





















Defining the Middle Corona

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Abstract The middle corona, the region roughly spanning heliocentric altitudes from 1.5 to 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 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 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 major solar remote sensing missions and 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. Although the region cannot be intrinsically separated from other regions of the solar atmosphere, there has emerged a need to define the region in terms of its location and extension in the solar atmosphere, its composition, the physical transitions it covers, and the underlying physics believed to be encapsulated by the region. This paper aims to define the middle corona and give an overview of the processes that occur there.

Keywords: Flares, Dynamics; Helicity, Magnetic; Magnetic fields, Corona

1. Introduction

Parker (1958) showed that the hot corona cannot maintain a hydrostatic equilibrium. Instead, the pressure-gradient force exceeds gravity and produces a radial acceleration of the coronal plasma to supersonic velocities, the *solar wind*. Early solar wind velocity observations by the Ulysses spacecraft showed that the solar wind was split rather simply between fast and slow components, the fast wind emanating generally from the interiors of (polar) coronal holes and the slow wind originating near the ecliptic plane. Observations frequently deviate from this traditional fast/slow dichotomous view, so models of coronal heating and solar-wind acceleration must encompass a much more diverse set of conditions and phenomena to truly achieve a realistic description of the physics of the solar wind (Verscharen, Klein, and Maruca, 2019).

The solar wind acceleration region was originally thought to originate beyond 10 R_{\odot} ; however, new observations suggest that this critical region originates closer to the solar surface (Wexler *et al.*, 2020). This height is dictated by the interplay between the open and closed magnetic field, their origins and boundaries, as described by open flux corridors and the S-web (Antiochos *et al.*, 2011; Titov *et al.*, 2011). A new system of potential source, release, and acceleration mechanisms for solar wind types characterized beyond the traditional fast-slow wind dichotomy was presented in Viall and Borovsky (2020). Several of those mechanisms (e.g., streamer blob release) take place at locations within the *middle corona*.

The middle corona is a critical transition region between the highly disparate physical regimes of the inner and outer solar corona¹. Nonetheless, it remains poorly understood due primarily to historical difficulty in observing the region. The boundaries of the region have been debated for many years, and keeping in mind the role that different physical mechanisms can play will vary from place to place in the corona, a consensus has emerged: $\sim 1.5 - 6 R_{\odot}$. The inner boundary roughly traces the typical tops of the closed magnetic field structures that dominate the inner corona, below which loops appear and hydrostatic scale heights are sometimes applicable (e.g. Koutchmy and 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). It is also around this height that “Sheeley Blobs,” small-scale density inhomogeneities frequently observed flowing both inwards and outwards in streamers, are believed to be fully pinched-off through magnetic reconnection (e.g., Sanchez-Diaz *et al.*, 2017).

The region 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 (Vourlidas *et al.*, 2020). A list of the transitions occurring in this region can be found in Table 1.

New observations reported by Seaton *et al.* (2021) suggest heliospheric solar wind structures not only originate in the inner corona (e.g., DeForest *et al.*, 2018), but can originate from complex dynamics in the middle corona. The region is also believed to influence the inner corona, where inflows have been shown to interact with structures in the inner corona. For example, supra-arcade downflows (SADs; e.g., Savage, McKenzie, and Reeves, 2012; Shen *et al.*, 2022) observed in the wake of eruptions correspond to plasma pile up in the inner corona, and smaller or fainter downflows may also be ubiquitous in the less dynamic atmosphere (Sheeley and Wang, 2002). Such downflows may trigger larger scale eruptive phenomena, or erode magnetic fields that could trigger eruptions through mechanisms such as magnetic breakout (e.g., Antiochos, DeVore, and Klimchuk, 1999). Thus, the middle corona not only plays an important role in shaping outflow, as the region through which all outflow and eruptions must pass and be modulated, but the middle corona physics also has important implications for unified coronal-heliospheric models.

Historically, the solar corona has most commonly been studied using a combination of extreme ultra-violet (EUV) and X-ray observations of the inner corona with visible-light coronagraph observations of the outer corona, as shown in Figure 1. The observations in the figure, from 2014 when the Sun was near the peak of its activity cycle, include an EUV image in the center (yellow color scale), from the large field-of-view (FOV) *PROBA2* Sun Watcher with Active Pixels and Image Processing (SWAP; Seaton *et al.*, 2013b; Halain *et al.*, 2013) imager, whose passband is centered on 174 Å, and a visible-light image (red color

¹Throughout this article we will adopt the common nomenclature of *inner* and *outer* corona, as opposed to *lower* and *upper* or *extended* corona.

Table 1. A table of transitions, in the inner and middle corona where: FSW=Fast Solar Wind, SSW = Slow Solar Wind, PFSS=the potential field source surface.

Type of transition	Inner corona	Middle corona	Context
Structure		Closed-to-open magnetic field configurations	SSW, streamer regions
		Density structures/“blobs” released into outflow	SSW, streamer cores
	Confinement regime with elevated density power law radial dependence	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	Plasma $\beta \ll 1$		Coronal Holes & FSW
	Plasma $\beta < 1$ in innermost corona	Broad range of β spanning < 1 to > 1	SSW, streamer regions
	Charge state freeze-in		FSW
		Stabilization/freeze-in of ionization charge states	SSW
	Gravitational settling affecting FIP abundances		Streamer bases
		Gravitational settling affecting FIP abundances	Streamer cores
	Coulomb collisions to kinetic plasma processes		FSW
	Coulomb collisions to kinetic plasma processes	SSW	

scale) from the *SOHO*/Large Angle and Spectrometric Coronagraph (LASCO; Brueckner *et al.*, 1995) C2 coronagraph, around the edge.

Figure 1 is annotated to highlight atmospheric regions, characteristic solar wind speeds, and various coronal transitions. The EUV observations of the inner corona reveal the shape of structures permeating the region – highlighted by the emitting plasma – that are constrained by the corona’s magnetic field. EUV observations of this region reveal it to be largely dominated by closed magnetic structures. In contrast, the visible-light observations reveal more stri-

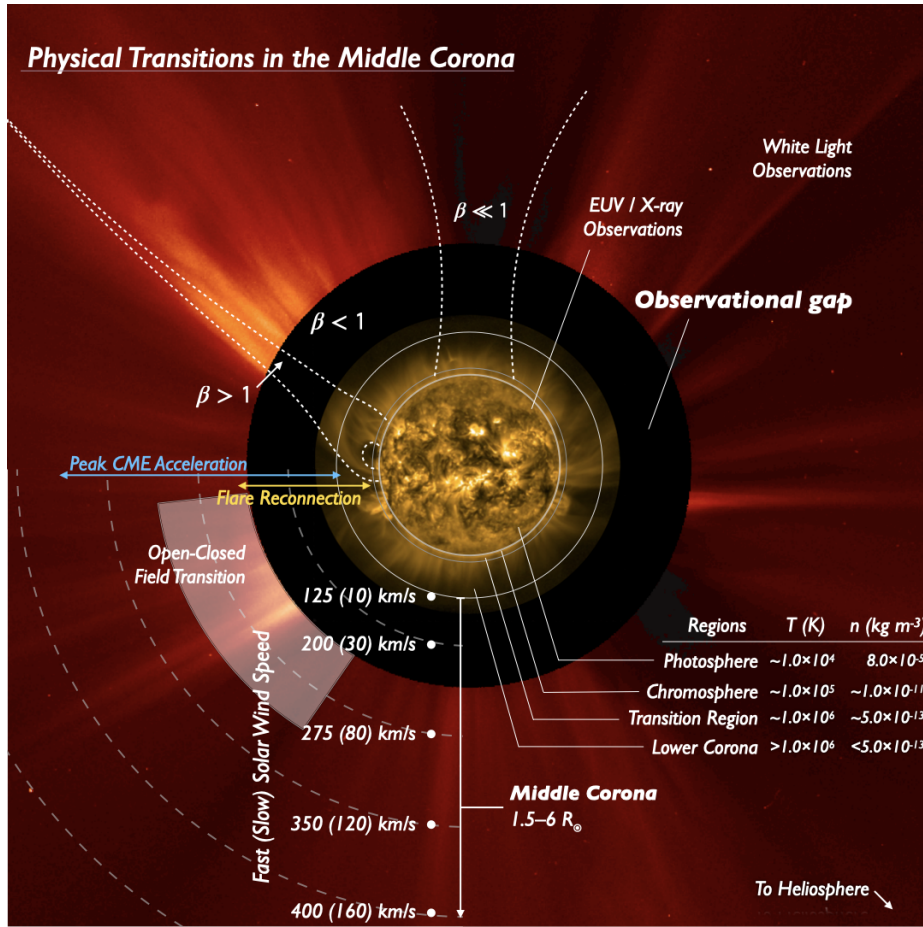


Figure 1. A SWAP and LASCO composite image highlighting the middle corona, and the physical transitions that extend through the region. The image also highlights the observational gap between EUV observations of the inner corona and visible-light observations of the outer corona, currently experienced from the Earth perspective (e.g., Byrne *et al.*, 2014). The image is annotated to highlight key heights, coronal characteristics, and physical transitions.

ated structures, indicative of open magnetic structures, extending out into the heliosphere.

Although EUV and visible-light observations have both served as synoptic probes of the corona, these two observational regimes have generally been focused on different regions of the middle corona, and through disparate passbands. Thus they 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 between the different methods of observation, especially from the Earth's perspective (highlighted by the observational gap in Figure 1) can lead to ambiguity, both when tracking structures and inferring plasma properties such as temperatures and densities. Methods to continuously infer plasma properties include extrapolation and modeling (e.g., Lynch, 2020;

Schlenker *et al.*, 2021); however, even for the relatively simple case of a quiet sun-streamer structure, various different estimates of the densities and temperatures have been published (Del Zanna *et al.*, 2018). To fully elucidate the mechanisms effecting the large-scale structural and dynamic changes occurring over the middle corona, complementary observations that overlap adjacent zones are essential.

In this article, we propose a definition for the region called the middle corona, we review how we observe it and what we know about it, and we present both the open questions concerning the region and a strategy to explore it. In Section 3 we describe how we currently – and historically – observe the middle corona; in Section 4 we describe the properties and topology of the middle corona; in Section 5 we describe some of the efforts to model and extrapolate properties of the region. Finally, in Section 6 we present a discussion of the region, in the form of open questions pertaining to the region and ways of answering them.

