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SYNOPSIS: Novel fundamental constraints on coronal magnetism are available through high resolution coronal spectropolarimetry at visible and infrared (IR) wavelengths. We advocate for investments in **the highest resolution spectropolarimetric methods** at large-aperture coronagraphic facilities. We identify necessary instrumentation development pathways including the need for **off-limb solar adaptive optics**, which could be supported by technologies such as (or similar to) the proposed **ORCAS** mission, *i.e.* the **Orbiting Configurable Artificial Star Mission Architecture**.

CONTEXT OVERVIEW: Coronal loops are often considered building blocks of the solar coronal magnetic field. Despite the wealth of understanding gained from simple 1D models, a paradigm shift has occurred in recent years that demands increased understanding of these apparent structures as 3D features embedded in an inhomogeneously-excited continuous magnetic field. Current observational techniques, however, face many challenges. One example is the limited 3D perspective gained by remote imaging, which even stereoscopic methods do not always remedy. In this white paper, we identify spectropolarimetry of forbidden and permitted coronal spectral lines at optical and IR wavelengths as a promising method to gain insight into the 3D nature of apparent coronal loops. Utilizing these methods has previously been hindered by the lack of large-aperture coronagraphic facilities. The recently-commissioned, **National Science Foundation's Daniel K. Inouye Solar Telescope (DKIST)** solves this issue for the upcoming decade and provides a vehicle for realizing the techniques discussed here. However, investments are still necessary in the coming decade to advance these observations to the spatial and temporal scales required to address the fundamental physics of coronal magnetic fields and their loop-like manifestations.

1. Science Motivation: *Coronal Fine Structure Heating - Loops or Veils?*

The active corona is finely structured by apparent curvilinear loops (Figure 1) that have captured the intrigue of solar physics for many decades [2]. Acting as tracers of the coronal magnetic field lines, the plasma that is presumed to be confined along these apparent narrow loops offers key insight into significant open questions in solar plasma physics, i.e., *What governs the fundamental structure, composition, and evolution of the solar corona?* and *How are the corona and solar wind heated and accelerated?* The distribution of loop features, their physical parameters, and their relationship to the solar magnetic field offer fundamental constraints on coronal heating mechanisms, especially as judged through simple parameterizations of a one-dimensional coronal heating function that treat apparent loops as 1D objects [3, 4, 5, 6].

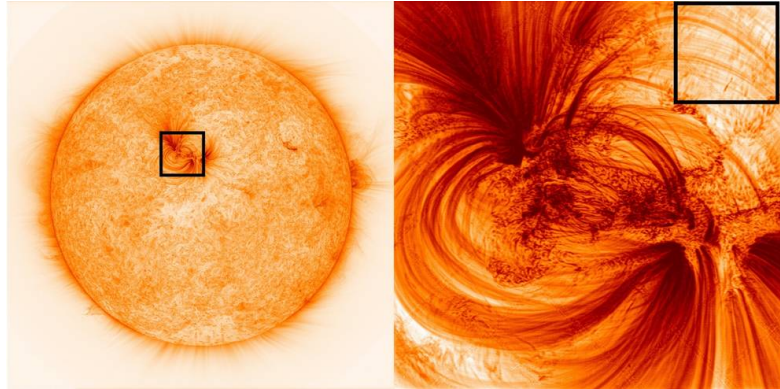


Figure 1: NASA's *High-resolution Coronal Imager 2.1* images showing coronal strand widths near 0.1 Mm ($\approx 0.14''$ from Earth) NASA [MSFC]/UCLAN/SAO. Reference: [1]

On the other hand, the apparent coronal loops may be beguilingly too easy to interpret as simple 1D curvilinear features. There are many observed features of loops that remain difficult to understand [7]; for example, their near uniform cross-sectional width as a function of height. Furthermore, the data analysis techniques involved often lend to biases and uncertainties, many of which derive from the limited ability to isolate the feature from the foreground and background emission [8]. The addition of stereoscopic imaging via the NASA/STEREO mission has improved loop identification; however, due to the optically thin nature of the corona, multi-vantage point observations still suffer interpretative ambiguities [9]. Moreover, many of the key parameters remain unmeasured, in particular the magnetic field intensity along the coronal loop [4, 6].

