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A Strategy to Close Key Questions about the Middle Solar Corona During this Decade

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Synopsis

The middle corona, the region roughly spanning heliocentric altitudes from 1.5–6 $R_\odot$, encompasses almost all of the influential physical transitions and processes that govern the behavior of coronal outflow into the heliosphere. Eruptions that could disrupt the near-Earth environment propagate through it. Importantly, it also modulates inflow from above that can drive dynamic changes at lower heights in the inner corona. Consequently, this region is essential for comprehensively connecting the inner corona to the heliosphere and for developing corresponding global models. Nonetheless, because it is challenging to observe, the middle corona has been poorly studied by any solar remote sensing missions or instruments, extending back to the Solar and Heliospheric Observatory (SoHO) era. Thanks to recent advances in instrumentation, observational processing techniques, and a realization of the importance of the region, interest in the middle corona has increased.

This paper summarizes the modern definition of the middle corona and key questions about it, and presents **strategic recommendations to conquer the unsolved physics of the region** based on integrated, multi-modality observational campaigns including:

- prioritizing coordinated, comprehensive middle corona imaging and spectroscopy,
- prioritizing radio facilities with middle corona capabilities,
- prioritizing multi-perspective and coronal magnetic field measurements, and
- improving data assimilation capabilities to integrate new, multi-perspective observations into data-driven coronal models.

1 Defining the Middle Corona

More than sixty years after Parker's 1958 seminal paper, the solar wind's origins and acceleration mechanisms are still unclear. Deep understanding of the two primary types of wind – fast and slow – requires models that encompass an extremely diverse set of conditions (Verscharen et al., 2019). Early theories held that the solar wind was primarily accelerated outside of 10 $R_\odot$; however, new observations suggest that this critical acceleration region is closer to the solar surface (Antiochos et al., 2011; Titov et al., 2011; Wexler et al., 2020). The new framework of Viall & Borovsky (2020) moves beyond the traditional fast-slow dichotomy to describe the source, release, and acceleration mechanisms of the solar wind, and points out the important influence of the physical processes that occur within the the newly defined *middle corona* (West et al., 2022).

The middle corona, defined by West et al. as the region from $\sim$1.5–6 $R_\odot$, is a critical transition region between the highly disparate physical regimes of the inner and the outer solar corona (Table 1). Nonetheless, it remains poorly understood, due primarily to the historical difficulty in observing the region. The region's inner boundary roughly traces the tops of the typical closed magnetic field structures that dominate the inner corona, below which loops appear and hydrostatic scale heights are sometimes applicable (e.g. Koutchmy & Livshits, 1992; Winebarger et al., 2002; Koutchmy, 2004). The outer boundary is roughly pinned to where the solar atmosphere is believed to have fully transitioned to an outflow regime, and is observed to be fully radial in structure (e.g., McGregor et al., 2008). Consequently, the middle corona encapsulates several important physical transitions, including the change from predominantly *closed* to *open* magnetic field structures and the change from *low* to *high* plasma β in quiet sun regions (See WP by Vourlidas et al., 2022).

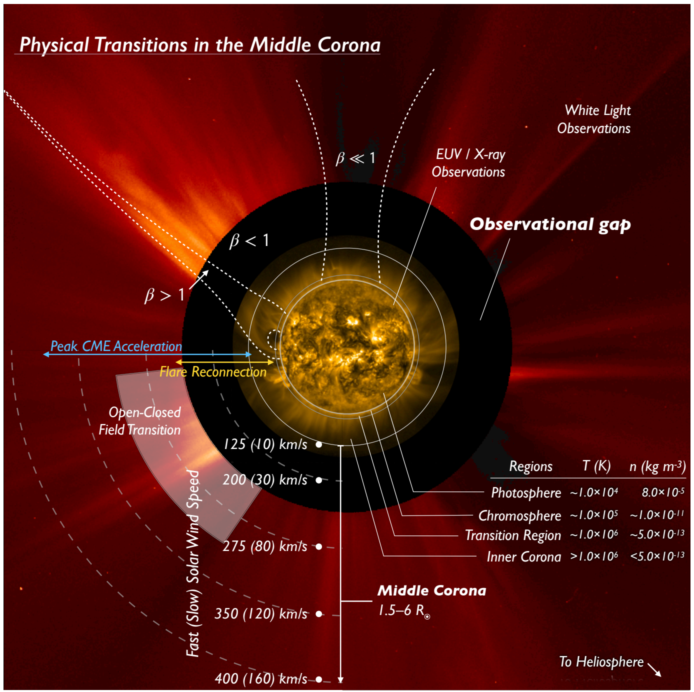


Figure 1: SWAP (Seaton et al., 2013; Halain et al., 2013) and LASCO (Brueckner et al., 1995) composite image highlighting the middle corona, its physical transitions, and observation gap. Reprinted from West et al. (2022).

