DKIST coronal diagnostics during early operations

Advancing high spatial/spectral resolution remote sensing of the off-limb solar corona and opening a new era in diagnostics of the coronal magnetic field.

Cryo-NIRSP Spectrograph

Fe XIII λ10747 ; Log(T) ~ 6.22
Fe XIII λ10797 ; Log(T) ~ 6.22
He I λ10830 ; Log(T) ~ 4*
Si X λ14300 ; Log(T) ~ 6.13
Si IX λ39350 ; Log(T) ~ 6.04

Cryo-NIRSP Context Imager

Fe XIII λ10747 ; Log(T) ~ 6.22
He I λ10830 ; Log(T) ~ 4*
Si IX λ39340 ; Log(T) ~ 6.04

DL-NIRSP Spectrograph

Fe XI λ7892 ; Log(T) ~ 6.13
Fe XIII λ10747 ; Log(T) ~ 6.22
Fe XIII λ10797 ; Log(T) ~ 6.22
He I λ10830 ; Log(T) ~ 4*
Si X λ14300 ; Log(T) ~ 6.13

VBI Imaging

Fe XI λ7892 ; Log(T) ~ 6.13

VISP Spectrograph

Various lines: 380 to 900 nm

Topics:
1. Polarized visible/IR line formation in the corona
2. Techniques for extracting useful diagnostics
3. Background-limited measurements at DKIST
4. Useful Resources

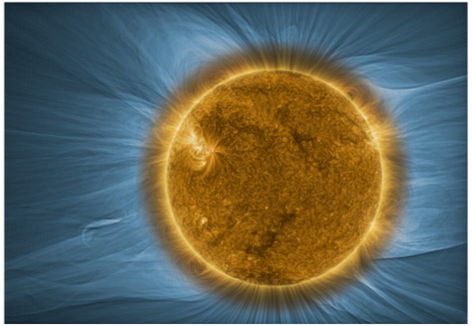
1. Polarized visible/IR line formation in the corona

- VIS/IR coronal spectral lines (unlike EUV lines) are both collisionally and radiatively excited.

- I_{coll} depends on n_e^2 ; I_{rad} depends on n_e (similar to Thompson scattered continuum). *Morphological structures seen in eclipse photos also expected in VIS/IR spectral intensity maps.*

- Spectral line analyses must include radiative component correction unless completely collisionally dominated.

- *Optically-thin.* Same line-of-sight integration challenges as in EUV.



Landi, Habbal, Tomczyk (2016); Image credit: Karen Teramura

1. Polarized visible/IR line formation in the corona

- VIS/IR coronal lines are typically magnetic-dipole (M1) transitions with polarization generated via:
  - Optical pumping effect of the incident radiation (i.e. scattering/atomic-level polarization)
  - The Zeeman Effect.

- Zeeman splitting increases as λ^2 → *major driver of infrared coronal observations*!
  - Low field strengths of corona make transverse Zeeman effect too weak.

- Atomic-level polarization is modified by both the ***Hanle Effect*** and ***Collisional Depolarization.***

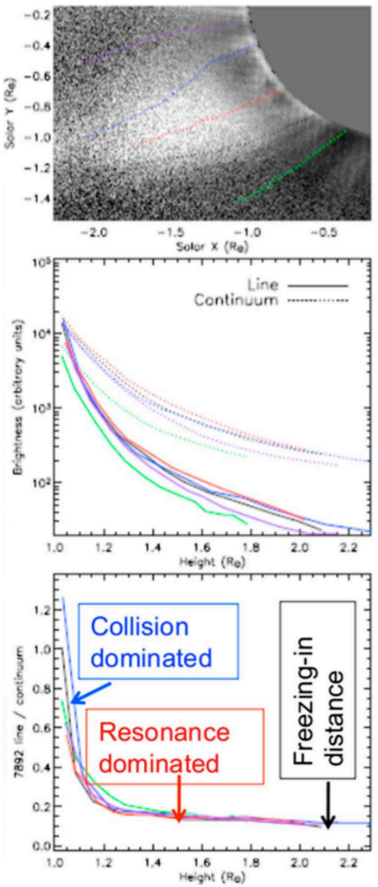
Resulting polarized sensitivities:

- Circular polarization of spectral lines is sensitive to *longitudinal magnetic flux*.
- Linear polarization direction only sensitive to *magnetic azimuth in plane-of-sky*.
- Amplitudes of both circular and linear polarization dependent upon degree of atomic-level polarization, which needs multiple lines to constrain or atomic polarization modeling.
- Linear polarization direction is subject to ambiguities (180^o and Van-Vleck) as well as the associated null points.