Treating the corona more realistically as a continuous 3D medium is now being achieved via high resolution radiative MHD models [10]. One recent work has advanced an interesting concept suggesting coronal loops are projections of highly corrugated 3D structures [7]. Calling this the ‘coronal veil’, loops appear due to the spatial warping of excited regions in the magneto-plasma that overlap along the line-of-sight, just as ripples in a lace curtain create apparent parallel structures in projection. Such an interpretation seems more in line with the continuous nature of the magnetic field; however, an observational dilemma subsequently arises as these two interpretations (and various intermediate hypotheses) do not offer an easy means for discriminating when and where they act in the real corona.

In this white paper, we identify spectropolarimetry of forbidden and permitted coronal spectral lines at optical and IR wavelengths as a promising method for gaining insight into the 3D nature of apparent coronal loops. These methods potentially aid in resolving two of the above issues, namely measuring the magnetic field along coronal loops and distinguishing between the 1D and veil hypotheses. Below we discuss these techniques in Section 2. Section 3 then identifies supporting instrumentation development pathways and then further discusses the need and promise of coronal/off-limb solar adaptive optics in the next decade.

2. Proposed Techniques: *Off-limb visible/IR polarimetry at frontier spatial resolution*

Spectropolarimetry of the off-limb solar corona offer unique diagnostics complementing those available from filter-based imaging and spectroscopy, which are the established methods for observational coronal physics at XUV wavelengths [11]. In this section, we discuss the value of these diagnostics at yet-to-be-achieved spatial resolution. At visible and IR wavelengths, line and continuum polarization is induced and modified by magnetized scattering, the Hanle Effect, and the Zeeman Effect [12]. Whereas XUV line excitation is governed largely by temperature-dependent ionization and collisional excitation, visible/IR lines are significantly photo-excited, which leads to an interplay of scattering-induced linear polarization and collisional depolarization for *forbidden* lines. Meanwhile, the Hanle Effect (in particular for *permitted* lines) and the Zeeman Effect, which is more readily measured at IR wavelengths, offer sensitivity to the magnetic field topology and intensity unlike most XUV lines [13, 14].

2.1. *Forbidden Coronal Emission Spectropolarimetry of Coronal Loops*

Polarimetric observations of forbidden coronal emission lines have significantly advanced in the last decade. The High Altitude Observatory's UCOMP¹ instrument, for example, synoptically observes linearly polarized lines (Figure 2) and their transverse oscillations, which in turn help infer some of the 3D magnetic field properties of the global corona [15, 16, 17, 18]. However, linearly polarized diagnostics, importantly, do not yield magnetic flux determinations. While a few circular polarized observations of the flux-sensitive Zeeman Effect exist [19], the demanding signal-to-noise requirements have long been an impediment, which in part motivated the construction of the National Science Foundation's Daniel K. Inouye Solar Telescope (DKIST)[20] and further motivates the construction of the COronal Solar Magnetism Observatory (COSMO) (see associated white papers [21]).

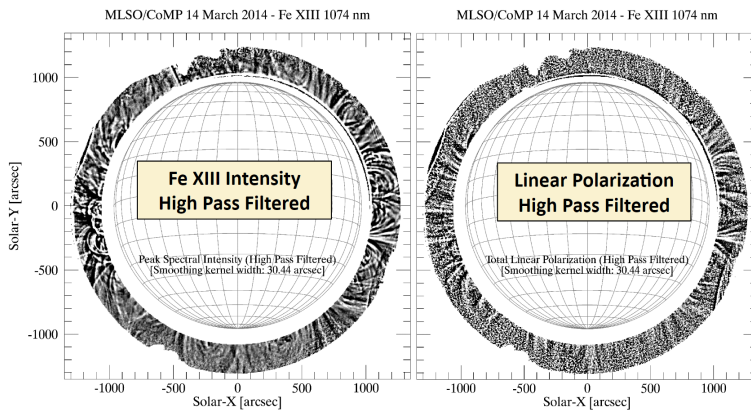


Figure 2: Coronagraphic HAO/COMP observations of the Fe XIII 1074.7 nm line and its linear polarization acquired from the Mauna Loa Solar Observatory. These images have been high-pass filtered to enhance loop features.

tion, loops are apparent (Figure 2) but not spatially resolved, especially in comparison to Hi-C (Figure 1). Meanwhile, the DKIST diffraction limit at 1075 nm is $0.07''$, roughly 2x better than Hi-C. However, DKIST coronagraphy currently cannot reach this resolution due to atmospheric