2. Partitioning the Solar Atmosphere

Although the sun is effectively a continuous ball of plasma with no physical boundaries, the solar interior is typically demarcated into layers based on the dominant physical processes that govern the energy transport in the respective regions. A similar logic is applied to the solar atmosphere, where the partitions are based on thermal and magnetic properties. These properties not only dictate the emission mechanisms and length-scales at play, but ultimately how we observe and model the different regions.

In general the high magnetic field strengths, temperatures, and densities experienced in the inner corona make formal calculations of its properties inherently complex, so the average properties of particles are often adopted. This introduces the magnetohydrodynamic (MHD) approach to modelling the region, which treats the plasma as a bulk magnetized fluid (Gombosi *et al.*, 2018, and references therein). In the outer corona, where length-scales have increased, kinetic models are used, and the equations of motion for each particle, subject to various forces, are calculated (Marsch, 2006, and references therein). The middle corona acts as the interface between these two regions, and therefore requires a combination of approaches.

The transitions between the three very distinct physical regimes of the inner, middle, and outer corona are not themselves distinct, largely due to the range in length-scales and scale heights experienced among different coronal regions (Chhiber *et al.*, 2022; Malanushenko *et al.*, 2022), and their variation throughout the solar cycle (Badalyan, Livshits, and Sykora, 1993; Edwards *et al.*, 2022). However, rapidly advancing observational and data processing techniques have provided new insights into the region, and new proposed missions to explore the region have led to the term “middle corona” entering the solar and heliospheric physicists’ lexicon in recent years. There is a clear need to define both the terminology describing this region as well as its properties, which is the goal of this paper.

3. How we observe the middle corona

There are a variety of reasons that the middle corona has not been as well characterized as other regions of the solar atmosphere. These include limitations on instrumentation and instrumentation capabilities, prioritization of other investigations, and the observation of other regions. Nonetheless, through dedicated observation campaigns and increasingly sophisticated spectroscopic, image, and data processing techniques, large portions of the middle corona have been intermittently probed. Figure 2 presents a rough overview of many past, present, planned, and proposed observatories that contribute to our knowledge of the region.

Many of the most prominent observations of the middle corona have been made in wavelengths ranging from X-rays to infrared, but radio imaging and radio measurements of the middle corona have provided important insights into the underlying plasma characteristics. Spectroscopic instruments, particularly in the ultraviolet, have also made important contributions to our understanding of the properties and dynamics of middle corona plasma.

In general instruments that make continuous observations in visible-light, EUV, and X-ray passbands are located on space-based platforms, where they can observe the corona unencumbered by the Earth’s atmosphere and day-night cycles, whereas observations at radio wavelengths are made from ground based sites due to the size of instruments. Both sets of observation utilize different observing techniques, and rely on different emission mechanisms, which we review below. The following section has been divided in to two main subsections: the first examines observations made through IR, visible-light, EUV, and X-ray wavelengths (3.1), and the second covers observations made through radio imaging and measurements (3.2).

3.1. Short Wavelengths: Infrared, Visible, UV, and X-Rays

Although there remain persistent observational gaps (Byrne *et al.*, 2014), the middle corona has occasionally been observed by a disparate set of instruments in passbands that range from the infrared to X-ray. The most extensive observations have been made with visible-light images, both from coronagraphs and eclipses, as well as direct EUV imaging, primarily through dedicated off-point campaigns by imagers designed to observe the inner corona. Figure 3 shows examples of several such observations, from a coordinated campaign during April 2021, that included offpoints by the GOES Solar Ultraviolet Imager (SUVI), the Mauna Loa Solar Observatory’s K-coronameter (KCor), and LASCO on SOHO. These coordinated observations allow us to characterize different aspects of the middle corona, leveraging several different mechanisms through which plasma in the region manifests itself. Here we provide a brief overview of the history of these observations and the variety of phenomena observed here using these approaches.

3.1.1. Observed Emission Mechanisms

The inner corona exhibits temperatures ranging between $T \approx 5 \times 10^5$ and $>2 \times 10^7$ K, and consequently highly ionized atoms, emitting at UV, EUV and X-ray wavelengths, provide a key diagnostic of temperature and are very commonly

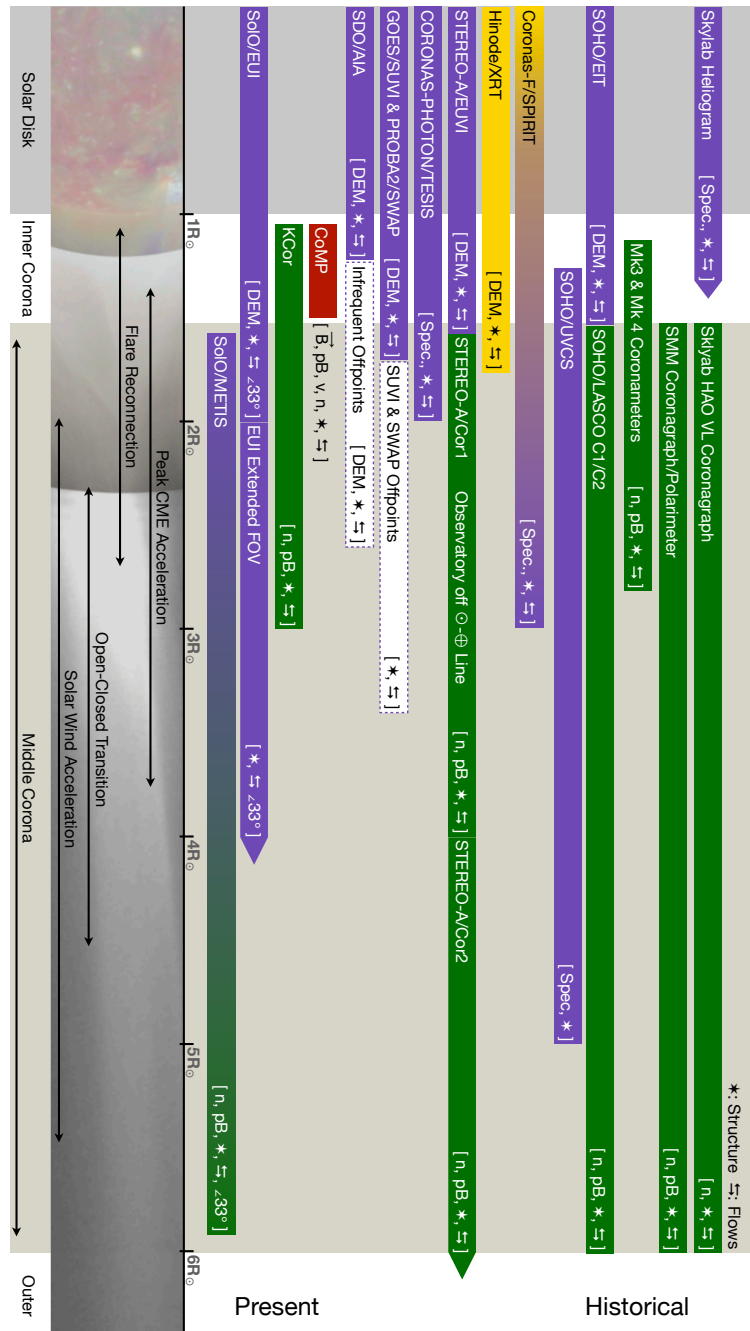


Figure 2. A. Summary of past, present, planned, and proposed middle corona observatories. The type of observation is indicated in the brackets, with key to symbolic abbreviations in upper right of the figure. Color corresponds to the wavelength regime of the observation, X-ray (Gold), EUV/UV (Violet), Visible (Green), Infrared (Red), and Radio (Gray).

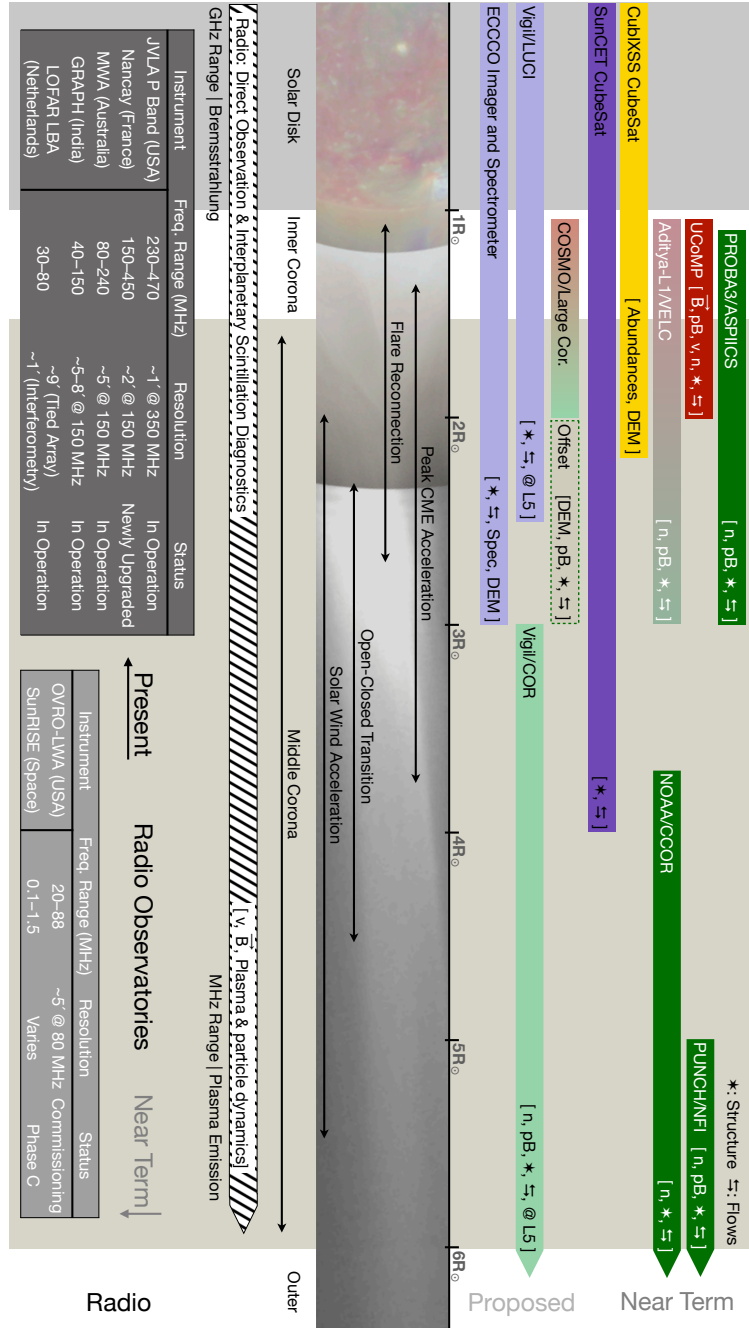


Figure 2. B. Continuation of middle corona observatories.

