Infrared Imaging Spectropolarimetry of the Solar Chromosphere and Corona with DKIST

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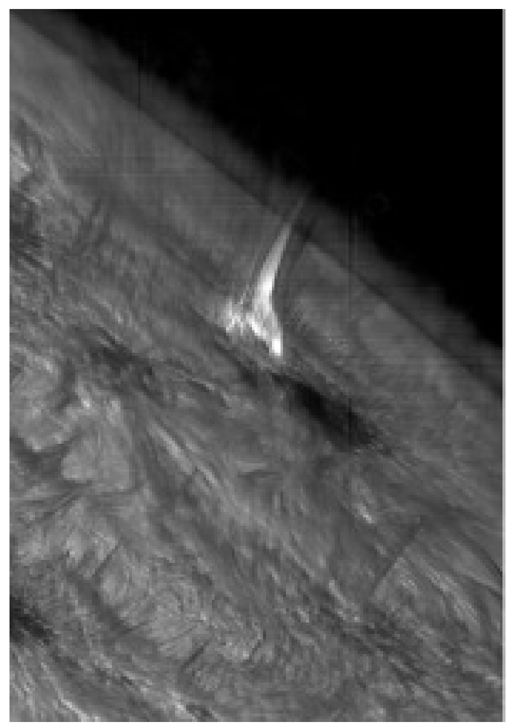
Synopsis

We describe how imaging spectro-polarimetry in the infrared (1-1.6 microns range) will be crucial for addressing several key science goals of the solar physics community: 1) *robust measurements of the chromospheric magnetic field* to aid in the modeling of the field extending into the corona and heliosphere; 2) *high-time-cadence measurements of the dynamics of the corona*; and 3) *direct measurements of the magnetic field of filaments* prior to and during eruptions to understand the field reconfiguration during such events as well as their geoeffectiveness.

These goals are best achieved by an instrument that obtains spatially contiguous images over an extended field of view in a tunable, spectrally resolved bandpass. Installed as a second-generation instrument on the Daniel K. Inouye Solar Telescope (DKIST), this Near Infrared Tunable Filter (NIRTF) will sample the solar atmosphere with sufficient signal to accurately record chromospheric and coronal line profiles, with a cadence suitable for studies of dynamic phenomena at the appropriate spatial scales. We discuss the functional advantages and conceptual underpinnings for such an approach, and note the heritage and ongoing technical developments that indicate the feasibility and limited risk of this instrument.



He I 10830 Å image
with BBSO/GST/NIRIS
(Cao+2012)

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Introduction

The strategic deployment of instrumentation that combines well-understood spectral diagnostics with mature observational capabilities will allow us to address many key questions on the structure of the solar atmosphere. We outline here such an instrument, designed to make advances in several key science topics but also flexible enough to allow for a broad range of investigations. *The innovative approach is to combine imaging spectropolarimetry, which has been an important tool for understanding the solar chromosphere in recent years, with unique and powerful spectral lines in the infrared.* This Near Infrared Tunable Filter (NIRTF) is proposed as a second-generation instrument on the Daniel K. Inouye Solar Telescope (DKIST), taking advantage of the increased collecting area and the low scattered light to *extend high resolution imaging spectroscopy to the solar corona for the first time*. We discuss below several of the key science targets to be addressed by this instrument.

Key Science Target #1: Chromospheric Magnetic Field Measurements

Magnetic field information in the whole (3D) atmospheric volume is necessary to investigate magnetic free energy variations and MHD instabilities, both crucial elements of active regions' evolution and flare development. While nonlinear force-free field (NLFFF) modeling has been used extensively, it is known that modeling based only on photospheric magnetic fields can be inconsistent with the force-free assumption. The measurement of chromospheric magnetic fields is necessary to resolve this issue, as discussed e.g. by Kawabata+2020 (Fig. 1), who quantify the underestimation of non-potentiality of the coronal fields when performing "classical" NLFFF extrapolation.