2. Techniques for extracting useful diagnostics

Integrated quantities and radial dependencies:
[see Landi, Habbal, & Tomcyzk 2016; Del Zanna & DeLuca 2017]

a) **<u>Electron density</u>** as function of radial distance can be related to continuum-polarized brightness
   i) DKIST Data → CN or DL full Stokes spectra with source separation.
b) **<u>Plasma DEM, Φ(T)</u>** constrained by VIS/IR lines using EUV analysis techniques when collisionally dominated and coordinated with EUV diagnostics.
   i) DKIST Data → CN or DL-NIRSP intensity (or full Stokes) spectra.
c) **<u>Elemental abundances</u>** can be derived from line ratio of two charge states from same ion in radiatively dominated regime. Good for FIP analysis, for example.
   i) DKIST Data → Candidate observation: Si X 1430 nm and Si IX 3935 nm.
d) **<u>Electron density</u>** derived from line ratio of different transition of same ion with same charge state.
   i) DKIST Data → Sequential maps in Fe XIII line pair at 1074 nm and 1080 nm.
e) **<u>Excitation mechanisms</u>**: Ratio of line to continuum intensity (or continuum-polarized brightness) discriminates collisionally and radiatively dominated regimes.
   i) DKIST Data → CN or DL-NIRSP intensity (or full Stokes) spectra with background source separation.
f) **<u>Integrated longitudinal magnetic flux</u>:** Stokes V observation in M1 line proportional to longitudinal magnetic flux.
   i) DKIST Data → CN or DL-NIRSP full Stokes spectra
g) **<u>Non-thermal line broadening</u>**



2. Techniques for extracting useful diagnostics

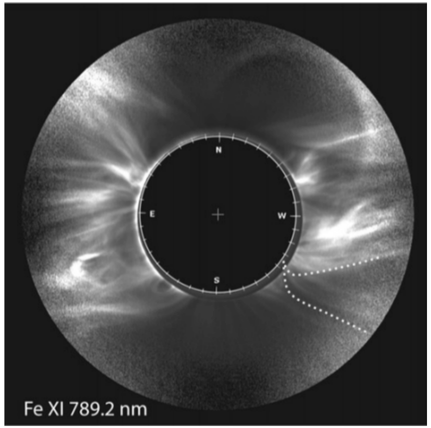
Local structure morphology, dynamics, and single-point inversions
[see, e.g., Habbal et al. 2011; Judge, Habbal,& Landi 2013; Tomczyk et al. 2007]

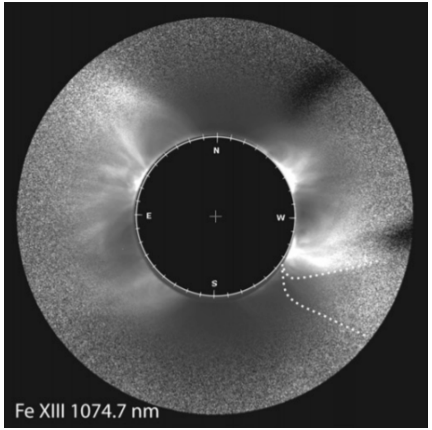
a) **Temperature distribution/morphology**: Maps of spectral line intensity in different diagnostics provide thermal tomographic imaging.
   i) DKIST Data → CN or DL-NIRSP Stokes I spectral maps, CN context images, VBI 789.2 nm images.

b) **Doppler and translational velocities of eruptions**: Simultaneous imaging with spectral scans (or fast narrow FOV scans) give 3D velocity of eruptive events.
   i) DKIST Data → CN or DL-NIRSP Stokes I data cubes with CN or VBI imaging.

c) **Doppler shift oscillations and wave propagation**: Alfvenic and MHD modes have been observed in VIS/IR lines. Slit alignment along structures or 2D coverage provided by DL-NIRSP give chance to measure propagation speed/direction.
   i) DKIST Data → CN slit or DL-NIRSP IFU Stokes I spectral data time series

d) **Single-point inversion of coronal magnetic field:** Isolated structures identified in Stokes I maps suggest use of single-point magnetic field inversions [see Judge, Habbal,& Landi 2013 and Plowman 2014]
   i) DKIST Data → CN or DL-NIRSP Full Stokes mapped data cubes





Habbal et al. 2011

2. Techniques for extracting useful diagnostics

Forward model comparisons using synthesized observables.
[Gibson et al. Frontiers, 2016; Gibson et al. 2017; Dalmasse et al. 2016]