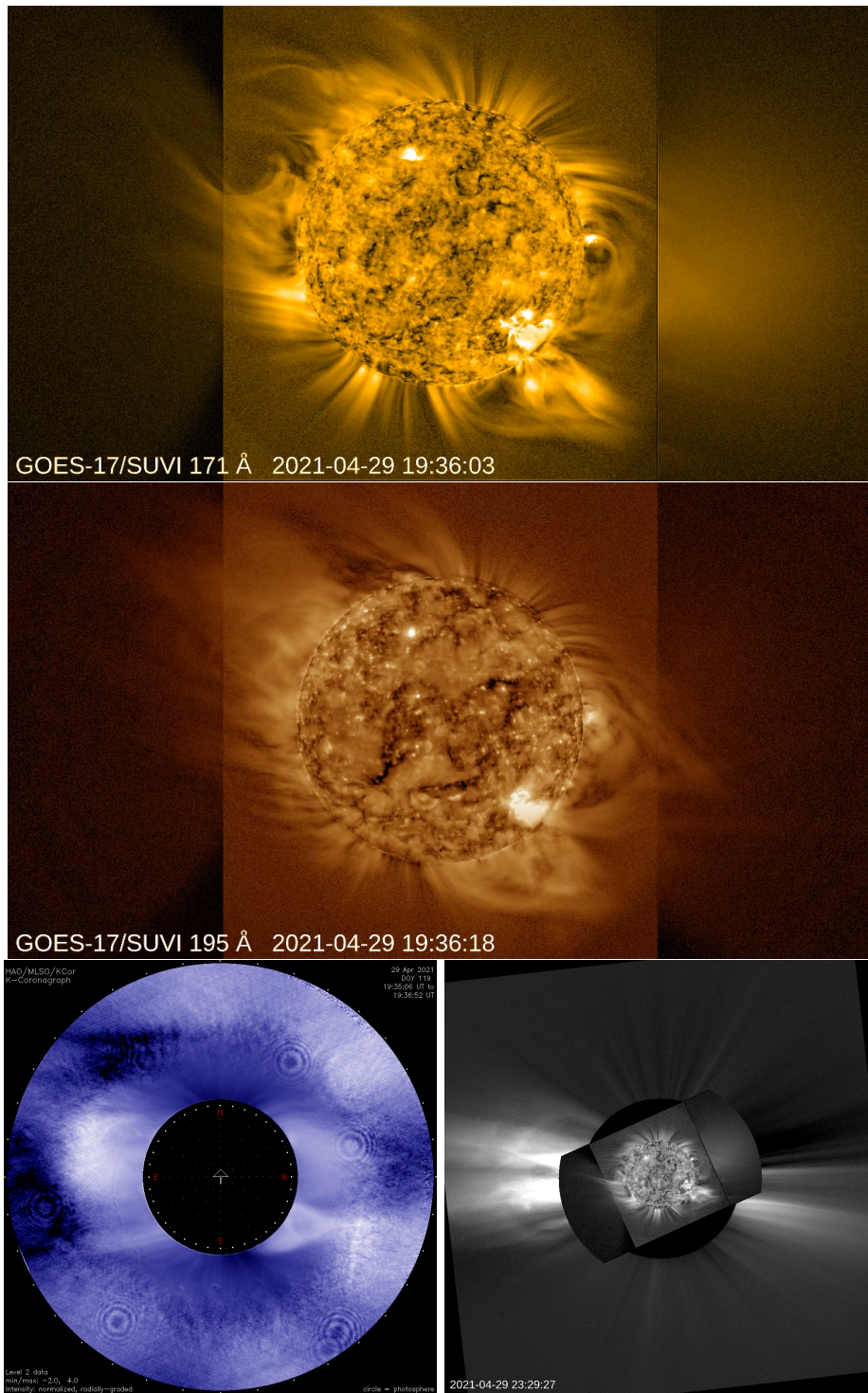


Figure 3. Different views of the middle corona, observed on 29 April 2021, from SUVI (top in 171 Å and middle in 195 Å) KCor (bottom left) and LASCOCO (bottom right; with SUVI superimposed). Images are in camera coordinates and not necessarily co-aligned, though solar north is generally upwards in each frame.

used to observe this region. This highly ionised emission is strongly dependent on density (n). The dominant emission mechanisms are spontaneous emission following *collisional excitation* and *resonant scattering* of incident light by ions. The intensity of emission resulting from scattering mechanisms is proportional to number density ($\propto n$) while emission from collisional excitation is proportional to density squared ($\propto n^2$). In the innermost corona, collisional excitation dominates all emission mechanisms other than broadband Thomson scattering, and in the absence of large scale structures, its $\propto n^2$ relationship gives rise to a rapid drop-off in brightness as density decreases with height. The belief that this drop-off would limit the viability of EUV observations above $1.5 R_{\odot}$ led most past observational efforts in these wavelengths to focus only on the inner corona.

At larger heights, resonant scattering can begin to dominate the ion and neutral emission. The relative contribution of resonant scattering and collisional excitation to the total emissivity of the plasma depends on the local density (both ion and electron), temperature, the collisional excitation rate coefficient, and the incident radiation at a given wavelength. The resonant scattering generally increases the emission, but for some lines, those excited by radiation from particularly strong chromospheric emission lines, Doppler-dimming can lead to a strong decrease of the amplitude of the scattered radiation. As the solar wind leaves the inner corona, it is accelerated until it reaches such a velocity that the incident light is no longer at the same wavelength as the spectral line at rest, thereby reducing the total amount of photon scattering from that particle. Note that in addition to the bulk outflow velocities, there are large thermal motions of the ions (with a dependence on atomic mass) that effectively smears out the relative velocities with respect to the solar surface and reduces the amplitude of the dimming. Occasionally, the scattering can lead to Doppler-pumping, where a Doppler shift causes the resonant wavelength of the coronal ions to match the wavelength of a spectrally-adjacent line, such as is the case with O VI 1038. Figure 4 from Gilly and Cranmer (2020) highlights the Relative proportion of resonant scattering to the total emissivity as a function of wind speed, pointing to a potential diagnostic for solar wind acceleration in the middle corona.

New EUV observations (e.g., Goryaev *et al.*, 2014; Seaton *et al.*, 2021) have shown that resonant scattering of emission from EUV-bright inner-corona features ($\propto n$) occurs in many structures. Thus the brightness of the EUV corona declines less precipitously than anticipated for purely collisionally excited emission. This resonantly scattered emission can enhance the visibility of large-scale features in the middle corona for a new class of coronal observatories (see Sec. 3.1.2).

In contrast to emission line diagnostics, broadband visible light observations from coronagraphs and eclipses reveal Thomson scattered emission (Inhester, 2015), which is only sensitive to electron density. Differences in the nature of complex 3D structures that are manifested in these different emission mechanisms cannot always be reconciled in multi-wavelength studies. Thus visual confusion in the fine structure of this region has led to additional barriers to resolving key questions about the middle corona.

In narrowband visible and near infrared, because of the much greater flux from the photospheric radiation, resonant scattering begins to dominate the emission

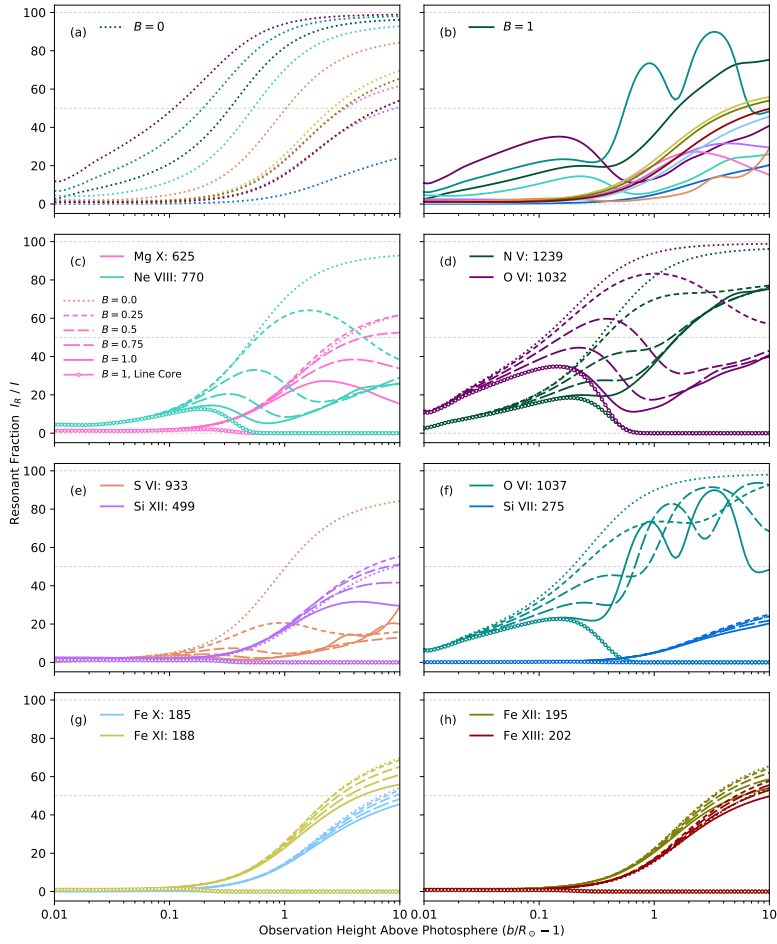


Figure 4. Relative proportion of Resonant Scattering to total emissivity as a function of wind speed. B is a scalar factor applied to the radial wind speed profile, with $B=0$ indicating no wind and $B=1$ indicating wind at modelled values. (Figure 17 of Gilly and Cranmer, 2020, used with permission).

processes for lines in this spectral interval already at relatively low heights above the surface. Because of the scattering of that same photospheric emission in the Earth’s atmosphere, and the near lack of spaceborne coronagraphs capable of observing coronal emission lines, it is more typical to study the whitelight corona at these wavelengths, both at eclipses and using a polarization-discriminating coronagraph (but see Ding and Habbal, 2017, for emission line measurements at $2 R_{\odot}$).