DKIST brings forth a new era for coronal spectropolarimetry. It provides coronagraphic observations with an unobscured 4 meter aperture, thereby collecting 400 times more light than the 20 cm COMP/UCOMP telescope. In comparison to UCOMP, which samples the corona with $3''$ pixels, DKIST's coronal instrumentation nominally targets $0.5''$ samples, for which DKIST theoretically provides $\sim 11\times$ more light than UCOMP. At COMP's resolution,

¹Prior to its 2021 upgrade, UCOMP was referred to as COMP for the *Coronal Multichannel Polarimeter*

seeing and the lack of coronal adaptive optics. DKIST does uniquely provide limb-tracking for near-limb occulting, but this only provides image stabilization along one axis. With this capability, however, the pursuit of high resolution polarimetric observation at seeing-limited scales ($\sim 1''$) is underway using DKIST. One aim includes refining estimates for the non-thermal energy flux of upward propagating waves, which suffers from superposition along the line-of-sight and coarse spatial resolution [22]. Here, though, we recognize the additional and critical value that forbidden line polarimetry could provide at even smaller scales.

As discussed, resolving the true nature of coronal fine structure—whether it be loops, veils, or some combination—is currently challenging. No doubt, high cadence EUV spectroscopy at sub-arcsecond scales, as expected from the Multi-Slit Solar Explorer (MUSE) [23] and the Solar-C (EUVST) mission [24], will lend to key advances. Meanwhile, independent or contemporaneous forbidden line polarized observations at high spatial resolution provide unique constraints on coronal fine structure while also offering magnetic field diagnostics otherwise unattainable.

In Figure 3, a simple toy model is used to illustrate one of the advantages of high resolution measurements, in particular of the linear polarization. Due to the interplay of scattering-induced linear polarization and collisional depolarization, the linearly polarized emissivity can non-linearly deviate from the total intensity emissivity point-to-point, as these are differentially sensitive to density perturbations. On the left, a simple, circular cross-section structure of a single temperature and density displays an integrated “observed” profile (bottom panel) that matches in total emission and linear polarized emission. Meanwhile, for a more complex structure with gradients in density and/or pressure (right column panels in Figure 3), these integrated profiles show spatially separated peak locations that denote complex structuring along and transverse to the line-of-sight, and discount the simple interpretation of the peak in the intensity profile as an isolated loop.

This argument continues along lines similarly advanced by the ‘coronal veil’ hypothesis [7], which using simulated intensity observables demonstrated that apparent loop-like features need not be directly associated with isolated features of the corona. In Figure 4, we show comparable forward synthesized polarized observations through an advanced coronal 3D radiative MHD model [10, 25]. As in our toy model, we highlight that the apparent structures visible in the different polarized states do not always spatially match, as previously reported (see Figure 20 in [25]). Instead, the structures arise from complex contributions along the line-of-sight, as in the veil hypothesis. ***The important point here is that a single forbidden line polarized observation provides strong diagnostic potential for discerning between***

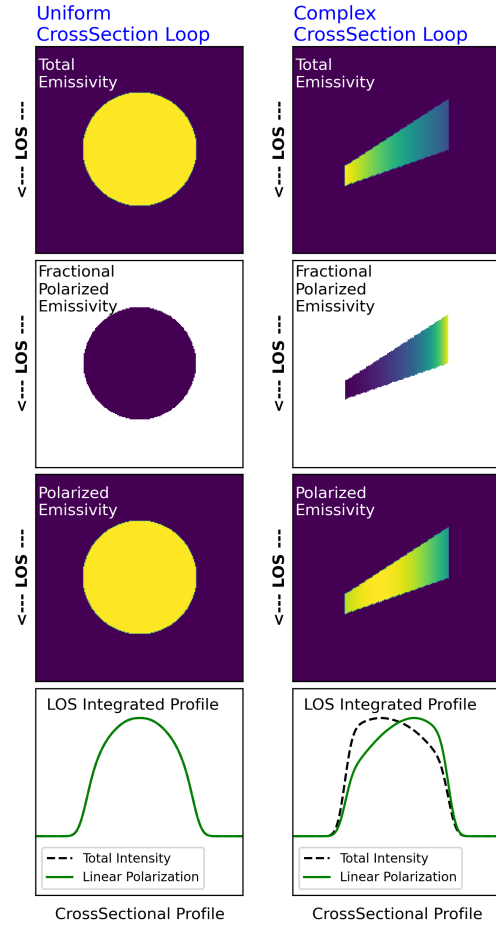


Figure 3: A simple illustration of how polarized measurements can help distinguish between simple and complex coronal density structures. Color scales are relative and proportionally increase in brightness relative to the quantity illustrated.

the veil and loop hypothesis. However, this require yet-to-be-achieved high spatial resolution observations with high polarimetric sensitivity, i.e. on order of the same sensitivity as needed for a Stokes V detection as targeted by DKIST.