The He I 1083 nm line provides excellent diagnostics of the upper chromospheric velocity and magnetic fields, and *imaging polarimetric observations of the He I 1083 nm line with NIRTF will greatly improve our understanding of the 3D structure of magnetic fields in active regions*. An important capability of the NIRTF will be observations at a high temporal cadence of a large field-of-view (FOV; ~1.5 arcmin); this is necessary to trace the temporal evolution of the 3D field at the onset of a flare and capture the triggering of instabilities. We note that the Diffraction Limited Near-IR Spectropolarimeter (DL-NIRSP) on DKIST will also perform imaging spectropolarimetry with an integral field unit in this same spectral line; their FOV is however quite limited, and a large mosaic is needed to cover a typical active region area. Observations with NIRTF will provide chromospheric magnetic field maps covering a significant portion of an active region, to better investigate the connectivity and temporal evolution of the chromospheric magnetic field which, crucially, satisfy the force-free condition. Time-series of chromospheric magnetic field maps will be a powerful input into data-driven simulations.

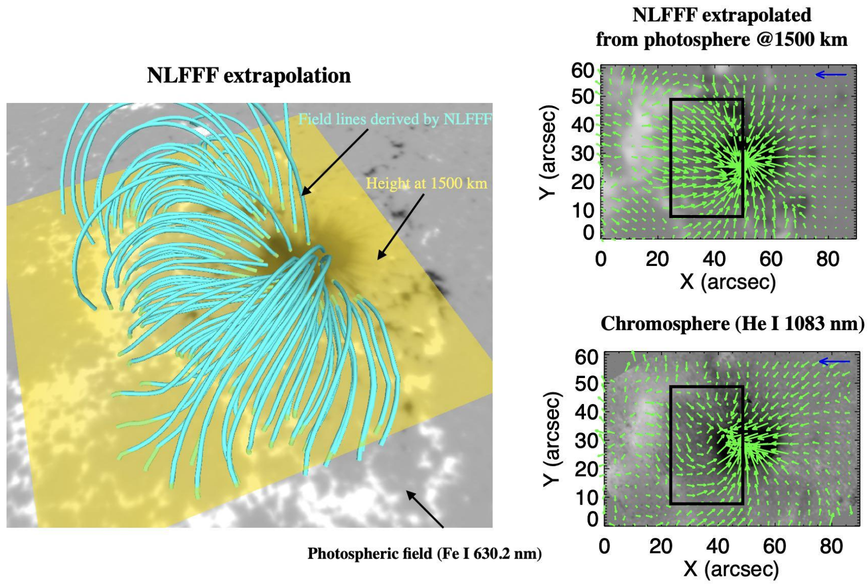

Figure 1: Comparison between chromospheric magnetic field derived from an NLFFF extrapolation and He I 1083 nm measurements. (*Left)* 3D view of the NLFFF extrapolation from photosphere. *(Right)* the chromospheric magnetic field derived from the NLFFF (upper) and He I 1083 nm (lower). Green arrows show the horizontal magnetic field.

Key Science Target #2: Spectral Imaging of Coronal Dynamics

The coronal imaging capabilities of SOHO/EIT, TRACE, SDO/AIA, and now Solar Orbiter/EUI have revealed the configuration and evolution of coronal loops, probing the role of waves and reconnection in both the quiescent and active corona. Because coronal loops are extended (and curved) and because flares, jets, and other explosive events are rapid but sporadically occurring, capturing large fields of view on short timescales is essential to understanding coronal dynamics and heating.

However, these EUV imagers use broadband filters that only measure integrated emission line intensities. Combining imaging with spectral diagnostics would allow line-of-sight velocities to be measured, giving a full 3D picture of the coronal motions. Further, combining measurements of the pair of FeXIII lines at 1074.7 and 1079.8 nm, it is possible to directly derive local densities in the plasma where these lines are emitted. These two lines will also be measured by DL-NIRSP, but the required mosaicking of the integral field unit may result in a relatively low sampling cadence for extended fields. The VELC instrument of the Indian ADITYA-L1 satellite will measure just the 1074.7 nm line, but using a single slit spectrograph and a relatively low cadence.