3.1.2. Optical Observations

Images of the middle corona are primarily produced in visible and infrared light using coronagraphic instruments or during eclipses, or in UV, EUV and

X-ray passbands using telescopes that can directly image the solar disk. High quality eclipse observations that include the middle corona date to the nineteenth century (Holden, 1894), while coronagraphic observations extend the pioneering work of Lyot (1939).

The space age opened the door to both higher quality coronagraphic observations and exploration in EUV and X-Rays. An important milestone was the *Skylab* mission, which carried both the High Altitude Observatory (HAO) visible-light Coronagraph (MacQueen *et al.*, 1974), whose FOV covered the middle corona more or less exactly – 1.5 to 6.0 R_{\odot} – and the Naval Research Lab’s Extreme Ultraviolet Spectroheliogram, which made spectrally dispersed images of the inner and, occasionally, middle corona over a wide range of EUV wavelengths (Tousey *et al.*, 1973, 1977). An even more significant breakthrough in middle corona studies came with the *Solar Maximum Mission (SMM)* coronagraph and polarimeter instrument (MacQueen *et al.*, 1980), which shared significant heritage and its FOV with the *Skylab* coronagraph but made many more systematic observations.

These space-based visible-light observations were augmented by a more sporadic set of ground-based observations: numerous eclipses, coronagraphs such as HAO’s several instruments on Mauna Loa (including, notably, the Mark III K-coronameter Fisher *et al.*, 1981), and subsequent instruments. These visible-light instruments and their space-based counterparts exploit the scattering of photospheric light by electrons in the corona (Thomson scattering) to image the corona, and must contend with the challenge of eliminating light from the photosphere, which is nearly 10^7 times brighter than the corona at 1.5 R_{\odot} . Coronagraphic imaging therefore requires very efficient stray light suppression, which must overcome both scattering of light and diffraction at the edges of optical components. This is generally easier to achieve with instruments having large separations between occulter and primary objective, in the case of externally occulted instruments, though the specifics of the designs of these instruments differ considerably. The challenge of observing close to the solar limb is particularly acute, and as a result, coronagraphic observations of the innermost middle corona are generally affected by stray light.

Nonetheless, in the more than 25 years since the beginning of the SOHO mission, most of the middle corona has been observed in visible-light by the LASCO suite (Brueckner *et al.*, 1995) and in the UV/EUV by the UVCS spectrometer, in EUV in the far edges and corners of images from the Extreme-ultraviolet Imaging Telescope (EIT; Delaboudinière *et al.*, 1995), and subsequently by a fleet of instruments that observed in visible-light, EUV, and X-Rays, including from multiple perspectives. These include the EUV/Visible Sun-Earth Connection Coronal and Heliospheric Investigation (SECCHI) on the twin STEREO spacecraft (Howard *et al.*, 2008), the SPectrographIc X-Ray Imaging Telescope-spectroheliograph (SPIRIT; Zhitnik *et al.*, 2002), the TElescopic Spectroheliographic Imaging System telescope (TESIS; Kuzin *et al.*, 2009), the SWAP EUV Imager on PROBA2 (Seaton *et al.*, 2013b; Halain *et al.*, 2013), the GOES Solar Ultraviolet Imager (SUVI; Darnel *et al.*), the GOES Soft X-Ray Imager (SXI; Hill *et al.*, 2005; Pizzo *et al.*, 2005), the *Hinode* X-Ray Telescope (XRT; Golub *et al.*, 2007), the *Solar Orbiter* Extreme Ultraviolet Imager (EUI; Rochus *et al.*,

2020) and the Metis coronagraph (Antonucci *et al.*, 2020). Additional planned missions will soon push the boundaries of observations of the middle corona both farther outwards (in EUV) and inwards (for coronagraphs).

Arguably the most important innovation in middle corona studies of the last decade has been a series of exploratory campaigns using off-pointed EUV images. These include both short-term campaigns with the SWAP imager (O’Hara *et al.*, 2019; Goryaev *et al.*, 2014) and long-term campaigns using SUVI (Seaton *et al.*, 2021; Chitta *et al.*, 2022). Such observations, using instruments with medium fields of view in novel ways to extend their observational range, along with a handful of reports from less well known instruments with dedicated larger fields of view (e.g., Reva *et al.*, 2017) definitively proved the feasibility of middle corona observations with dedicated EUV instruments. The most recent and prominent of these instruments is the Full-Sun Imager (FSI) in Solar Orbiter’s EUI suite, with a varying instantaneous FOV due to its highly variable distance from the Sun. Preliminary FSI observations have already demonstrated its ability to track erupting prominences from their genesis to the outer edge of the middle corona (Mierla *et al.*, 2022).

These pioneering EUV instruments have paved the way for a new generation of EUV instruments and techniques that focus specifically on the middle corona, including the Sun Coronal Ejection Tracker (SunCET) CubeSat (Mason *et al.*, 2021, 2022), in development now, and proposed EUV CME and Coronal Connectivity Observatory (ECCCO; previously referred to as the COronal Spectrographic Imager in the EUV or COSIE; Golub *et al.*, 2020) and Lagrange eUv Coronal Imager (LUCI; West *et al.*, 2020).

Likewise, pioneering visible and near-IR observations both from coronagraphs and eclipses, have paved the way for a new generation of coronagraph instruments with improved imaging capabilities in the inner and middle corona. These include the Coronal Solar Magnetism Observatory (COSMO; Tomczyk *et al.*, 2016), a suite of ground-based coronagraphic instruments, and Association of Spacecraft for Polarimetric and Imaging Investigation of the Corona of the Sun (ASPIICS; Shestov *et al.*, 2021), the visible coronagraph on the PROBA3 formation-flying space mission. See Figure 2 for a summary of notable historical, active, and planned and proposed middle corona observations.

Middle corona studies have also benefited from the development of advanced image processing techniques during the past two decades. The steep gradient in intensity as a function of height in the corona, both in visible and shorter wavelength observations, means that the dynamic range of solar images is far greater than can be captured in a single exposure by typical scientific cameras or displayed on a computer screen. Therefore, techniques that can overcome this to generate high-quality, large-FOV images, which still preserve fine details on many scales have been developed. There are over 20 separate methods in the literature that process solar imagery to draw out hidden detail (e.g., Druckmüllerová, Morgan, and Habbal, 2011).

Historically, such dynamic range challenges were addressed with radially varying optical filters (Eddy, 1989; Newkirk and Lacey, 1970). Contemporary imaging techniques include the stacking of multiple short exposure observations to approximate a long exposure (e.g., West *et al.*, 2022) and the use of detectors

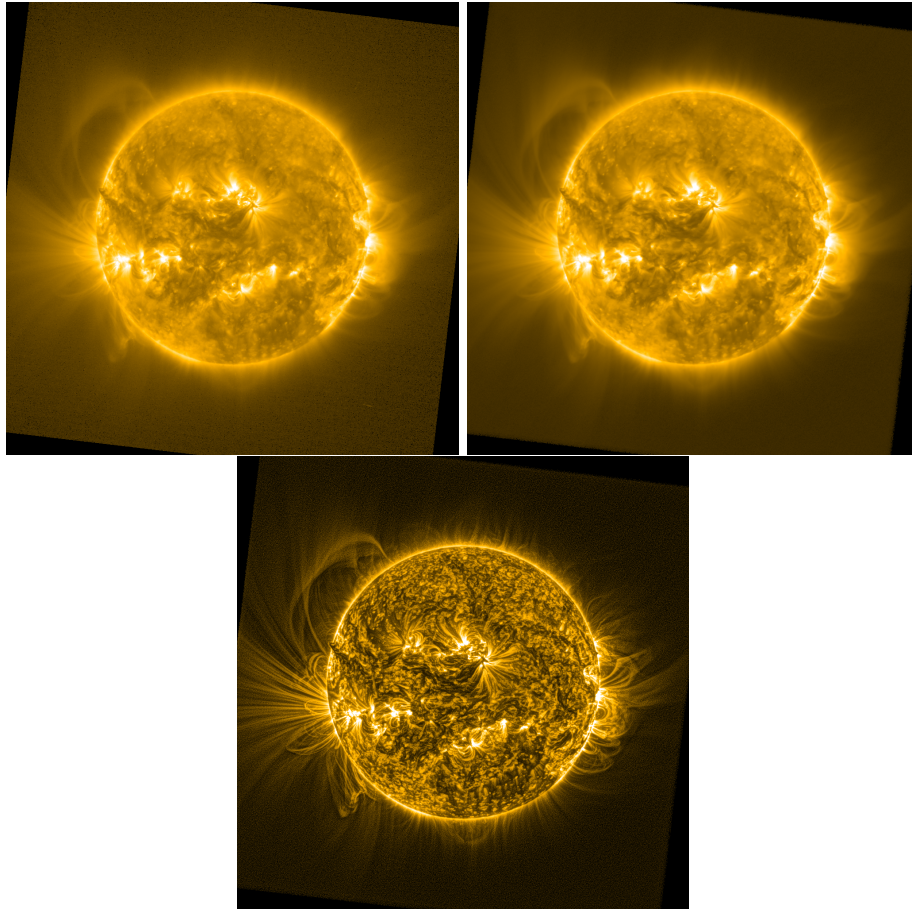


Figure 5. An example of how large FOV images can be processed to reveal structures extending into the middle corona. The three images show: a nominal SWAP observation from Nov 10 2014 (top left), a stacked image from the same time (top right), and the same image with MGN technique applied (bottom; Morgan and Druckmüller, 2014).

with locally variable exposure times (Mason *et al.*, 2022). Post-processing techniques, which improve the display of these high-dynamic-range (HDR) images, include computational radial graded filters (e.g., Martinez, 1978), wavelet-based techniques (Stenborg, Vourlidas, and Howard, 2008) and Multiscale Gaussian Normalization (MGN) (e.g., Morgan and Druckmüller, 2014). Figure 5 shows a SWAP EUV 174 Å image from Nov 10 2014 (top left) and an HDR stacked image from the same time (top right) with improved noise characteristics in the outer FOV. The bottom image shows how image processing with the MGN technique can improve the visibility of finer structures.

