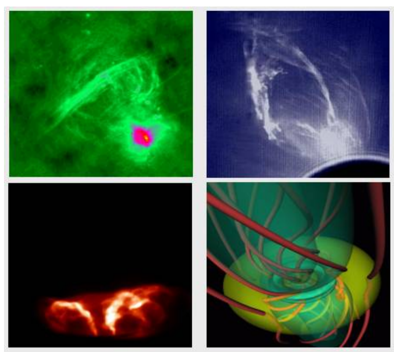
An Introduction to Science with the DKIST

As we begin the 21st century, fundamental physical processes that govern the behavior of the Sun and many other astrophysical objects remain elusive. The Sun provides the laboratory where crucial details of non-linear dynamics in a highly ionized magnetic plasma can be observed and understood; models can be tested and refined. Such models then can be extended to other astrophysical domains.

Magnetic Fields and Dynamical Processes in Astrophysics



(/node/318) *Top left: A radio map of the galactic center made with the NRAO Very Large Array indicates that the hot plasma structure is controlled by weak magnetic fields, as is the plasma in an erupting prominence (top right, HAO), which led to a coronal mass ejection. The spheromak experiment (bottom left, P plasma by magnetic fields in the laboratory shares similarities with the coronal case. Bottom right: A 3-D MHD simulation of a jet driven by magnetic twisting in an accreting black hole (M. Nakamura, Uchida Lab) exhibits phenomena that can be resolved on the Sun. (Click on the image for a larger version (/node/318) .)*

The field of solar physics has developed rapidly over the last decade to a point where sophisticated theories and models await critical observational tests. But existing instrumental capabilities no longer are sufficient to meet this challenge. The recent demonstration of a practical adaptive optics system, coupled with other advances in unique and powerful instrumental techniques, now promises a major advance in solar observing capabilities.

DKIST at a Glance

The Daniel K. Inouye Solar Telescope (DKIST) is a 4-m facility that will have broad impacts on astronomy, plasma physics, and solar-terrestrial relations by resolving fundamental astrophysical processes in space and time on the Sun. The DKIST will attack critical details of the non-linear dynamical processes that govern the highly conducting, turbulent solar plasma. The broad scientific questions are:

- How are cosmic magnetic fields generated and how are they destroyed?
- What role do cosmic magnetic fields play in the organization of plasma structures and the impulsive releases of energy seen ubiquitously in the universe?
- What are the mechanisms responsible for solar variability (that ultimately affects the Earth)?

The Sun provides a unique opportunity to probe cosmic magnetic fields with unprecedented resolution in space and time and to test theories of their generation, structure, and dynamics. Observational progress requires a solar telescope with:

- An angular resolution of 0.1 arcsec or better to resolve the pressure scale height and the photon mean free path
- A high photon flux at the critical spatial resolution for precise magnetic and velocity field measurements
- Access to a broad set of diagnostics, 0.3 to 35 mm

No other current or planned ground-based or space-based solar telescope meets these requirements. The following major advances in technology and instrumentation make it possible to realize the DKIST before the end of the coming decade:

- Functioning solar adaptive optics systems in the visible
- An open-air solar telescope that provides diffraction limited images
- Large-format infrared cameras

DKIST baseline parameters and their science drivers

Sensitivity: 4 meter photon collection aperture

- to study the ubiquitous weak magnetic field and test models of a turbulent dynamo in the upper convection zone
- to measure waves in magnetic flux tubes and test models of chromospheric and coronal heating
- to measure magnetic fields in the corona

Field of view: 5 arc minutes

- to test models of the eruption of flux that form active regions from the strong-field dynamo in the lower boundary layer of the convection zone
- to test models of large-scale coherent processes that lead to flares and coronal mass ejections
- to observe large-scale oscillations in prominences and compare with models

Wavelength range: 0.3 to 35 μm

- to observe the widest variety of diagnostic spectral lines and spectral regions to constrain atmospheric properties from the photosphere to the corona

Spatial resolution: >~ 0.1" using adaptive optics

- to resolve the photon mean free path and the pressure scale height in the photosphere
- to probe the IR signature of cool clouds in the chromosphere and test models of their radiative cooling

Polarization accuracy: 10^{-4} of intensity

- to precisely measure the magnetic field vector and test models of wave generation in magnetic flux tubes by the surrounding granulation

- to test models of extremely weak magnetic fields in the photosphere, chromosphere, and in prominences using the Hanle effect

Scattered light: <10% in sunspots, coronagraphic in thermal IR

- to test models of magneto-convection in the darkest parts of sunspots
- to measure properties of the coronal magnetic fields and test models of coronal heating

Location: best possible site in terms of seeing and sunshine hours

- to maximize the telescope performance and minimize the cost of adaptive optics

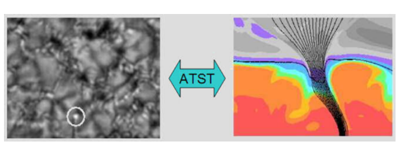
Why does solar physics need a large-aperture telescope?