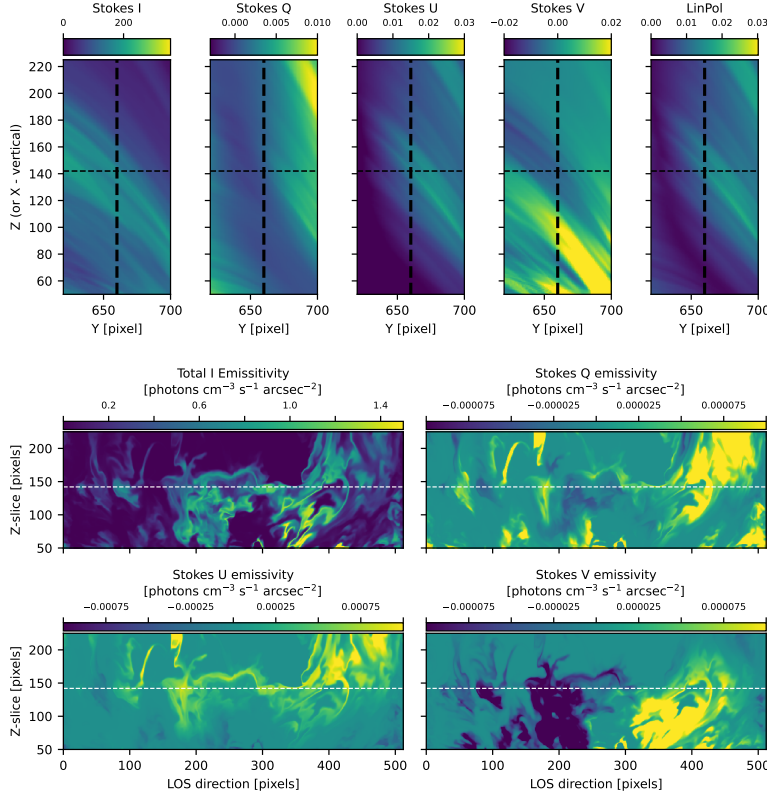


Figure 4: *Top:* Forward synthesized maps of polarized intensities in the Fe XIII 1074.7 nm line through an advanced 3D MHD coronal model exhibiting loop like features [25]. *Bottom:* Stokes emissivities as a function of spatial coordinate along the line-of-sight and the Z slice indicated by the dashed vertical line in the top panels. Horizontal lines at $Z = 142$ are shown for reference. The grid spacing is 48 and 96 km along the Z and X-Y axes.

This fact combined with line-of-sight superposition, high contrast features, and coarse spatial resolution, lead to complicated data analysis and undermine our ability to fully constrain the various parameters of the coronal heating function discussed above. ***High polarimetric sensitivity on coronal loop spatial scales is needed to ensure high-fidelity determinations of the loop field intensity using these methods.***

2.2. Spectropolarimetry of Cooled Coronal Plasma

Complementary to forbidden line observations of highly-ionized species, further polarized diagnostics of coronal fine structure are available using permitted lines emitted from cooled coronal plasma. Modern observations indicate the chromosphere-corona mass and energy cycle produces a large fraction of cooled material in the corona, which subsequently becomes gravitationally-unstable and generates dynamic, finely-structured raining events [30]. Figure 5 shows coordinated observations of coronal rain that combines SDO/AIA, NASA/IRIS, and ground-based observations of the neutral helium triplet at 1083 nm from the Dunn Solar Telescope [31]. Clearly, rain blobs

Many further arguments can be made for increased spatial resolution of polarimetric loop observations, especially to conduct full Stokes magnetometry using the Zeeman Effect. Provided sufficient spatial resolution, the magnetic field intensity along loops may be assessed with forbidden line full Stokes observations and used to directly constrain the coronal heating function [4, 6]. However, this work is challenged by the optically-thin nature of the coronal signals and the difficult association of a given signal with a particular loop. Single-point inversion methods based on full Stokes coronal forbidden line observations have been proposed [26, 27, 28, 29] but remain unverified. Moreover, in addition to apparent coronal fine structure observed in intensity, the active corona hosts fine scaled flows and wave activity.

appear more isolated and contrasted in comparison to hot loops in Figure 1 and are further distinguishable through their dynamics. As such, cooled plasma offers a fine localized probe of the conditions in the corona undergoing cooling (see related WP by Antolin et al. [32]).