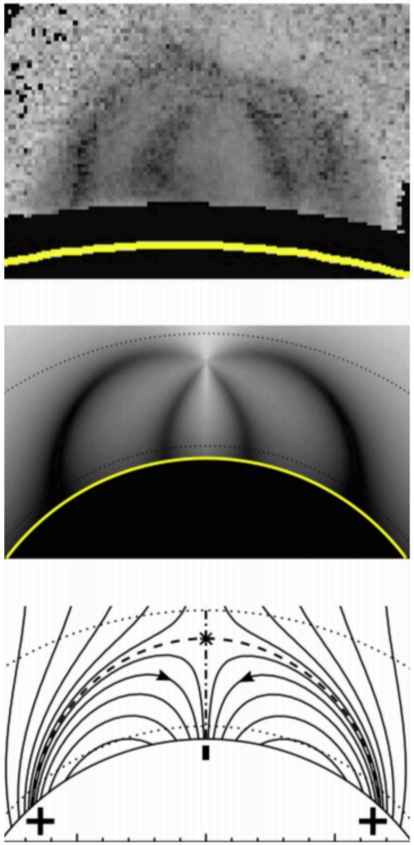
VIS/IR polarization diagnostics of the corona constrain numerical models of the 3D magnetic field. New magnetically sensitive observables that can be used to validating numerical models include

a) **Integrated linear polarization amplitude**
b) **Linear polarization direction in plane-of-sky**
c) **Integrated circular polarization amplitude**

DKIST Data → CN or DL Full Stokes spectral data cubes in multiple spectral lines.

It’s critical to include DKIST spectropolarimetric data as the primary magnetic model constraint within a range of coordinated EUV and VIS/IR observations.

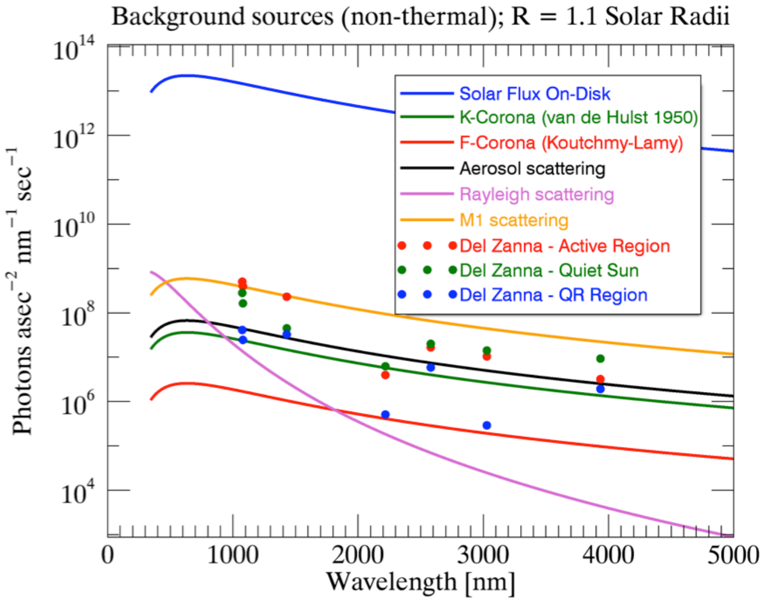
Model-data fitting (i.e. inversions) techniques are in their infancy for coronal magnetometry. (see Dalmasse et al. 2016).



Gibson et al. 2017

3. Background-limited measurements at DKIST.

- Sensitivity of coronal measurements at DKIST are limited by background radiant sources.
- Line intensities are ≲ 10^{-5} of the disk intensity; and the degrees of linear and circular polarization are a few-10% and ~ 10^{-4} of line signal, respectively.



Thermal radiation background not included in this Figure.

Modeled line radiances from Del Zanna & DeLuca (2017)

Mirror scattering and sky conditions are the major limitations.

Primary mirror (M1) scattering is determined by mirror microroughness and *dust accumulation.* Figure assumes mirror has been *cleaned/washed* within 1 day of observation.

Occulters at prime focus and gregorian focus limit illumination of downstream optics. *Lyot stop* rejects diffraction ring of primary.

4. Useful Resources

References:

- Casini, R., White, S.M., Judge, P.G. (2017) *Magnetic Diagnostics of the Solar Corona: Synthesizing Optical and Radio Techniques*. Space Sci Rev,210, 145
- Del Zanna, G., & DeLuca, E. (2017) *Solar coronal lines in the visible and infrared. A rough guide.* ARXIV.
- Gibson, S. E., Rachmeler, L. A., White, S. M., eds. (2017). Coronal Magnetometry. Lausanne: Frontiers Media. doi: 10.3389/978-2-88945-220-0
- Judge, P.G., Habbal, S., Landi, E. (2013) *From Forbidden Coronal Lines to Meaninggul Coronal Magnetic Fields.* Solar Physics, 288, 267.
- Landi, E., Habbal, S.R., Tomczyk, S. (2016) *Coronal Plasma Diagnostics from Ground-Based Observations*. J. Geophys. Res. Space Physics, 121, 8237

Spectral line synthesis:

- Chianti v8 (http://www.chiantidatabase.org/)

Multiwavelength Coronal Forward Synthesis

- FORWARD (https://www2.hao.ucar.edu/modeling/FORWARD-home) [Gibson et al. 2016]