The NIRTF will provide imaging measurements with a top spatial resolution of ~0.2 arcsec and a sampling rate of approximately ten seconds to scan both Fe XIII line profiles over a field of 100x100 Mm^2 (or 0.15 $R_\odot$). This performance is comparable to that expected with NASA's Multi-Slit Solar Explorer (MUSE) mission, which also targets science goals that are only achievable with high-cadence coronal spectroscopy.

For example, NIRTF could image the plasma sheets that are predicted at the sites of energy release due to magnetic reconnection, sometimes appearing in limb flares (Fig. 2; Takasao+2012; Li+2018). Better information on the magnetic field, density, temperature, and velocity in these regions would allow us to quantify the energy release and physical plasma processes with fewer assumptions. *High-cadence imaging spectroscopy measurements will also be able to track and characterize Alfvén waves* *moving along coronal loops, which can then be used to derive the local magnetic field strengths and directions.* Imaging polarimetry of the coronal structures should also be possible with NIRTF, with the simplest case being the linear polarization due to scattering processes in the corona. The more challenging observation will be the direct measurement of the much weaker Zeeman splitting signal from the relatively weak coronal fields, which may require integration times of hundreds of seconds and reduced spatial resolution, but would allow the mapping of the coronal field topology as it evolves before and after flares or CME's, for example.

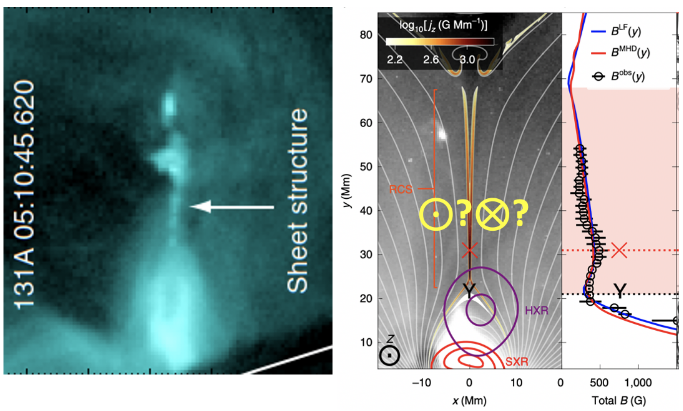

Figure 2: (*Left*) Plasma sheet structure seen in the extreme ultraviolet image associated with a limb flare (Takasao+2012). (*Right*) Example of estimation of the magnetic field strength along the plasma sheet based on microwave observation (Chen+2020).

Key Science Target #3: Filament and Prominence Characterization

Filaments and prominences are cool and dense plasma suspended by twisted magnetic fields in the solar corona (Fig. 3a). These filaments sometimes erupt due to drastic reconfiguration of the magnetic field (Fig. 3b) and produce coronal mass ejections (CMEs). Because the magnetic instability could happen either around the filament/prominence itself (e.g., the kink instability), or in the surrounding corona (e.g., the torus instability), we need to observe the temporal evolution of both structures to understand the eruption mechanism. Moreover, *monitoring the chromospheric and coronal magnetic field during a prominence eruption is critical for space weather effects*, as the amplitude of perturbations produced by a CME in the geomagnetic field strongly depends on the direction of the magnetic field accompanying the CME. DKIST is the most suitable telescope to study this science target, because diagnosing the direction in the line-of-sight component of the magnetic field requires a large number of photons to detect the weak Stokes-V signal produced through the Zeeman effect.

