

Revealing Fundamental Physics of the Sun with DKIST

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Summary: The Sun's atmosphere represents a unique testbed for deciphering fundamental plasma processes in regimes not accessible by laboratory experiments, as well as a template for a multitude of astrophysical settings. We here advocate that we will only enhance our understanding of this system through an integrative, data-driven approach that necessarily intertwines the interpretive power of state-of-the-art numerical simulations and the physical touchstone of cutting-edge, highly-resolved solar observations. The desired goal is a deep knowledge of how the solar atmosphere behaves across a range of temporal and spatial scales, and the ability to make projections about its dynamic behavior. From a broader perspective, these results will inform on very general phenomena such as magnetic reconnection, shocks, turbulence, multi-species plasmas, and, crucially, their interconnections. Such an approach well satisfies one of the overarching goals for NASA Heliophysics from the 2013 Decadal Survey, to "discover and characterize fundamental processes that occur both within the heliosphere and throughout the universe," while following the guiding principle, that "to make transformational scientific progress, the Sun, Earth, and heliosphere must be studied as a coupled system."

The 4-meter-diameter Daniel K. Inouye Solar Telescope ([DKIST](#); Rimmele *et al.*, 2020), funded by the National Science Foundation (NSF), will play a fundamental role in these efforts, as it has been designed to provide information on crucial, and yet poorly known, physical properties of the solar atmosphere such as the chromospheric and coronal magnetic fields. DKIST's early science goals, summarized in the Critical Science Plan [[Rast *et al.*, 2020](#)], are rich and far reaching, with significant discovery science. Looking forward, DKIST, will evolve as scientific questions and available technologies advance. It is anticipated to remain at the forefront of ground-based observational solar physics for the next three decades and will be essential to achieving a comprehensive view of the solar atmosphere. It will also be an integral partner with space-based missions in multi-messenger heliophysics enabling a holistic understanding of the heliosphere [[Martinez Pillet *et al.*, 2020](#)].

The solar atmosphere as a multi-scaled problem: The solar atmosphere, spanning from the convectively driven photosphere into the tenuous, magnetically dominated corona, is a complex environment permeated by a range of plasma processes on many scales. The steep density drop of 8–10 orders of magnitude and rapid temperature rise of 3 orders of magnitude through these regions leads to an intricate interplay of physical processes, including non-potential magnetic fields, partial ionization, 3-D radiative transfer effects and their temporal variations. These processes interconnect across atmospheric regions and multiple spatial scales, structuring and modulating the plasma behavior and dynamics.

Remote sensing observations with increasing diagnostic capacity are essential to characterize this puzzling environment. In the coming decades, the Inouye Solar Telescope will be the primary tool used to obtain detailed observations that reveal the intricacies of a complete stellar atmosphere. Employing a suite of complementary instruments, it will allow investigators to tailor measurement strategies (e.g. spectral feature, spatial resolution, cadence, polarimetric sensitivity, etc.) to their specific scientific goals. This will open new avenues for the study of the solar atmosphere on multiple scales, and provide new diagnostic tools to probe, in particular, the motions and magnetic configurations in the photosphere and chromosphere. The DKIST is expected to revolutionize even more profoundly the field of coronal physics, as it provides for the first time a coronagraphic facility of sufficient effective aperture to routinely measure the

tenuous coronal emission lines and their weak polarization signals at high spatial and temporal resolution, thereby paving the way for huge advances in coronal magnetometry. The achievable spatial resolution and fields of view span spatial scales from a few tens of kilometers to over one hundred thousand kilometers, allowing it to probe phenomena with sizes varying by several orders of magnitude. Processes acting on the small scales not only reveal fundamental physical mechanisms, such as energy release through reconnection or shocks, but also have significant influence and control on large-scale or even global processes like the creation of the solar wind [Cranmer & Winebarger 2019]. Studying such behavior provides the opportunity to address fundamental plasma processes in regimes not accessible by laboratory experiments, but which are typical of numerous astrophysical settings.

The importance of forward/numerical models: However, even the rich remote observations obtained by DKIST still require multiple approximations and inferences to interpret the observed intensities in terms of physical parameters of the radiating atmosphere. This is of particular relevance for the optically thick lines that form in the upper photosphere and chromosphere, for which non-equilibrium effects, level populations controlled by the 3D radiation field, quantum interferences, time-dependent ionization, and other complications can reveal details about the atmosphere, but only when interpretation is based on a precise understanding of the radiative processes. The optically thin nature of the corona on the other hand poses different challenges for the derivation of the coronal magnetic field, for example due to the superposition of contributions of multiple independent features along the line of sight. A major ongoing basic research task is how to determine vector magnetic fields throughout the solar atmosphere, with an eventual goal of producing routine 3D reconstructions spanning different plasma regimes.