3.1.3. Spectroscopy

Extensive UV spectroscopy of the middle corona was obtained by the Ultraviolet Coronagraph Spectrometer (UVCS) aboard the SOHO satellite. It covered

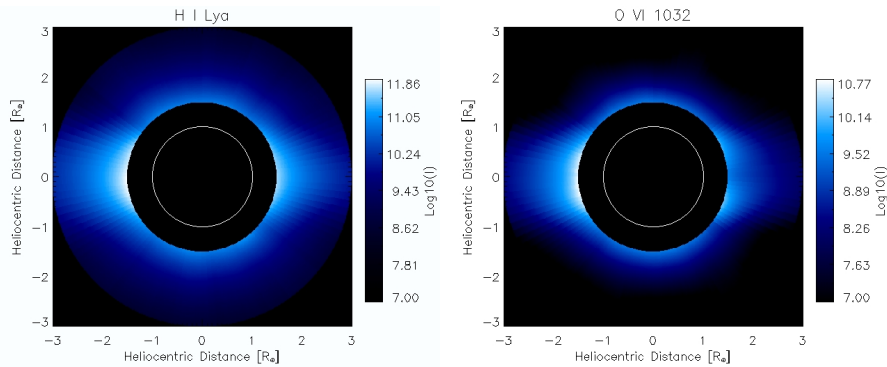


Figure 6. Intensity images of H I Ly α and O VI λ 103.2 reconstructed from the sets of UVCS synoptic images during 1996 June 1 through June 3. Note the different morphologies above the West limb.

heights generally above $1.5 R_{\odot}$ (often extending out to $5 R_{\odot}$) and a wavelength range from 500 to 1350 Å. Its spatial and spectral resolutions were about $7''$ and 30 km/s per pixel, but for most observations the pixels were binned due to telemetry limitations. A review is given in Kohl *et al.* (2006). Daily synoptic observations covered a range of heights at eight position angles around the Sun, and they were used to reconstruct intensity images such as those shown in Figure 6.

A wide variety of plasma parameters were measured from the UVCS spectra. Line intensity ratios among different ions of a single element yield the ionization state, which directly gives the electron temperature at low heights where the plasma is in ionization equilibrium. Once the ionization state has been established, intensity ratios of lines of different elements give their abundances, and because the Lyman lines of H I are measured, these are absolute abundances. The column density along the LOS is obtained from the intensity of a line such as Ly α , that is produced by scattering on photons from the disk. It is like the densities obtained from visible-light images, so it is an average density. A second density estimate comes from collisionally excited lines such as Mg X, whose intensity is proportional to the density squared. In some cases density sensitive line ratios such as O V 121.8/121.3 nm are available.

The spectral line widths give effective temperatures, which include both the kinetic temperatures of the ions and bulk motions due to turbulence or expansion. A unique diagnostic method using UV lines is Doppler dimming measurement of the velocity component away from the Sun. For example, the O VI doublet has both collisional and radiative scattering components, and their intensity ratio depends on the Doppler shift of the absorption profile away from the emission profile of disk photons. Analysis of line widths and intensities O VI combined with Ly α or visible-light data makes it possible to infer temperature anisotropy. It is also possible to use sungrazing comets as probes to measure density, proton temperature and wind speed at points along the trajectory, rather than integrated LOS averages (Bemporad *et al.*, 2007; Jones *et al.*, 2018).

Some important results of these methods have been strong preferential heating of O and Mg ions compared to H in coronal holes and at heights above $3 R_{\odot}$ in streamers (Cranmer *et al.*, 1999; Strachan *et al.*, 2002; Frazin, Cranmer, and Kohl, 2003). Strong oxygen temperature anisotropies in the coronal hole plasma were also indicated. Outflow speeds increase from around 20 km/s at $1.5 R_{\odot}$ to around 550 km/s at $6 R_{\odot}$ in coronal holes (Cranmer, Panasyuk, and Kohl, 2008; Raymond *et al.*, 2018), while reaching speeds of about 100 km/s or more by $6 R_{\odot}$ in streamers (Sheeley *et al.*, 1997; Wexler *et al.*, 2020). Elemental abundances in streamers show a first ionization potential fractionation (FIP fractionation; see Sec. 4.1) similar to that seen in the slow solar wind, but the absolute abundances in streamer cores are reduced by at least a factor of 3, probably by gravitational settling (Raymond *et al.*, 1997; Feldman *et al.*, 1998; Uzzo *et al.*, 2006).

Ultraviolet observations of CMEs in the middle corona have also determined the temperatures, thicknesses and turbulent velocities in current sheets (Ciaravella and Raymond, 2008; Bemporad, 2008) and the Mach numbers and electron equilibration in CME shocks (Frassati, Mancuso, and Bemporad, 2020). Studies of the energy budgets of CME ejecta have shown that they continue to be heated after leaving the solar surface, and that the cumulative heating is comparable to the kinetic energy (Murphy, Raymond, and Korreck, 2011; Wilson *et al.*, 2022).

Recent technical advances enable great strides in UV spectroscopy of the corona under a variety of launch platforms that can provide fundamental observations of coronal plasma that are inaccessible with other means (Ko *et al.*, 2016; Laming *et al.*, 2019; Strachan *et al.*, 2017), including the recently launched Ultraviolet Spectro-Coronagraph (UVSC) Pathfinder instrument, which has a thirty-fold increase in sensitivity compared with UVCS and a multi-slit design to simultaneously observe two heights. Improved spatial and spectral resolution and increased spectral range are also feasible.

3.1.4. Phenomena Observed

Structures that pervade the middle corona can roughly be divided into long-lived and dynamic phenomena. The long-lived structures are generally those that make up the background coronal environment; the dynamic phenomena are more transient, often passing through the region, and are often influenced by the background structures.

Long-lived structures. Long-lived structures are generally larger structures that persist for weeks to months – and in certain cases even years – and make up the background coronal environment. These include streamers and pseudostreamers (e.g., Pneuman and Kopp, 1971; Wang, Sheeley, and Rich, 2007), both of which are observed in the outer corona as bright radial features extending outwards. However, the inner and middle coronal magnetic topology cannot be discerned from such observations. Large-FOV EUV observations allow the magnetic topology to be traced from the inner corona out into visible-light observations. Several studies have focused on the extended streamer structures; Rachmeler *et al.* used SWAP with Coronal Multichannel Polarimeter (CoMP

Tomczyk *et al.*, 2008) (1074.7 nm), and Chromospheric Telescope (ChroTel; Bethge *et al.*, 2011) (H α 656.3 nm) observations to investigate a long term evolution of a streamer-pseudostreamer structure extending into the middle corona. Guennou *et al.* (2016) also used SWAP data to investigate a pseudostreamer/cavity system, determining its large-scale three-dimensional structure, temperature, and density, and its associated cavity. Separately, Pasachoff *et al.* (2011) used ground-based eclipse observations combined with EUV observations of a streamer structure to draw comparisons between the observations in the different passbands.

Coronal fans are another example of an extended large-scale structure, observed as fan like structures extending off the solar limb (see e.g., Koutchmy and Nikoghossian, 2002; Morgan and Habbal, 2007). They overlie polar crown filaments, bending over before extending outwards, and are often observed to be composed of open magnetic fields that extend out into the heliosphere. Seaton *et al.* (2013a) showed they are the single largest source of brightness at heights above $1.3 R_{\odot}$ in SWAP 174 Å observations and can persist for multiple rotations. Mierla *et al.* (2020) extended this study and showed some fans can persist for over a year, and can be observed extending out to at least $1.6 R_{\odot}$ in EUV observations.

Dynamic phenomena. Dynamic phenomena come in many forms, and persist for hours to days, and include all structures that pass through the middle corona, traveling both inwards and outwards (Seaton *et al.*, 2021). The most prominent and energetic structures to pass through the middle corona are CMEs (e.g., Zhang *et al.*, 2021). CMEs come in a range of sizes, ranging from halo CMEs to eruptions whose angular widths are barely wider than their smaller counterparts, coronal jets (e.g., Sterling *et al.*, 2015). These structures also have a range of speeds, from a few hundred to thousands of km/s (e.g., Yashiro *et al.*, 2004). The faster eruptions develop a shock front ahead of the ejecta front (e.g., Zhang and Dere, 2006), which in turn can produce solar energetic particles (SEPs; Reames, 1999).

Beyond their impulsive drivers, eruptions are mainly influenced by the background corona/solar wind (e.g., Mierla *et al.*, 2013; Schrijver *et al.*, 2008), especially in the dense inner and middle coronal regions. Sieyra *et al.* (2020) used wide field EUV imagers to assess where CMEs can become deflected, and found deflections often occur in the lower or middle corona during the acceleration phase.

The evolution of eruptions through the middle corona has been studied by many authors. Many discuss the difficulties linking structure in the EUV and visible-light passbands. O’Hara *et al.* (2019) used unique SWAP EUV (17.4 nm) off-point observations to directly trace an eruption from EUV observations (up to $\sim 2.5 R_{\odot}$) into white-light LASCO coronagraph observations. Although the overarching kinematics could be matched, exact features were difficult to reconcile due to the emitting plasma and differences in the observing passbands.