The main driver for a large aperture is the need to spatially resolve the fundamental length scales in the solar atmosphere: the photon mean-free path and the pressure scale height. To resolve both fundamental length scales, a resolution of 70 km or 0.1 arcsec is required in the photosphere. In addition, simulations have shown that some magnetic structures might be as small as 35 km (0.05 arcsec) in cross section.

Current solar telescopes cannot resolve such scales because of their limited aperture. The near-infrared spectrum around 1.5 μm has many advantages, particularly for magnetic field studies; an aperture of 4 m is needed to clearly resolve features at 0.1 arcsec in the near infrared. Access to even longer wavelengths in the thermal infrared requires an open-air telescope design.

In addition to the diffraction limit, time resolution is also a major driver for a large aperture. The number of photons per angstrom per second is independent of aperture size at the diffraction limit. Photospheric structures can move with surface speeds of 7 km/s, so for 0.1 arcsec or smaller features one must collect photons for only a few seconds to avoid spatial smearing. Thus, the total number of available photons collected with diffraction-limited spatial resolution actually decreases with increasing aperture. To obtain the necessary signal-to-noise ratio at a given spatial resolution, the required aperture is larger than required by diffraction alone. An accurate measurement in the visible of the vector magnetic field at 0.1-arcsec resolution and 5-second integration time requires a 4-m aperture.

Flux tubes, the building blocks of stellar magnetic fields



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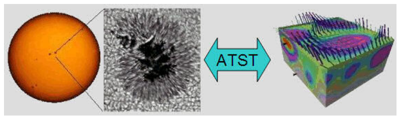
Observations have established that the photospheric magnetic field is organized in small fibrils or flux tubes. In these elemental structures, the magnetic field intensity is strong enough to control the local environment, but the flux tubes have a group behavior controlled by the photospheric convective patterns. Except for sunspots, these structures are mostly unresolved by current telescopes. Flux tubes are the most likely channels for transporting energy into the upper atmosphere, and thereby influence the solar irradiance. 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 other astrophysical situations such as the accretion disks of compact objects, or proto-planetary environments. Current solar telescopes cannot provide the required 0.05 arcsec resolution spectroscopy to explore these enigmatic structures.

Phase-diversity reconstruction of solar photosphere showing bright structures associated with magnetic fields (Paxman, Seldin, Keller, 1999); simulation of interaction between convection and flux tubes (O. Steiner). (Click on the image for a larger version (/node/319) .)

Interaction of magnetic fields and mass flows



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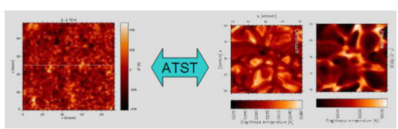
In sunspots, the total magnetic field is large enough to completely dominate the hydrodynamic behavior of the local gas, a regime very different from that of the rest of the solar atmosphere. To test numerical simulations of sunspots, 0.05 to 0.1-arcsec resolution vector polarimetry with low-scattering optics is required. The interaction of magnetic flux and mass flows is crucial for our understanding of the behavior of magnetic fields from the scales of planetary magnetospheres, to star forming regions, to supernova remnants, to clusters of galaxies. Sunspots allow us to test those theories in a regime where magnetic fields dominate mass flows.

Full-disk solar continuum image by NSO; sunspot at very high spatial resolution obtained with NSO Dunn Solar Telescope (T. Rimmele); simulation of convection in oblique magnetic fields (Hurlburt & Matthews 1997). (Click on the image for a larger version (/node/320) .)