Given these difficulties, numerical simulations provide a complementary approach to probe the underlying physical conditions in the solar atmosphere. This approach has been very successful for the case of the denser, lower photosphere, for which hydrodynamical simulations, started in the late 1980's and coming to full fruition in the mid 2000's, have been able to properly reproduce important details of the surface convection [Nordlund, Stein & Asplund, 2009], even though the larger scale, supergranular convection has yet to be fully understood or accurately reproduced. The inclusion of magnetic fields, ubiquitously detected at the solar surface, adds much complexity to the simulations through additional heating mechanisms and anisotropies. For example, state-of-the-art simulations of sunspots only form a penumbra when using artificial upper boundary conditions [Rempel, 2012], whereas observations show that penumbrae exist under a wide range of sunspot topologies. The challenges become ever more daunting within the rarefied upper atmosphere (chromosphere, transition region and corona), with its host of non-linear effects such as shocks and turbulence, multi-fluid and partially ionized regimes, and rapid spatio-temporal magnetic field variations. While many fundamental plasma processes are now starting to be understood in some regimes (e.g. collisionless plasmas, [Burch et al. 2016]), simulations have barely scratched the surface of the complex interplay between processes (e.g., reconnection and turbulence) and between spatial scales (kinetic to fluid). Addressing these complexities, common to a multitude of astrophysical settings (ISM, ionospheres, planetary magnetospheres, accretion disks, etc.) will require coupling of numerical codes that have for now been tailored to disparate plasma environments using different approximations.

Achieving the integrated view using data-driven techniques: It is not trivial to compare the outputs from these numerical experiments with direct observations of comparable solar structures. Those same radiative transfer complications that make the interpretation of spectral diagnostics so challenging still need to be addressed to properly forward model the expected emergent intensity from these physical models. Even then, the observations and simulations represent different realizations of the atmosphere, bedeviling most quantitative, non-statistical or

non-phenomenological comparisons. The broad category of *data assimilation* techniques, which can act as an alternative type of data inversion, offer a new and powerful approach for validating physical models against the observations [Bannister, 2017]. New "nowcasting" methods are being developed to allow the adjustment of the initial conditions of a simulation run in order to challenge the model fidelity by assessing its agreement with time-series observations. The ability to directly reproduce the solar behavior will provide confidence that the numerical models properly capture the essential physics at work in a given atmospheric system. Such approaches are however computationally expensive and there are challenges in matching model variables that may not be well sampled in the available observations. Augmenting these, deep learning techniques may allow neural networks to efficiently emulate simulations but development is needed to jointly quantify the errors in models, observations and reconstructions.

The 2050 desired state: As detailed above, the studies of the solar atmosphere require a multi-pronged attack, with the future decades bringing significant advances in observational and numerical capabilities. The time appears ripe to bring these different elements together more closely in a synergistic approach, with the goal of obtaining a clear model of how and why the solar atmosphere behaves the way it does. This understanding will only arise from the interplay between highly capable models and detailed observations. Simulations at active region scales, but with spatial grids comparable to DKIST resolution, including a wider range of physical processes, and spanning the full height of the solar atmosphere, will reach maturity over this period. Observations will provide both the starting conditions for such simulations as well as validation that the models capture the relevant physics that allow us to faithfully predict the atmospheric evolution. The DKIST is a crucial asset in this enterprise. Planned as a versatile and flexible facility, it is also amenable to continuous improvements and upgrades. A multi-conjugate adaptive optics system is already in development, to allow larger seeing-corrected fields of view. Second-generation instruments that capture additional spectral information, more quickly, over large fields of view are foreseen. Further out, instruments making use of new detector technologies and designed to exploit machine-learning-type analysis will continue to expand the diagnostic capabilities of the facility, allowing it to remain at the forefront of ground-based solar observations through 2050. As computing capacity, numerical modeling methods, and data interpretation techniques evolve significantly in the coming decades, it is fundamental to have ongoing access to state-of-the-art observations to properly validate and constrain the models. The key components that will be needed to fully realize this much richer state of understanding of our nearby star encompass the following:

- Derivation of the 3D and time-dependent structure of the magnetic field in the corona and chromosphere is fundamental to everything else, and will require interpretation of Zeeman and Hanle diagnostics accessible with advanced large aperture polarimetry;
- Development of multi-fluid, multi-species, numerical simulations, that model the transition from a collisionally dominated fluid to a collisionless plasma;
- Development of more realistic and efficient radiative transfer methods that enable robust feedback between observational and model-based determination of plasma properties throughout the solar atmosphere;
- Improved techniques for validation of numerical models based on observational inputs, including machine-learning (e.g. model emulation), data assimilation (e.g. nowcasting), or other statistical approaches;
- Access to computing resources, for analysis and inversion of large volumes of spectrally rich observations as well as multiple runs of complex, realistic numerical simulations;
- Development of new instrumentation and observing strategies guided by simulations through forward modeling and optimized to leverage advanced data analysis techniques.