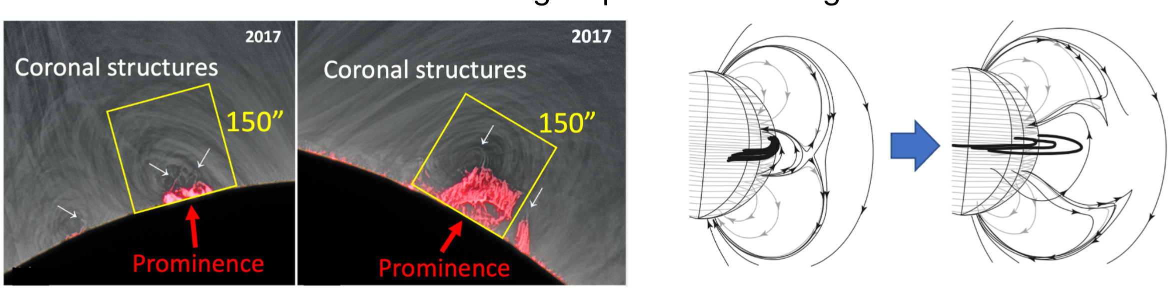

Figure 3: (a) Prominences and coronal images during total solar eclipse (Habbal+2021). (b) A possible mechanism explaining prominence eruptions (Antiochos+1999).

Advantages of Infrared Observations:

The science targets described above make use of the key diagnostic capabilities of the well-known He I 1083.0 nm chromospheric line, and the Fe XIII 1074.7 and 1079.8 nm coronal doublet. The 1000-1600 nm interval however includes many other valuable diagnostics: a- the *Fe I doublet at 1565 nm*, which allows the measurement of photospheric magnetic fields with increased sensitivity with respect to visible wavelengths; b- *several Hydrogen lines in the Paschen series* that are sensitive to the Zeeman and Stark effects, useful for measuring electric fields in the solar chromosphere (Anan+2014); c- the *Mn I 1526 nm line* whose hyperfine structure makes it extraordinarily sensitive to weak field strengths (e.g. Asensio Ramos+2009); d- *molecular bands* seen only in sunspot umbrae, which can be used to understand the structure and evolution of these cool regions (e.g., Berdyugina+2001; Afram+2007).

The reduced spatial resolution at near-infrared wavelengths is compensated by several advantageous properties that makes this interval well suited for high-quality observations on a regular basis: 1) Much *improved seeing stability* in the infrared. Combined with DKIST's Adaptive Optics (AO) system[1], NIR imaging spectroscopy will provide long sequences of stable and diffraction limited observations, allowing the retrieval of the temporal evolution of the solar magnetic field and plasma motions; 2) *reduced scattered light* from both the Earth's atmosphere and the telescope optics, allowing more routine and detailed observations of the solar corona; 3) *reduced instrumental polarization* that will ameliorate the cross-talk problem affecting low signal-to-noise observations such as linear polarization of weak magnetic fields.

Advantages of Tunable-Filter Imaging Spectroscopy:

Several high resolution, imaging spectropolarimeters based on tunable Fabry-Perot Interferometers (FPI) have been implemented over the past two decades (IBIS [Cavallini 2006]; CRISP [Scharmer 2006]; VIS [Yurchyshyn+2014]; NIRIS [Cao+2012]; CHROMIS [Scharmer+2017]). The availability of fast detectors, reliable adaptive optics systems, and post-facto image-reconstruction techniques have resulted in *diffraction-limited imaging over an extended field while maintaining high spectral discrimination*. Their potential has been best demonstrated in studies of the chromosphere, where the plasma structures are shaped by the 3D topology of the magnetic field, connecting distant locations (e.g. Vecchio+2007), and where rapid evolution of small features is often observed (e.g. the ubiquitous chromospheric spicules, Samanta+2019). Recently, NIRIS has shown how different parts of rapidly evolving chromospheric flare kernels display different spectral characteristics in the He I 10830 line, betraying sites of particles' impact (Xu+2022). No slit-based spectrographs can obtain data on such extended features at the necessary cadence. These instruments have also started to measure the elusive chromospheric magnetic field, in both the quiescent and flaring

[1] as well as with its under-development multi-conjugate AO system and the possible off-limb-AO, see the White Papers by Wöger+ 2022 and Schad+ 2022.

Sun (Kleint 2017; Leenaarts+2018), with even a serendipitous measurement of the coronal field strength attesting to their versatility (Kuridze+2019). Such studies are still hampered by low SNR, but the upcoming Visible Tunable Filter (VTF) for the DKIST (Schmidt+2016) promises to much improve the achievable polarimetric sensitivity.