Inhomogenous Stellar Upper Atmospheres



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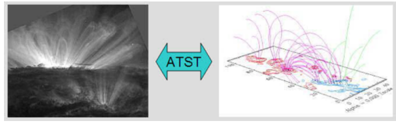
Measurements of CO absorption spectra near 4.7 µm show surprisingly cool clouds that appear to occupy much of the low chromosphere. Only a small fraction of the volume apparently is filled with hot gas, contrary to classical static models that exhibit a sharp temperature rise in those layers. The observed 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. Such observations would further explore the dynamical basis of the thermal bifurcation process, a fundamental source of atmospheric inhomogeneities in late type stars.

CO maps at 4.7 µm (Uitenbroek, Noyes & Rabin, 1994). 3-D radiative transfer through model of convective overshoot predicts cold clouds in the chromosphere (Uitenbroek 1999). (Click on the image for a larger version (/node/321) .)

Magnetic Fields and Stellar Coronae



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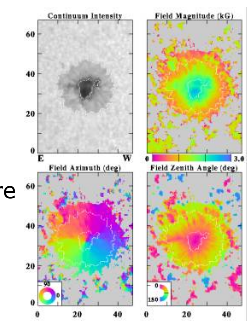
The origin and heating of the solar corona, and the coronae of late-type stars, are still mysteries. Most of the proposed scenarios are based on dynamic magnetic fields rooted at the 0.1-arcsec scale in the photosphere. However, none of the processes have been clearly identified by observations or theory. 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 interplanetary space and inspire geomagnetic disturbances. Using remote sensing techniques, it is feasible to measure coronal magnetic fields with a large telescope like the DKIST, particularly in the infrared where scattered light is more easily controlled.

Coronal loop as seen with TRACE (A.Title); extrapolated coronal magnetic field lines (Meudon Observatory). (Click on the image for a larger version.)

(/node/323) **Vector Polarimetry**



Precise measurement of the magnetic Stokes vectors needed to accurately deduce the solar vector magnetic field is a fundamental driver for a large-aperture solar telescope. For example, a typical magnetic measurement requires intensity measurements at 5 or more wavelength positions across a solar line. Photometry at a signal to noise ratio of 2000 (assuming an optimistic 10% instrument efficiency) requires at least 5 minutes at the diffraction limit (independent of aperture). Because solar magnetic features on the 0.1 arcsec scale evolve within 30s, we need an aperture of at least 3m to achieve a SNR within 30s at 0.1 arcsec resolution, and even larger to measure the smaller magnetic features which have been predicted by theory.

Data courtesy B. Lites and ASP team. (Click on the image for a larger version.)

Observational Characteristics

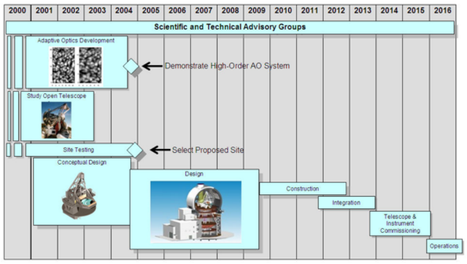
The science cases outlined above require a large-aperture (4 meter), open-air, all-reflecting telescope with adaptive optics. The DKIST will be designed to complement other existing and planned solar observatories on the ground and in space, and it will permit us to explore spatial, temporal, and spectral regimes unavailable to the other facilities. The DKIST will be sited at a location that offers superb seeing and clear weather for sustained periods of time.

- The large aperture and the adaptive optics provide the high spatial resolution needed to resolve elemental magnetic features and fine-scale plasma flows and jets.
- The large aperture provides a high photon flux that is critical for measuring the structure and dynamics of the ubiquitous magnetic fields, which play fundamental roles in solar activity and atmospheric heating. In spite of the proximity of the Sun, measurements using narrow spectral band-passes are "photon starved" in present-day solar telescopes.
- The large aperture and all-reflective design provide high-resolution access to the near and thermal infrared. This permits imaging of spatial and temporal inhomogeneities in the crucial layers connecting the plasma-dominated photosphere and the magnetic-dominated corona, allowing observers to trace the effects of magnetic foot point motions, and atmospheric waves,

as the energy propagates outward, heating the gas along the way.

Technology Roadmap

Design and implementation of the DKIST will be led by the National Solar Observatory in close collaboration with other centers and universities. Participation also will be sought from other interested US agencies, as well as from potential international partners. High-order adaptive optics, open-air telescope design, and site testing are critical technical issues for the DKIST. A scientific and technical advisory group will guide the overall process.



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Submitted by Ruth Kneale (/staff/rkneale) on 30 July 2015 - 3:52pm