Figure 1 presents an overview of the inner and middle coronae, highlighting atmospheric regions, characteristic solar wind speeds, and various coronal transitions. EUV observations of the inner corona reveal the shape of magnetic structures permeating the region – traced by collisionally-excited emission from hot plasma – that are constrained by the corona's magnetic field, which, outside of coronal holes, is largely composed of closed magnetic structures. In contrast, visible-light observations at greater heights reveal largely radial, open magnetic structures extending out into the heliosphere.

The middle corona plays an important role in shaping solar wind outflow, and its physics also have important implications for unified coronal-heliospheric models. New observations (Seaton et al., 2021) suggest that complex dynamics in the middle corona are

Table 1: Transitions in the middle corona (condensed from Table 1 in West et al., 2022).

Type of transition	Middle corona	Context
Structure	Closed-to-open magnetic field configurations	SSW, streamer regions
	Density structures/"blobs" released into outflow	SSW, streamer cores
	Density radial dependence drops to near inverse-square scaling	SSW, streamer regions
Dynamics	Subsonic-to-supersonic solar wind outflow	SSW
	CME main acceleration and initial shock formation	CME
Plasma physics	Broad range of β spanning <1 to >1	SSW, streamer regions
	Stabilization/freeze-in of ionization charge states	FSW, SSW
	Gravitational settling affecting FIP abundances	Streamer cores
	Coulomb collisions to kinetic plasma processes	SSW

FSW = Fast Solar Wind, SSW = Slow Solar Wind

often the source of heliospheric solar wind structures (e.g., DeForest et al., 2018). Downflows originating from the middle corona have also been shown to interact with structures in the inner corona. These include supra-arcade downflows (SADs; Savage et al., 2012; Shen et al., 2022), observed in the wake of eruptions, and weaker downflows in the quiet corona (Sheeley & Wang, 2002). Such downflows may trigger large-scale eruptive phenomena through mechanisms such as magnetic breakout, which erode magnetic fields (e.g., Antiochos et al., 1999).

Although EUV and visible-light observations both have long served as synoptic probes of the corona, these two observational regimes capture different physical characteristics of the underlying plasma: emission measure in the case of EUV and electron density in the case of visible light. The general lack of overlap in time and/or space of the fields of view and observed properties between the different methods of observation, especially from the Earth's perspective, have exacerbated the gaps in our understanding of the properties of this important region. Various methods, including modeling and extrapolation, allow us to continuously infer plasma properties (e.g., Lynch, 2020; Schlenker et al., 2021) from coronal observations, in spite of observational gaps. However, even for the relatively simple case of a quiet sun-streamer structure, many different estimates of the radial densities and temperatures have been published (Del Zanna et al., 2018).

To fully elucidate the mechanisms that determine the large-scale structure and dynamic changes within the middle corona, additional research including coordinated and overlapping observations, complete characterization of the mechanisms of emission, and new global models are required. In this white paper we introduce some of the important unanswered questions about the middle corona (Sec. 2) and discuss the key requirements of a strategy to close them (Sec. 3).

2 Open Questions About the Middle Corona

The middle corona has occasionally been referred to as the *the transition corona* (e.g. Masson et al., 2014; Vourlidas et al., 2020; Golub et al., 2020). Its transitions include the change from predominantly closed to open magnetic field structures, evolution in plasma emission mechanisms, and the change from low to high plasma β in specific regions. The middle corona is inextricably connected to both the inner and outer corona (and heliosphere by extension) through the continuation of the medium, and the bulk plasma and kinetic motions that pass from one to the other. Processes that occur within the middle corona can have consequences much farther afield, including at the Earth, as the result of its modulation of solar wind outflow and CME kinematics.