Most of the instruments just mentioned work in the visible range and were not designed to include coronal capabilities. The tunable-filter approach for the corona has been applied at low spatial resolutions with the full-disk Coronal Multichannel Polarimeter (CoMP [Tomczyk+2008]), and its successor UCOMP (Tomczyk+2021), both based on tunable birefringent filters. Sampling only six points through the line profile, CoMP has observed intensities, velocities and scattering polarization in the Fe XIII lines at 1074.7 and 1079.8 nm and demonstrated how an imaging instrument can provide unique information on coronal dynamics (Tomczyk+2007), magnetic fields (Yang+2020), and even flare physics (French+2019). Some of the same analysis methods can be applied to NIRTF observations, which will have higher resolution and polarimetric sensitivity albeit with a much smaller field of view.

Requirements:

For on-disk observations of the photosphere and the chromosphere, the spatial resolution needs to be better than 0.1 arcsec to resolve the individual magnetic elements and fibrils. At the same time, the field-of-view (FOV) should be larger than 1 arcminute (goal: 1.5 arcmin) to cover a typical active region. This in turn indicates the need for a detector with at least 2k x 2k pixels. In order to achieve high spatial resolution across the field of view, we expect to apply post-processing image restoration techniques to on-disk observations (Wöger+2008; van Noort+2005). This will require individual exposure times less than 0.1 sec and a detector capable of frame rates of 10-30 frames per second.

Item	Requirements
Spatial resolution and FOV	For the photosphere and the chromosphere • 0.1” resolution with FOV > 60” (to cover super-granulation and a sunspot) For the off-limb corona and a prominence • 0.5” resolution with FOV > 150” (to trace MHD wave propagation)
Scanning time & temporal resolution	<10 sec for spectroscopy <1 min for spectro-polarimetry
Spectral coverage	1000 nm to 1600 nm • Fe I 1564 nm (Photosphere V and B [Zeeman]) • He I 1083 nm (Chromosphere V and B [Zeeman+Hanle]) • H I 1020 nm (P7) /1094 nm (P6) (Chromosphere V, B, and E [Zeeman+Stark]) • Fe XIII 1074.7/1079.8 nm (Corona V, ρ, and B [Zeeman+Hanle])
Spectral resolution	• $\lambda/\Delta\lambda_{FWHM}$ > 100,000 for the photosphere and the chromosphere • $\lambda/\Delta\lambda_{FWHM}$ > 10,000 for the corona
Spectral scan range	Cover spectral line widths • >0.5 nm needed for the corona • >0.3 nm for the photosphere and the chromosphere

For off-limb observations of the solar corona and prominence, we need to cover coronal eruptions and propagation of MHD waves along field lines. According to past observations, the correlation length of propagating Alfven waves was 40-100 Mm (Tomczyk+2007), so we will need a FOV $\gtrsim$2 arcmin (~ 90 Mm) and enough resolution to resolve the dynamics. In particular, propagating Alfven waves require a temporal resolution better than 30 sec. The spatial resolution requirements are lower because these waves are coherent over transverse scales of ~1000 km (1.5 arcsec). The minimum spectral range for the instrument is from 1000–1600 nm. This covers a wide array of interesting diagnostics, as detailed above. The requirement to the instrument is to have a spectral resolution sufficient to fully resolve the spectral profiles and enough free spectral range to detect velocities on the order of 100 km/sec in the corona.

Instrumental Concepts:

Based on the above science targets and resulting requirements, the most suitable approach to provide the necessary high throughput and high cadence over an extended FOV is an imaging-spectropolarimeter based on a narrow-band tunable filter.