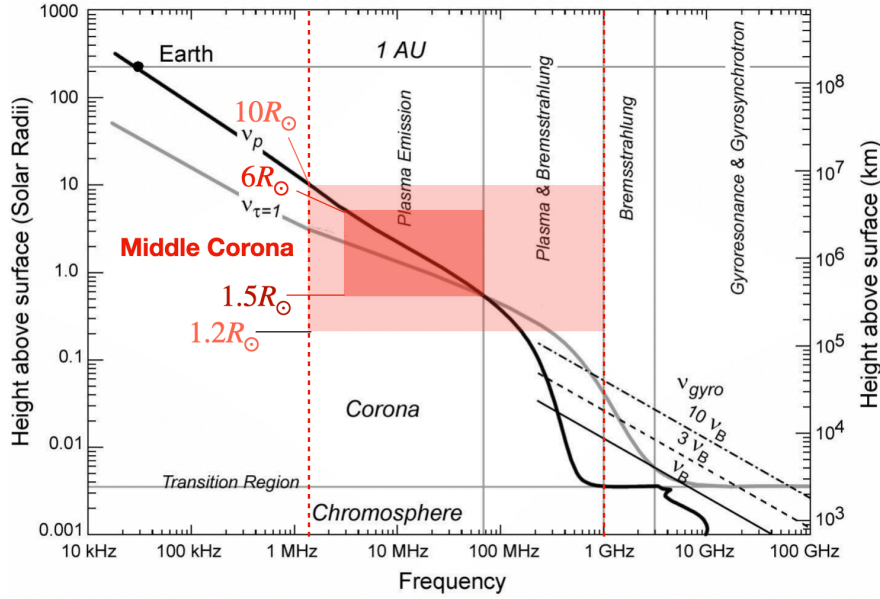


Figure 7. Characteristic radio frequencies in the solar atmosphere. The middle corona includes a critical region where the transition of radio emission mechanisms occurs. The dark pink box marks the nominal range of the middle corona ($\sim 1.5\text{--}6 R_{\odot}$) and the light pink box marks an extended range taking into account the highly structured and dynamic nature of the corona. The corresponding frequencies that are relevant to radio observations of the middle corona range from <10 MHz to ~ 1 GHz. (Adapted from Gary and Hurford 2004.)

3.2. Radio Wavelengths

From the perspective of radio observers, the middle corona includes the coronal heights where the key transition from incoherent radio emission to coherent radio emission occurs. Figure 7 (adapted from Gary and Hurford, 2004), shows the variation of plasma frequency (ν_p ; thick black curve), gyrofrequency (ν_B ; thin black curve), and the frequency of the free-free opacity ~ 1 ($\nu_{\tau=1}$) layer as a function of coronal height under typical quiescent coronal conditions.

The transition region and the innermost inner corona ($\lesssim 1.1 R_{\odot}$ from the center of the Sun) are dominated by incoherent gyromagnetic emission and free-free emission. At around $1.5 R_{\odot}$, the plasma frequency ν_p layer takes over and becomes higher (closer to the observer) than both the $\nu_{\tau=1}$ curve and the curves of ν_B and its harmonics. Such a transition has a profound implication on radio observations: the quiescent free-free radio corona is no longer playing a dominant role due to the strong refraction near the plasma frequency. Meanwhile, bright coherent radio bursts, due to plasma radiation occurring near ν_p and its second harmonic, start to be important among the observed radio phenomena. Of course, even in the region where the coherent plasma radiation dominates, incoherent radio emission from transients (e.g. CMEs) can still be observed,

providing crucial diagnostics for these coronal transients, including the magnetic field and nonthermal electrons trapped in the CME or accelerated by the CME-driven shock (e.g., Bastian *et al.*, 2001; Mondal, Oberoi, and Vourlidas, 2020; Chhabra *et al.*, 2021). Therefore, at radio wavelengths, a broad frequency range of <10 MHz to \sim 300 MHz is relevant to the highly dynamic and structured middle corona (light pink box in Figure 7). It is worth emphasizing that the magnetic field and non-thermal electron distribution diagnostics in the middle corona are unique to the radio techniques, and they are otherwise difficult to achieve (if not unavailable) for remote sensing at any other wavelengths.

3.2.1. Observed Emission Mechanisms

There are numerous radio emission mechanisms relevant to the solar corona, which include gyroresonance (thermal electrons gyrating in the coronal magnetic field), gyrosynchrotron (nonthermal electrons gyrating in the coronal magnetic field), bremsstrahlung (or free-free; electrons interacting with ions), as well as a variety of coherent emissions such as plasma radiation (e.g., the nonlinear growth of Langmuir waves) and electron cyclotron masers (i.e., the nonlinear growth of plasma waves at harmonics of the electron cyclotron frequency). These emission mechanisms co-exist, but because the physical parameters differ in various coronal locations/conditions, the importance of each emission mechanism also varies. In particular, the plasma density n_e and magnetic field B vary dynamically throughout the corona, and hence the corresponding plasma frequency ν_p and gyrofrequency ν_B , thus the dominant radio emission mechanism varies over the corona, and can change due to local conditions.

3.2.2. Radio Observations

Observing the middle corona at radio wavelengths requires a wide frequency coverage from <10 MHz to \sim 300 MHz (c.f. Figure 7). The >20 MHz range is generally accessible from the ground, but the lowest frequencies can only be observed from space due to the ionospheric cutoff. Currently, multiple ground-based instruments have been available to observe in the frequency range relevant to the middle corona. In space, new missions, such as the the Sun Radio Interferometer Space Experiment (SunRISE), are being designed to locate radio bursts. The Table in Figure 2 summarizes the currently operating and upcoming radio facilities that provide imaging capabilities in the frequency range relevant to middle corona studies. This list is representative, as there are, of course, a large number of additional radio instruments that provide total-power (full-Sun integrated) dynamic spectral measurements.

Over the past decade, new advances have been made with radio facilities equipped with *broadband dynamic imaging spectroscopy*. This exciting new technique allows simultaneous imaging and spectroscopy to be performed over a broad frequency range and at a high time cadence. In other words, a detailed spectrum can be derived from *each pixel* in the radio image for spectral analysis. First realized by the Karl G. Jansky Very Large Array at the decimetric wavelengths (Chen *et al.*, 2013) and followed by the commissioning of LOFAR,

MWA, EOVS, and MUSER, this technique is just beginning to reach the full potential of radio studies using the rich diagnostics tools available (Carley *et al.*, 2020, e.g.).

3.2.3. Phenomena Observed

Type II Bursts and Coronal Shocks Type II radio bursts are commonly seen in metric wavelengths and are notable for their relatively slow drift to lower frequencies (~ 1 MHz/s) over the course of a few minutes (see Panel A in Figure 8). Type II radio bursts are regarded as the radio signature of shock-accelerated electrons (due to coherent plasma radiation) propagating outward at super-Alfvénic speeds. Recently, thanks to the imaging spectroscopy capability provided by instruments such as LOFAR, new insights have been provided into their source region at the CME-driven shock front. For example, recently, Morosan *et al.* (2019) found shock-accelerated electrons “beaming out” from multiple acceleration sites located at the nose and flank of the shock.

Type III Bursts and Electron Beams. Type III radio bursts are produced by fast electron beams (~ 0.1 – $0.5c$) escaping along open magnetic field lines (see, e.g., Reid and Ratcliffe, 2014, for a review). Type III bursts are commonly observed in metric wavelengths and exhibit notable frequency drift. However, in comparison to Type II bursts, Type III bursts drift significantly faster (~ 100 MHz/s). In the middle corona, these bursts are predominantly associated with open field lines. With imaging spectroscopy provided by general purpose facilities such as LOFAR and MWA, new advances have been made in tracing the trajectories of the electron beams (e.g. Panel B in Figure 8) which, in turn, outline the electron-beam-conducting magnetic field lines in the middle corona (e.g., McCauley *et al.*, 2017; Mann *et al.*, 2018).

The emission frequencies and fine structures in the dynamic spectra have been used to derive the coronal density variation in height and properties of the coronal turbulence (Kontar *et al.*, 2017; McCauley, Cairns, and Morgan, 2018; Mann *et al.*, 2018).

Type IV Bursts and Radio CMEs. Electrons accelerated and trapped by CMEs can also emit incoherent gyrosynchrotron radiation as a Type IV burst. Since the emission occurs at large harmonics of the electron gyrofrequency, this emission can be found at frequencies above the local plasma frequency, thereby being less affected by the scattering effects. When spatially resolved, approximately at frequencies between 100 MHz and 400 GHz, they usually resemble the morphology of the CME bubbles (see review by Vourlidas, Carley, and Vilmer, 2020). Such radio sources are usually referred to as *Radio CMEs* (e.g., Panel C in Figure 8). Thanks to their incoherent nature, when observed at multiple frequencies, they can be used to derive the coronal magnetic field and non-thermal electron distribution associated with the CMEs (see, e.g., Bastian *et al.*, 2001; Mondal, Oberoi, and Vourlidas, 2020; Chhabra *et al.*, 2021).

Propagation Effects. The propagation effects of radio waves provide other means for studying the middle corona. These observations utilize a known, point-like background radio source (e.g. a spacecraft transmitter or a natural celestial source such as a pulsar or radio galaxy) to “shine through” the corona. The observed radio signatures can be used to probe the structure and dynamics of the middle corona. Importantly, these trans-coronal radio sensing methods are applicable in all solar activity states and do not rely on observations of specific episodic outburst phenomena. Signal delays at different frequencies (i.e., dispersion measure) can be used to constrain the coronal density. Signal broadening and scintillation provide information on the density inhomogeneities in the turbulent coronal plasma (Rickett, 1990). Analysis of radio scintillation and frequency fluctuations (Panels D and E in Figure 8) can provide estimates of solar wind speed (Imamura *et al.*, 2014; Wexler *et al.*, 2019, 2020). In addition, modulations of the signal polarization due to Faraday rotation (Panel F in Figure 8) can be used to constrain the coronal magnetic field and its fluctuations (see, e.g., Wexler, Jensen, and Heiles, 2021; Wexler *et al.*, 2017; Kooi *et al.*, 2022, and references therein).

4. Properties and Transitions in the Middle Corona

The inner corona exhibits a broad range of temperatures, which can be in excess of $T > 10^7$ K in case of flares, and electron densities of $\sim 10^{15} \text{ m}^{-3}$ in closed structure regions. These closed magnetic field regions are generally associated with the relative confinement of plasma, with subsonic flow speeds and increased elemental abundances. The open-field configurations associated with coronal holes are known to produce fast solar winds and relatively low scale-heights, and exhibit FIP elemental abundances close to those of the photosphere. In contrast, the outer corona is generally a region of supersonic solar wind outflow, with an open magnetic field pattern and stabilized ionization charge states.

The characteristics of the middle corona straddle those of the inner and outer corona, and accordingly the region hosts a number of structural, dynamic and plasma physics transitions, as described in Table 1. The most important structural change is the transition from a mix of open and closed magnetic configuration to almost exclusively open-field structures.

Due to instrumental limitations, the middle corona has not been continuously or comprehensively probed by instruments that can provide self-consistent plasma parameters. As a result, the multiple physical transitions that occur here have not been fully characterized, and methods to study plasma properties must include extrapolation and modeling, often drawn from measurements of surrounding regions (e.g., Lynch, 2020; Schlenker *et al.*, 2021). Table 2 presents a list of canonical plasma properties measured/derived on either side of the middle corona illustrating the transitions that occur within the region.