The global-scale transitions that occur in the middle corona are neither tidy nor monotonic, and they depend strongly on the structures in which they occur. Plasma β, to highlight a particularly important transition, varies widely within the middle corona and with it the drivers of dynamics. In general, $\beta \ll 1$ in the inner corona, where the magnetic field controls plasma dynamics, while in the outer corona, β can be variably above or below one depending on local conditions. The location at which this transition occurs depends strongly on the type of structure observed and, in particular, the structures' embedded magnetic field. Some observations (Seaton et al., 2021) suggest that large-scale dynamic processes in the middle corona can be driven by the gas dynamics of plasma flows.

Ultimately the plasma kinetic energy dominates the magnetic field structure in the super-Alfvénic flow regime beyond 10–20 $\mathrm{R}_\odot$ (Fox et al., 2016), even as plasma β varies across the unity threshold (Wexler et al., 2021). In purely *open* field structures such as plumes (DeForest et al., 2001) or coronal holes it is believed $\beta > 1$ mainly in the outer corona, where plasma can flow freely outwards. However, complex topology of quiet sun and active region inner corona permits the plasma pressure to overwhelm the magnetic pressure under certain conditions (see e.g., Vásquez et al., 2003). The dominance of a particular force can have significant consequences for dynamic events. The dominance of magnetic pressure in the inner corona allows for the build up of magnetic energy, and field-aligned currents, which are released as solar eruptions. The relative magnetic easing from very low β to the increasing influence of gas pressure that occurs in the middle corona has implications for the plasma dynamics that govern flows and eruptions.

In spite of these important transitions, remote sensing observations in both radio and shorter wavelengths have been insufficient to definitively characterize global properties such as the evolution of β. Occasional instrumental off-points, eclipses, and radio imaging have helped bridge the gap, but only intermittently. The absence of continuous and self-consistent observations, and an incomplete understanding of the underlying plasma properties, has exacerbated the challenge of developing a deep understanding of the middle corona and its properties and behavior. We are left with important questions that must be addressed to close this knowledge gap.

2.1 Questions Concerning Transitions

What is the nature of middle corona plasma, and how does its nature change from inner to outer boundary?

The many variable and intermittent transitions that occur within the middle corona include changes in magnetic topology, the change from low to high plasma β in quiet sun regions (e.g., Vásquez et al., 2003), and changes in emission properties. The lack of comprehensive, systematic, and self-consistent observations that could provide density, temperature, and magnetic field estimates through the region, has impeded progress in determining where and how these transitions occur. Developing this understanding is critical to determining where and how processes such as solar wind acceleration, ionization state freezing-in, supersonic flows, and eruption and flow kinematic shaping occur.

Where does freeze-in occur in the middle corona? What can it tell us about the origins of solar wind accelerated within middle corona structures?

The "freeze-in" altitude is the height at which charge states become fixed due to the plasma becoming too tenuous to sustain ionization and recombination processes any further. After this transition, ions become uncoupled from thermodynamic changes in the plasma and remain fixed. As a consequence, charge states are directly related to the heating and cooling experienced prior to freeze-in, making them an indirect diagnostic of coronal conditions. Fully characterizing freeze-in requires developing improved understanding of the still unresolved roles of different EUV emission mechanisms in the middle corona as well (i.e., collisional excitation vs. resonant scattering; Goryaev et al., 2014; Del Zanna et al., 2018; Gilly & Cranmer, 2020; Seaton et al., 2021).

How does the magnetic topology of the corona transition from mostly closed to almost entirely open in the middle corona? What is the role of topology in determining dynamics within the region?

Outside of coronal holes, this transition occurs almost entirely within the middle corona, but neither existing observations nor models have fully characterized how this transition occurs or the important role it plays in determining the dynamics that occur here. Simulations (Higginson, 2016) and observations (Chitta et al., 2022) suggest how the complex topology of this region and the interactions that occur in the S-web dictate the structure embedded within the heliosphere and its influence on geospace (Viall et al., 2021), but systematic observations are urgently needed.

2.2 Questions Concerning Outflow and Inflows

How does the large-scale evolution of the middle corona drive the structures that shape outflow into the solar wind?