There are two main methods to achieve a tunable filter with sufficiently narrow spectral passband: Fabry-Perot interferometers (FPI) and Lyot filters. A FPI is based on the interference of light in a cavity between two parallel reflecting surfaces. Its transmission wavelength can be tuned by changing the separation between the two air-gapped reflecting surfaces (e.g. IBIS, CRISP, etc.) or by electrically changing the refractive index of a crystal plate (solid state etalon, e.g. SMART, Nagata+2014, or SO/PHI, Solanki+2020). To achieve the high spectral resolution needed for photospheric and chromospheric lines, often two FPI are used in series. The Lyot filter consists of a stack of birefringent crystals and linear polarizers and waveplates, whose transmission wavelength can be tuned by using active birefringent retarders, such as liquid crystals (e.g. CoMP, Tomczyk+2008, or SDDI, Ichimoto+2017). Because of the different trade-offs in terms of the spectral resolution and range, throughput, wavelength tuning speed, and achievable fields of view, the selection of the filter type will be clarified in the instrument design phase based on the finalized requirements. For observations of the faint coronal lines, tradeoffs will be made in both spatial (reduced to 0.5", 25x increased flux) and temporal resolution (1-5 seconds per wavelength position, factor of 1000). In addition, because of the larger widths of the coronal lines (~0.2 nm FWHM for the Fe XIII lines), a lower spectral resolution is allowable (5-10 times increase in throughput), which could be implemented through an automated adjustment of the tunable filter bandpass (e.g. removal of one of the two FPI).

Much ongoing development of tunable filter components and instrument design considerations (e.g. Bailén+2020, 2021) provides a strong heritage for such an instrument, and indicates that there are not significant technological hurdles preventing a timely and successful development. Groups involved with this whitepaper have been working with several prototypes. Two tunable Lyot filters (Φ32 and 40mm) using liquid crystal variable retarder have been developed in Hida observatory since 2014, covering a wavelength interval of 500-1100 nm (Hagino+2014). Studies on a design covering the spectral range of NIRTF are in progress. Two paired lithium-niobate FPI etalons of 70 mm aperture have been fabricated by a Japanese optical company (Kogaku Giken), optimized in ordinary ray transmission for both He I 1083 nm and Fe I 1564.85 nm lines. The etalons are Y-cut lithium-niobate wafers coated with highly reflective and conductive (ITO) layers covering all the lines of interest. Studies using these prototypes (Suematsu+2022) have identified the means to improve optical and imaging quality of such etalons for an application to DKIST. For air-spaced FPI, development work has been undertaken with IC Optical Systems to validate a new symmetric design for large aperture plates (Φ150 mm) that minimizes mounting and gravity distortions. Tests have shown good performance and indicate the scalability to the marginally larger apertures necessary for NIRTF (Greco+2019, 2022).

Finally, work on an off-limb adaptive optics (AO) system to provide seeing-stabilized observations of prominences and coronal loops, has been proceeding as an NSF funded joint project between Big Bear Solar Observatory (BBSO) and the National Solar Observatory (NSO). Initial on-sky tests, with an 18-sub-aperture Shack-Hartmann wavefront sensor (WFS) and a single deformable mirror with over 250 sub-apertures, have revealed exciting and promising results in improving the off-limb image quality.

Development Cost and Timelines:

The development of an infrared tunable filter as described above would be suitable as a project for a second-generation instrument for DKIST. Its capabilities will address key science targets while providing sufficient flexibility in operational choices to allow PI-driven, discovery science on a broad range of topics.

The significant heritage of previous instruments and design work reduces risks and the need for extensive new technical studies. The ongoing evaluation of various tunable filter technologies will allow the choice of the most suitable approach to be made early on in the project. DKIST is in the process of procuring new large-format infrared detectors and it is expected that NIRTF could acquire the same model, which will lower development costs and risk. An off-limb AO system envisioned for DKIST would help improve NIRTF performance (see WP by Schad+2022). Tests of individual components or observing techniques could be undertaken at BBSO. Altogether, these efforts will reduce the development timelines, allowing the instrument to go from design phase to deployment at DKIST in approximately five years.

A full cost analysis of the instrument has not been performed, but relies on the experience with previous DKIST instruments and other large facilities. When considering the fully-costed manpower needed to develop the optical, mechanical, and software components of the system, the cost for such an instrument is expected to be in the range of 6-10 M$, depending on selected technical solutions. This falls into the scope of what might be funded in the NSF's Mid-Scale Innovations Program in Astronomical Sciences (MSIP). Contributions from international partners might also be a significant funding source for the project.

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