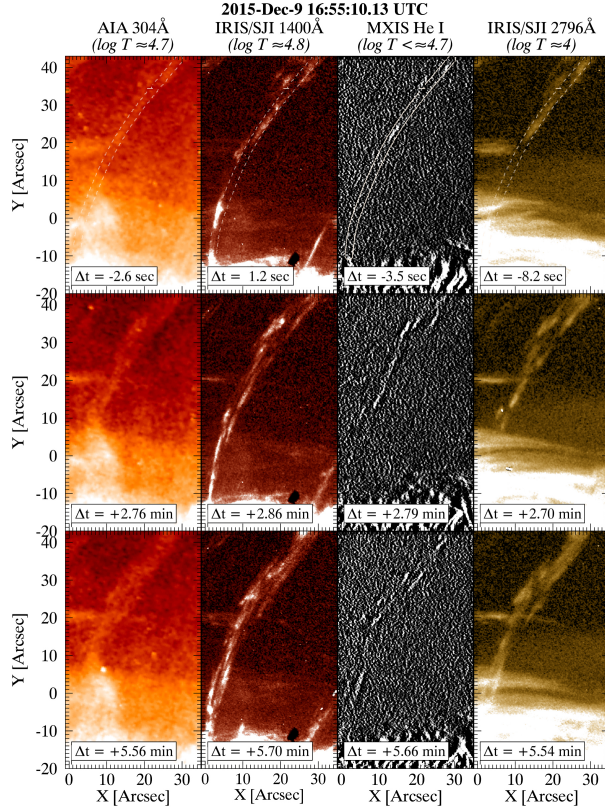


Figure 5: Coordination observations of coronal rain at UV wavelengths using SDO/AIA, NASA/IRIS and the He I 1083 nm triplet [31].

dynamic range polarimetry of coronal rain using visible and infrared orthohelium lines; however, the first generation instruments (in particular at IR wavelengths) require upgrades or new development in order to acquire polarized observations on the scales required with sufficient field-of-view and temporal cadence. Furthermore, while deconvolution techniques exist that may assist in reaching higher spatial resolution off-limb (if deliberately designed), the lack of off-limb adaptive optics is a hurdle to continued progress.

3. Enabling Technologies and Needed Investments

Motivated by the promise of high resolution coronal spectropolarimetry to address coronal loop physics, we advocate here for specific developments within the next decade.

3.1. Coronal Adaptive Optics for Increased Spatial Resolution

Ground-based solar observations off-limb remain seeing-limited at present, thereby severely limiting the achievable spatial resolution ($\gtrsim 1''$). Long exposure times needed for polarimetry further reduces the spatial resolution in the seeing-limited scenario. Prior advancements in solar adaptive optics (AO) [36] have provided the necessary breakthroughs that led to the construction of the

The existence of rain and strong radiative signatures in cooler “chromospheric” lines provides an opportunity for coronal polarimetry using permitted lines sensitive to the Hanle and Zeeman Effects. On-disk He I absorption observations within one such drainage event has already demonstrated that He I 1083 nm polarimetry can extract magnetic field strengths along isolated loops [33, 34]. Ca II 854 nm polarimetry has also been proven to offer unique insight into post-flare rain magnetic fields [35].

In contrast to the forbidden lines, spectropolarimetry of cool plasmas benefits from a greater number of previous studies that target polarimetry in key spectral lines. However, many challenges remain which have limited the use of these diagnostics until now, in the era of large-aperture solar facilities, especially using DKIST. Due to its relative low emissivity, small size, and fast evolution, coronal rain polarimetry requires highly efficient, large-aperture, dynamic instrumentation. A study of the signal-to-noise requirements [31] argues that DKIST offers sufficient light collection for high dy-

DKIST, especially as it could pursue unprecedented resolution on the solar disk. Off-limb adaptive optics has been pursued for prominence targets [37] and may lead to improved image quality for cooled plasma targets. DKIST is well positioned to pursue a low-order limb AO system, which we advocate for here to increase the resolution when there is cooled coronal plasma within the targeted field. However, more generally, a high contrast guide object is needed for coronal loop targets. Daytime laser guide stars have demonstrated early success and are worth continued investment [38, 39, 40]. Another possibility includes space-based artificial guide stars envisioned for deployment on unmanned aerial vehicles [41]) or artificial satellites like **ORCAS, the Orbiting Configurable Artificial Star Mission Architecture** [42]. The ORCAS mission targets full coverage of the Keck telescope’s available field from Mauna Kea and is highly synergistic with DKIST on Haleakala, Maui. It would provide a laser AO beacon with a predicted angular trajectory known to within ± 3 milliarcseconds from the ground.