Understanding solar wind formation requires understanding the connection between the solar corona and the heliosphere (Viall & Borovsky, 2020), particularly the connection between the open heliospheric magnetic field and the mostly-closed field lower in the corona. The boundary between these, situated in the middle corona around 2–3 $R_\odot$, fluctuates and is distorted by physical processes on a broad range of scales (e.g., magnetic reconnection, eruptions, and continual flux emergence; Abbo et al. 2016). The feedback between these processes and the open/closed transition boundary is poorly understood, largely due to the scarcity of continuous middle corona observations. Understanding this feedback is critical for heliospheric studies since it determines how hot magnetized plasma escapes the Sun into the interplanetary space. Furthermore, the open magnetic field and associated plasma flows are diverted from a purely radial direction by currents that produce a complex magnetic topology determined by photospheric evolution, prior dynamic events, and the field's global structure (Wang, 1996; Newkirk et al., 1968; McComas et al., 2007; Yeates et al., 2008). These deviations from the radial field have implications for the large-scale energy storage in the corona (See WPs by Mason et al., 2022a; Viall et al., 2022).

What is the nature of the interface between the inner, middle, and outer corona? How do changes within the middle and outer corona propagate back to the Sun?

Downflows, both gradual (Sheeley & Wang, 2014; Seaton et al., 2021) and impulsive (Savage et al., 2012), have been shown to interact the inner corona. Smaller or fainter downflows may be common and could trigger eruptions through mechanisms such as magnetic breakout (Antiochos et al., 1999). The exact nature of this interaction and the frequency of downflows have not been characterized, but is crucial for comprehensive coronal-heliospheric models.

2.3 Questions Concerning Impulsive Events

What role does the middle corona play in CME acceleration? How does the middle corona influence the overall evolution of CMEs?

Impulsive CME acceleration is known to occur in the middle corona (Bein et al., 2011) and interactions within the middle corona can sometimes alter the trajectories of mature CMEs (Byrne et al., 2014; D'Huys et al., 2017; Reva et al., 2017), potentially under the influence of the structure of magnetic field in the vicinity of the eruption (O'Hara et al., 2019) even to the point of preventing the CME from escaping at all (Thalmann et al., 2015; Alvarado-Gómez et al., 2018). Comprehensive, coordinated observations are required to fully characterize CME kinematics from the inner corona through the middle corona to ascertain how the large-scale solar atmosphere interacts with the eruption (See WP by Mason et al., 2022c).

How does magnetic reconnection in the middle corona release stored magnetic energy to accelerate CMEs and heat the surrounding environment? What determines where this occurs?

Theory predicts magnetic reconnection in eruptive solar flares occurs in the inner or the middle corona (Forbes et al., 2018), but only a few observations Yu et al. (e.g., 2020) have successfully isolated this location. Other manifestations of reconnection, such as SADs (Shen et al., 2022), can originate in the middle corona, posing a mystery: what is the relationship between SADs and reconnection outflow, and what do they have to teach us about one another? Likewise, magnetic breakout may occur high above pre-eruptive structures (Lynch & Edmondson, 2013), potentially within the middle corona, but existing observations have only revealed a few examples. Still other types of CMEs, so-called "stealth CMEs" (D'Huys et al., 2014) may be driven by reconnection in streamers. Comprehensive observations of the middle corona are needed to understand the role of magnetic reconnection in all of these disparate situations.

How do CME-driven waves and shocks propagate through and influence the middle corona, particularly to accelerate particles?

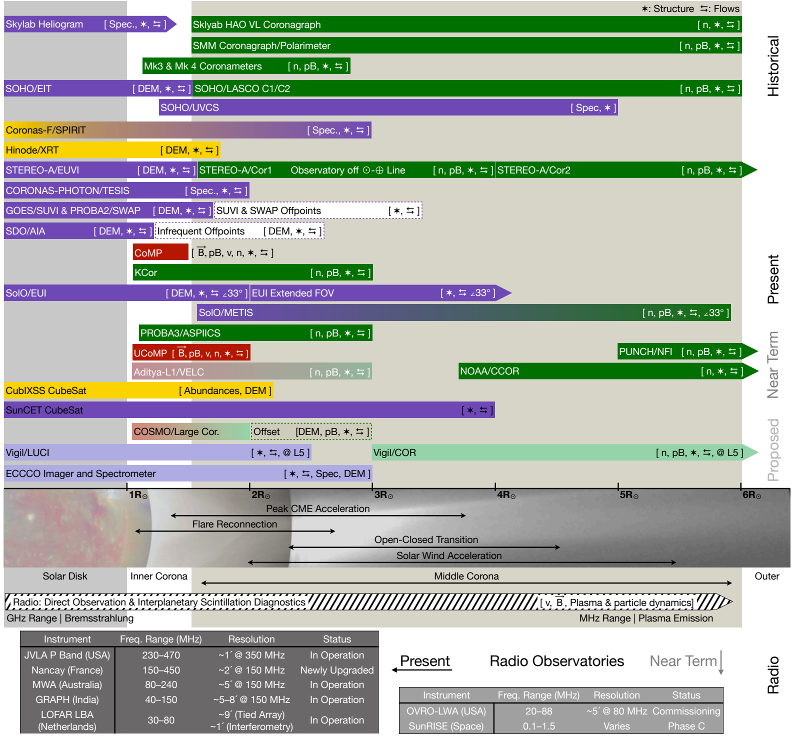
The interaction between CMEs and their associated shocks with the ambient middle corona is often studied from the viewpoint of how the CME kinematics are modulated by the ambient plasma conditions. However, the CME can also have important effects on the local surroundings. This can be manifest in many ways including: through downflows generated in the wake of eruptions (i.e., SADs); global disturbances of surrounding structures, which can in turn force remote restructuring of the coronal magnetic structure and potentially generate sympathetic eruptions (Török et al., 2011); and the generation of SEPs from CME-driven shocks interacting with surrounding structures, such as streamers (Kong et al., 2017; Frassati et al., 2020). Understanding these interactions is particularly important for the space weather community.