The parameters in Table 2 are also subdivided into categories of fast and slow solar wind, to represent the range of values that are present in the different regions. Coronal holes are considered the source of the fast solar wind, streamers and pseudostreamers contain slow solar wind, and the remaining regions are

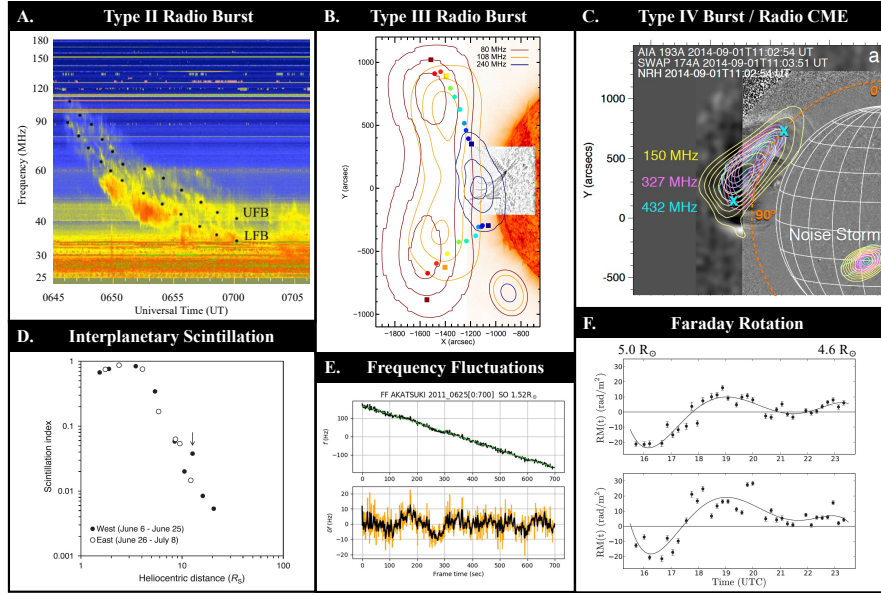


Figure 8. (A) Type II burst with a well-defined band-split into an upper and lower frequency branch (UFB and LFB, respectively), which can be used to estimate the coronal magnetic field strength (Figure 2 in Mahrous *et al.*, 2018). (B) Type III burst contours overlaid on an *SDO/AIA* 304 Å image. Tracking the radio burst over several frequencies illustrates an evolution from a single source in the inner corona to two separate sources split between two separate flux tubes in the middle corona (Figure 14 in McCauley *et al.*, 2017). (C) Type IV burst associated with a radio CME resulting from trapped non-thermal electrons emitting gyrosynchrotron radiation, which can be used to determine the CME’s magnetic field strength (Figure 2 in Carley *et al.*, 2017). (D) The scintillation index (representing the magnitude of the intensity fluctuations) as a function of heliocentric distance; intensity scintillation provides information on the plasma density and solar wind speed (Figure 3 in Imamura *et al.*, 2014). (E) Frequency fluctuations provide information on plasma density fluctuations and solar wind speed. Upper panel shows raw frequency data dominated by a Doppler shift and the bottom panel shows the frequency fluctuations with the Doppler shift removed (Figure 2 in Wexler *et al.*, 2020). (F) Faraday rotation provides information on the plasma density and magnetic field component along the line of sight. Differences between measurements along two closely-spaced lines of sight (provided here by a background radio galaxy) can be used to probe coronal electric currents (Figure 5 in Kooi *et al.*, 2014).

predominantly slow interspersed with some fast regions. In slow solar wind and streamer regions the supersonic solar wind outflow is achieved by approximately $5\text{--}6 R_{\odot}$ (Sheeley *et al.*, 1997; Wexler *et al.*, 2020).

As discussed in Sections 3.1 and 3.2, several instruments including UVCS and various radio arrays have probed the middle corona directly, providing measurements of density, proton temperature, ion temperatures, temperature anisotropy, outflow speed, ionization state and elemental composition. However, even for the relatively simple case of a quiet sun streamer various different estimates of the densities and temperatures have been published (Del Zanna *et al.*, 2018; Seaton *et al.*, 2021). This might be due to the large amplitude density contrasts on small

Table 2. Representative middle corona properties in fast and slow solar wind regions. The top portion includes representative measured and modelled quantities, the bottom portion includes derived quantities

Symbol	1.5 R_{\odot}		6.0 R_{\odot}		Units: Definition
	Fast	Slow	Fast	Slow	
n_e^a	1×10^{12}	7×10^{12}	6×10^9	3×10^{10}	m^{-3} : electron no. density
$T_{p,\parallel}^b$	1.6	2.0	1.9	0.85	MK: proton \parallel temperature
$T_{p,\perp}^b$	2.0	2.6	—	1.1	MK: proton \perp temperature
T_e^c	1.4	1.8	0.8	—	MK: electron temperature
$T_{O,\parallel}^d$	2	>1	60	>5	MK: oxygen \parallel temperature
$T_{O,\perp}^d$	10	20	200	20	MK: oxygen \perp temperature
V_{SW}^e	>100	<25	550	150	km/s: outflow speed
He/H ^f	—	8%	—	—	— : Helium/Hydrogen ratio
FIP _{bias} ^g	1.5–2.5	4–6	—	—	— : Elemental composition compared to photospheric composition
B^h	1.3×10^5	7×10^4	4×10^3	4×10^3	nT: magnetic field
C_S	150	170	160	100	km/s: sound speed
V_A^i	3000	600	1100	500	km/s: Alfvén speed
ω_{pe}	5.6×10^7	1.5×10^8	4.4×10^6	9.8×10^6	Hz: e ⁻ plasma frequency
β^j	< 0.01	≥ 0.08	< 0.1	≥ 0.04	plasma β , P_{gas}/P_{mag}

^a Bird and Edenhofer (1990); Guhathakurta *et al.* (1999); Raymond *et al.* (2018); Wexler *et al.* (2019)

^b Strachan *et al.* (2002); Frazin, Cranmer, and Kohl (2003); Cranmer, Panasyuk, and Kohl (2008); Cranmer (2020)

^c Raymond *et al.* (1997); Cranmer *et al.* (2009)

^d Strachan *et al.* (2002); Frazin, Cranmer, and Kohl (2003); Cranmer, Panasyuk, and Kohl (2008)

^e Woo (1978); Strachan *et al.* (1993); Raymond *et al.* (2018); Wexler *et al.* (2020); Romoli *et al.* (2021)

^f Moses *et al.* (2020)

^g Feldman *et al.* (1998); Young, Klimchuk, and Mason (1999); Raymond *et al.* (1997); Uzzo, Ko, and Raymond (2004)

^h Kooi *et al.* (2022); Yang *et al.* (2020); Wexler, Jensen, and Heiles (2021); Alissandrakis and Gary (2021); Hofmeister *et al.* (2017)

ⁱ Evans *et al.* (2008)

^j Gary (2001) for slow SW; note $\beta = \frac{C_s^2}{V_A^2}$

Note: 1 gauss (cgs) = 10^5 nT = 10^{-4} T (mks, S.I.).

scales (Raymond *et al.*, 2014) and estimates based on scattered light (average density) or emission lines (average density squared).

To a good approximation the magnetic field in the inner corona is force-free since the plasma beta is much smaller than unity. Throughout the middle corona the magnetic control is only partial. The confinement of plasma by closed fields diminishes, and stabilization or “freeze-in” of the ionization charge states occurs. This provides the basis for source region diagnostics based on measurements far from the middle corona. From the global heliospheric magnetic field modeling point of view, the middle corona is critical; the potential field

source surface (PFSS) is nominally placed at $2.5 R_{\odot}$, but actually may be more suitably placed at different middle corona region altitudes. With these several key transitions occurring over a relatively small radial distance range, intensive cross-disciplinary analysis is necessary to create internally-consistent models of the complex processes.

4.1. Elemental Composition

It is now well-established that the chemical composition of the corona varies depending on the structures observed and differs from the solar photospheric composition, although both recent revisions of older data and new analyses indicate that, at least up to 1 MK, the composition of the quiet solar corona is also close to photospheric (Del Zanna and Mason, 2018; Del Zanna *et al.*, 2018; Madsen *et al.*, 2019). The variability in chemical abundances depends, among other factors, on the First Ionization Potential (FIP) of the element and gravitational settling effects.

The FIP enhancement, in which elements whose neutral atoms have ionization potentials below 10 eV (e.g., Fe, Si) are increased relative to those with higher FIP (e.g., O, Ne) is around a factor of 2 to 4 in active region cores, helmet streamers, the slow solar wind and SEPs (Geiss, Gloeckler, and von Steiger, 1995; von Steiger *et al.*, 2000; Uzzo *et al.*, 2006; Baker *et al.*, 2013; Reames, 1999). In coronal holes and the fast wind the FIP enhancement is small or non-existent (Feldman and Widing, 1993).

Gravitational stratification (settling) of higher mass elements (compared to lighter ones) can appear in large, long-lived coronal structures, such as the cores of helmet streamers, which are observed throughout the middle corona (Raymond *et al.*, 1997). Spectral observations of helmet streamers from UVCS have shown a significant depletion of both low (FIP < 10 eV) and high (FIP > 10 eV) FIP elements (O, Si, Mg) in accordance to particle mass that is thought to be caused by gravitational settling taking place high in the corona (Uzzo *et al.*, 2003; Uzzo, Ko, and Raymond, 2004).

A similar effect was observed by SOHO/SUMER. This phenomenon results in mass fractionated coronal plasma where the loop apex becomes depleted of the heaviest elements as they sink towards the footpoints faster compared to lighter elements.