3.2. High-Resolution Efficient Instrumentation Development

Existing DKIST facility instruments offer vast flexibility to support a broad science mission [43]. First light coronagraphic instrumentation includes the CryoNIRSP and DL-NIRSP, which are single-slit-based and integral-field-based spectropolarimeters operating at infrared (IR) wavelengths. Plans for upgrading both of these instruments, in order to provide more efficient wavelength multiplexing and field-coverage, are already underway and should continue to be advanced in the next decade [44]. We advocate for multiplexing efforts that yield better efficiency of the available detector areas, so as to increase the field-of-view, and in particular for coronal rain, the temporal cadence. Supporting technologies that need continued investment include fast readout high performance IR detectors, multi-slit and image-slicer based field sampling methods, high performance ultra-narrowband interference filters, and IR compatible tunable filter-based instrumentation [45].

3.3. Facility Support Systems

We also recognize a need for facility level support systems to optimize coronagraphic performance of large aperture coronagraphs, like DKIST and COSMO. High dynamic range polarimetry of the solar corona is a background-limited observation that requires low scattered light telescopes and instruments. Monitoring, controlling, and mitigating environmental impacts on system performance will likely require more investment in the next decade than in prior ones to ensure solar coronagraphy remains viable. We advocate for robust support systems that meet the operational challenges and constraints of existing and proposed facilities.

4. Synergies and Broader Science Impacts

The above science case focuses on the unique advantages that polarimetry at the finest coronal spatial scales could offer. But the subject of coronal magnetism is vast and requires advancement on many fronts. Here we lend support to a few synergistic efforts:

- At fundamental scales of coronal energetics, the need for very high resolution polarimetry of the solar photosphere and chromosphere is critical to investigate small-scale magneto-convective interactions at the roots of coronal loops [46], and thus novel **2nd generation**

instrumentation at DKIST is essential. See WPs by Woeger et al. [44], Asai et al. [45], and Lin et al. [47].

- DKIST conducts coronal magnetometry through novel experiment-based and PI-driven campaigns, as part of a broad science mission that encompasses non-coronal science as well. We recognize the critical value provided by a synoptic large field-of-view coronagraph (i.e. COSMO) that is capable of routine, global scale coronal magnetic field inferences. See the **COroanal Solar Magnetism Observatory (COSMO)** white paper [21]. The high resolution methods that we discuss here will further benefit the interpretation of COSMO observables.
- The proposed **Frequency-Agile Solar Radiotelescope** provides frontier capabilities for studying the solar atmosphere and extends, complementary, the visible and infrared spectropolarimetric techniques for understanding the coronal magnetic field. We note in particular the need for high resolution DKIST polarimetry together with FASR for understanding flare-driven particle acceleration [48].
- Achieving a holistic view of the Sun as a dynamo-active sphere driving the corona and extended heliosphere is critical. The science we propose aims to better understand the linkages between small-scale energetics and the global scale system, for which we further recognize the need for 4π coverage of the Sun as proposed by the **FIREFLY mission** [49].
- Continuous multi-wavelength coverage of the Sun from the Earth perspective is an assumed prerequisite for many of the proposed science cases. Ground-based networks are critical to ensuring reliable, continuous coverage with the most advanced techniques covering the photosphere through the corona. The proposed **Next Generation GONG (ngGONG)** [50] meets these needs.

SUMMARY

- ★ The poorly understood nature of the fine scaled solar corona remains an impediment for resolving key questions in solar physics.
- ★ High resolution off-limb spectropolarimetric methods at visible and IR wavelengths offer unique insight into this fundamental problem.
- ★ Advancing off-limb coronal adaptive optics, potentially facilitated by space-based artificial guide stars, is a decadal scale challenge for heliophysics that is needed to realize these important diagnostics.
- ★ Instrumentation development aimed at high-throughput largely-multiplexed polarimetric instrumentation, at infrared wavelengths in particular, is necessary to advance this science problem as well as provide the data needed for global coronal field studies.
- ★ This work also benefits through collaborations with existing and proposed projects, e.g., COSMO, FASR, FIREFLY, ngGONG, MUSE, and EUVST.

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