3 A Strategy to Close these Questions

Strategic Recommendations

- Prioritize coordinated, comprehensive middle corona imaging and spectroscopy.
- Prioritize radio facilities with middle corona capabilities.
- Prioritize multi-perspective and coronal magnetic field measurements.
- Improve data assimilation capabilities to integrate new, multi-perspective observations into data-driven coronal models.

Figure 2 presents an overview of past, present, and future middle corona observations, highlighting the patchwork nature of coverage of this important region. Systematic EUV observations of the disk over the past few decades have successfully addressed many important questions concerning the inner corona. Proposed missions optimized for the middle corona presently could to lead to some scientific progress, however we remain a long way from the structured, well-coordinated observations needed to resolve many of the questions outlined in Section 2



Instrument	Freq. Range (MHz)	Resolution	Status
JVLA P Band (USA)	230–470	~1´ @ 350 MHz	In Operation
Nancay (France)	150–450	~2´ @ 150 MHz	Newly Upgraded
MWA (Australia)	80–240	~5´ @ 150 MHz	In Operation
GRAPH (India)	40–150	~5–8´ @ 150 MHz	In Operation
LOFAR LBA (Netherlands)	30–80	~9´ (Tied Array) ~1´ (Interferometry)	In Operation

Instrument	Freq. Range (MHz)	Resolution	Status
OVRO-LWA (USA)	20–88	~5´ @ 80 MHz	Commissioning
SunRISE (Space)	0.1–1.5	Varies	Phase C

Figure 2: Overview of past, present, planned, and proposed middle corona observatories, including radio (gray), IR (red), visible (green), ultraviolet (violet) and X-ray (gold) observations. (Condensed from West et al. 2022.)

Numerous studies (Byrne et al., 2014; O'Hara et al., 2019), have demonstrated how difficult it is to associate the complex, 3D features of the middle corona that are observed in EUV with those observed in visible-light. This is further complicated by the huge disparity in coronal brightness across the region, necessitating complex image processing to coherently reveal structures and dynamic events that span the region. **To bridge this gap, UV and X-ray observations must be extended to greater heights, which can only be achieved through the development of high-sensitivity instrumentation, incorporating both low-noise detectors and strategies to obtain higher dynamic range observations.** Large-FOV EUV missions like the SunCET CubeSat (in development; Mason et al., 2021, 2022d) and ECCCO (proposed; Golub et al., 2020) serve as important pathfinders, but only address some key questions.

Likewise, coronagraphic observations must be expanded to lower heights (See WP by Rabin et al., 2022). This can only be achieved with much-improved stray-light rejection. Multiple coronagraphs, including PROBA-3, Aditya's VELC, UCOMP and COSMO, may serve as pathfinders, but none provide imaging of the entire middle corona. **Strategic planning is required to ensure coordinated, co-temporal observations from all types of instruments.**

Spectral observations are crucial to determine the plasma properties of features captured in traditional images. Optical, UV, and EUV spectral diagnostics provide information on densities, electron temperatures, ionization states, elemental compositions, kinetic temperatures, temperature anisotropies, and flow velocities. Except for observations during eclipses, such observations of the middle corona have been largely limited to the UV spectra from UVCS, which operated 1996–2013, but was hampered by the technical limitations of the SOHO era. New designs like the LOCKYER mission concept (Laming & Vourlidas, 2019) could overcome these limitations, integrating spectral and imaging observations to greatly enhance the effectiveness of both measurements. (See WP by Ko et al., 2022)

While radio facilities are available around the globe, **there is no solar-dedicated radio instrument that provides true broadband dynamic imaging spectroscopy in the ~0.1–1 GHz spectral range, which is critical for middle corona science.** This includes CME initiation and acceleration; understanding the CME-accelerated electrons; and perhaps most importantly, providing unique measurements of CME magnetic field evolution and energetic particles.

CMEs are faint and diffuse structures that necessitate radio interferometers with a large number of antennas (~10s to 100s) to achieve sufficiently high-dynamic-range imaging ($>10^3$:1) and high surface-brightness sensitivity. These requirements for advancing radio studies of the middle corona science toward the next stage already comprise one of the core objectives of the Frequency Agile Solar Radiotelescope (FASR) concept, which must be prioritized to provide high resolution, high dynamic range, and high fidelity dynamic imaging spectroscopy over a wide frequency range (0.2–20 GHz). (See WP by Chen et al., 2022)

The corona is defined its magnetic field, but very few instruments can probe coronal magnetic fields at all. Only UCoMP (Landi et al., 2016) will generate global measurements anywhere close to the middle corona, though DKIST's Cryo-NIRSP (Rimmele et al., 2020) can make localized measurements near the top of the inner corona. Present estimates of the coronal magnetic field rely on extrapolations from photospheric magnetograms or other inferred measurements. **Hanle effect instruments, particularly in Lyman-α** (Raouafi et al., 2016), could more directly ascertain the strength and orientation of the coronal magnetic field (See WPs by Gibson et al., 2022; Tomczyk et al., 2022). **Transcoronal radio propagation studies can potentially extract essential magnetic field and electron density information** over the full range of the middle corona (Kooi et al., 2022; Wexler et al., 2020). **Type III radio bursts can be used to outline the topology of the fast-electron-beam-conducting magnetic field lines** threading the corona (e.g., McCauley et al., 2017). Expanded capabilities for enhanced multi-wavelength imaging and multi-point radio sensing could provide strong constraints on global models. These concurrent, complementary observations are required to improve our ability to understand the topology and evolution of the middle corona's complex magnetic field.

All of these individual measurements are important, but the middle corona is a dynamic, 3D environment that cannot be fully understood only from the Sun-Earth line. **Developing true understanding requires 360°/4π views of the Sun, including both the photospheric magnetic field and multiple lines of sight through coronal features and magnetic field structures** (e.g., WPs by Caspi et al., 2022; Raouafi et al., 2022). Such observations, coupled to global magnetic field models and advanced 3D reconstructions (e.g., Barbey et al., 2013; Plowman, 2021), can facilitate comprehensive understanding of the global corona and are required especially to characterize the complex, highly structured interfaces at the middle corona's boundaries. Given the exotic solar orbits required to achieve multi-perspective views, it is especially important to prioritize development of miniaturized instrumentation for multi-platform, deep space constellations. **The community must expedite the development such efforts via international collaboration** (see WP by Kepko et al., 2022) **and expanded opportunities within NASA's CubeSat and LCAS programs** (see WP by Mason et al., 2022b).

Trade studies are needed to prioritize limited resources in a coherent observing framework, balancing cost, risk, and criticality of observed physical parameters across the wide range of conditions in the middle corona. Some measurements can be made with distributed ground-based instrument networks, and some with miniaturized space-borne instruments, while others require significantly larger space-based investments. 360° or 4π observations – including out-of-ecliptic perspectives – should prioritize measurements that cannot be made from Earth's perspective, or that facilitate research or space weather forecasting using additional vantage points.

Coupling these new observations to global models is a major challenge, particularly determining how magnetic field and 3D observations can be assimilated to provide model constraints. **Advanced 3D reconstruction techniques and robust forward-modeling frameworks** (Gibson et al., 2016) **provide promising pathways to achieve better model/data integration, but further investments in models and model data assimilation are required** (e.g. WP by Seaton et al., 2022). Earth and atmospheric science models, which already have robust data-assimilation strategies (Lahoz & Schneider, 2014), can serve as useful pathfinders.

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