The gravitational settling shows strong spatial dependence, such that it becomes less pronounced between the helmet streamer core and legs. This variation is attributed to the transition between closed (core) and open/closed field (streamer edge) where plasma confined to the streamer core resides in the corona long enough for notable gravitational settling to take place, ~ 1 day, while plasma on the open/closed field boundary is released on a faster timescale (Lenz, Lou, and Rosner, 1998). These observations indicate that gravitational settling can be important in regulating the plasma's chemical composition in large coronal loops, and can be a distinctive compositional signature of helmet streamer plasma observed in the form of heavy element dropouts in the solar wind at 1 AU (Weberg, Zurbuchen, and Lepri, 2012; Weberg, Lepri, and Zurbuchen, 2015). These are believed to correspond to pulses of gas released from the cusps of

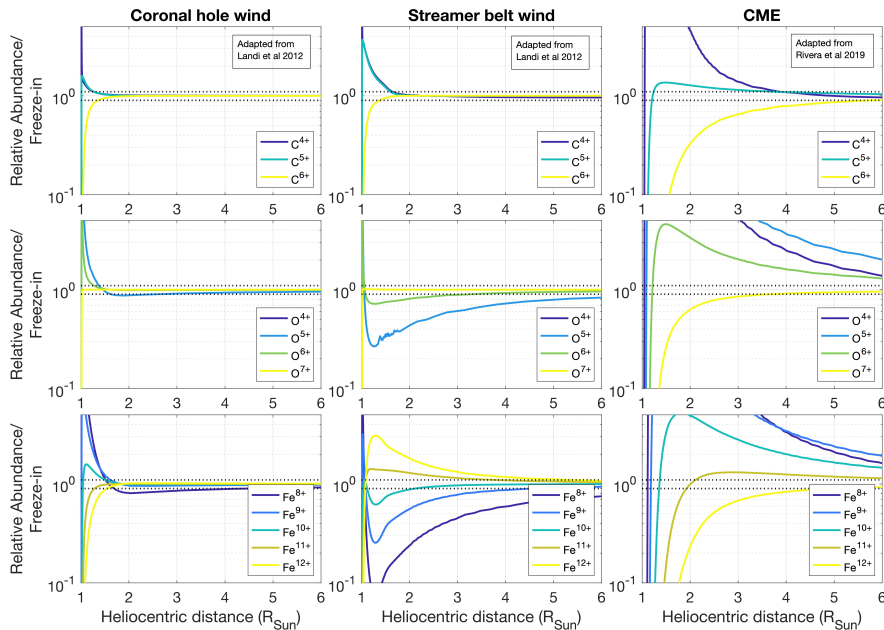


Figure 9. Radial evolution for selected C, O, Fe ions within simulated coronal hole wind, equatorial streamer belt solar wind, adapted from Landi *et al.* (2012), and a CME adapted from Rivera *et al.* (2019). The horizontal dashed lines represent ions reaching 10% of its freeze-in value.

helmet streamers by reconnection. However, further examination of gravitational settling and variability in the chemical composition across the middle corona is necessary to further characterize solar wind origin and the pathways to its formation and connection to heliospheric structures.

4.2. Charge State Evolution and Freeze-in Distances

One important transition point occurring in the middle corona is height at which heavy ion abundances in the solar wind and CMEs reach their “freeze-in” altitude (Hundhausen, Gilbert, and Bame, 1968; Owocki, Holzer, and Hundhausen, 1983). The so-called freeze-in process takes place as charge states become fixed at some radial distance from the Sun where the plasma becomes 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 throughout the solar wind’s radial evolution.

In-situ measurements of ions can be tied to their sources in the corona by comparing frozen-in populations. As a result freeze-in states can be used to probe the heating and cooling in the nascent solar wind prior to freeze-in.

Freeze-in distances are governed by the plasma’s electron temperature, density, and outflow speed, which result in large ranges of freeze-in distances among solar structures throughout the middle corona. (Boe *et al.*, 2018) used as a proxy for the freeze-in distances the regions where the resonant scattering dominates

in visible light observations of $\text{Fe}^{10,13+}$. They found in coronal holes and helmet streamers distances of $1.25\text{--}2 R_{\odot}$ and $1.45\text{--}2.2 R_{\odot}$, respectively. However, theoretical freeze-in heights can be considerably larger in pseudo-streamers (Shen *et al.*, 2018). Similarly, simulations of the solar wind have shown that freeze-in distances for other ions of C, O, and Fe in coronal hole wind can range between $1\text{--}2 R_{\odot}$, while in equatorial streamer belt wind ions may evolve beyond $5 R_{\odot}$, as shown in the left and middle column of Figure 9 (Ko *et al.*, 1997; Landi *et al.*, 2012; Gilly and Cranmer, 2020).

In CME plasma, ion freeze-in distances are predicted to reach beyond $6 R_{\odot}$ in the dense prominence core, as shown in the right column of Figure 9 (Rivera *et al.*, 2019). Also, the higher velocities in CMEs can be an important factor in the higher freeze-in heights (Rakowski, Laming, and Lepri, 2007). Simulations of the freeze-in process using nonequilibrium ionization (NEI) conditions have enabled studies of the corona’s thermodynamic state using heavy ion composition that reflect the plasma’s early stages of ionization evolution (see, e.g., Landi *et al.*, 2012; Gilly and Cranmer, 2020). Multi-wavelength observations throughout the middle corona will place more stringent constraints on the ion evolution at these critical freeze-in heights to strengthen the connection made between the Sun and in situ observations taken by orbiting spacecraft.

Anomalous charge states observed at 1 AU are believed to arise in the middle corona, where CMEs show very high (Fe^{+17}) and very low ($\text{Fe}^{+3,+4}$) charge states. Anomalous dropouts of fully stripped ions such as C^{+6} are also observed. However, there is no clear interpretation of how these bare ion dropouts occur (Kocher *et al.*, 2017; Zhao *et al.*, 2017; Rivera *et al.*, 2021).

4.3. Topology of the Middle Corona

There are three major distinct types of topology that dominate the middle corona: the closed streamers, including their cusps; rays of various types; and open field. The three have unique characteristic speeds, densities, plasma betas, compositional and FIP values. (An additional, transient, topological feature is large-scale closed loop systems, or giant arches, formed by magnetic reconnection during large eruptions, which can reach well into the middle corona and persist in active regions for days to weeks; West and Seaton 2015.)

Coronal holes undergo several changes in the middle corona region: the magnetic field expands super-radially and fast solar wind acceleration occurs, generally in the lower reaches of the middle corona (Cranmer, 2009, and references therein). The cause of this acceleration is still a topic of some debate, and is one of the middle corona’s most important open questions. In contrast, the slow solar wind is organized in the middle corona and initial acceleration to the supersonic threshold occurs. The wind is believed to become super-Alfvénic at varying distances between $10\text{--}25 R_{\odot}$ into the extended corona and heliosphere (Wexler *et al.*, 2021); where the kinetic energy dominates over the magnetic energy, regardless of the value of the plasma β .

Helmet streamer cusps lie in the middle corona region; these form the heliospheric current sheet, as well as some secondary topological surfaces (e.g., above

polar crown filaments; Rachmeler *et al.*, 2014). Here high-beta plasma and magnetic field fluctuations near the magnetic y-points pinch off to form plasmoids or “blobs” (Wang and Hess, 2018). While helmet streamers are generally fairly quiescent and contain the only magnetic field not directly connected to the solar wind in this region, they are also the source of streamer blow-outs, some of the largest and most internally-coherent coronal mass ejections in the heliosphere (Lynch *et al.*, 2010; Vourlidas and Webb, 2018).

Rays are a term that can be applied to any of various structures of the same basic null point topology. Plumes and jets, which generally lie in open field regions, have extensive collimated columns of enhanced-density plasma extending above their domes in the low corona, which have often been observed at several solar radii or more (Del Zanna, Bromage, and Mason, 2003; Raouafi *et al.*, 2016; Karpen *et al.*, 2017; Kumar *et al.*, 2019; Uritsky *et al.*, 2021). They have long been postulated as a small but relatively stable source of contributions to the solar wind, and some middle corona observations show outflows into such smaller-scale features (Seaton *et al.*, 2021).

Pseudostreamers, which are similar to streamers in appearance, but topologically more complex, also have outer spines that are often seen in coronagraph imagery, potentially appearing as miniature low-lying streamer cusps, as the narrow spines themselves, or rarely as dim fans curving away from the dome surface, depending upon the height and angle of viewing. Evidence shows that coherent magnetic structures attempting to escape the low corona can be destroyed by reconnection in these null-point topologies, leading to large streams of unstructured plasma being ejected into the solar wind from these narrow rays (Vourlidas *et al.*, 2017; Kumar *et al.*, 2021; Mason, Antiochos, and Vourlidas, 2021; Wyper *et al.*, 2021).

This collection of qualities is described by the S-web, a map of separatrices and quasi-separatrix layers (QSLs) in the heliosphere (e.g. Antiochos *et al.*, 2011). The major separatrix lines show the HCS, while the QSLs are smaller arcs corresponding to pseudostreamers, jets, etc. Taken together, the topological picture of this region is diverse and rich; the closed but dynamic streamer belt regularly extrudes blobs of closed field and relatively dense plasma into the otherwise narrow and well-structured heliospheric current sheet. Much of the remaining volume is filled in by the expanding field and tenuous plasma of the coronal holes, occasionally punctuated by tight spears of condensed field and plasma introduced by null-point topologies. New large-field-of-view EUV observations have recently provided direct imaging of the S-web and its complex dynamic behavior in the middle corona (Chitta *et al.*, 2022), validating models that predicted its importance in governing the topological and dynamic transitions that occur in here.

5. Modeling and Spectral Diagnostics of the Middle Corona

Because of the multiple physical transitions within the middle corona – and the instrumental limitations that have hampered a complete characterization of them – a unified model of middle corona physics does not yet exist. The lack

of continuous, comprehensive measurements of the region as a whole has also limited the availability of high-quality, data-based model boundary and initial condition parameters. However, a limited number of direct measurements from UVCS and various radio arrays have provided estimates of density, proton temperature, ion temperatures, temperature anisotropy, outflow speed, ionization state and elemental composition. (See Section 4 for a thorough discussion.)

5.1. Spectral Diagnostics and Forward Modeling

A general description of the underlying atomic data needed to model the coronal emission and obtain information on the plasma state appears in the Living Review by Del Zanna and Mason (2018). Modeling the visible/IR continuum emission resulting from the disk radiation being Thomson-scattered by the free electrons is relatively simple, although a knowledge of the spatial distribution of the electron density is required. Following van de Hulst (1950), in most cases the modeling assumes a homogeneous distribution with spherical/cylindrical symmetry. This is routinely used to infer the radial density profile from measurements of the polarized Brightness (pB). However, this is an over-simplification, as the corona is known to be finely structured (e.g., the images in Habbal, Morgan, and Druckmüller, 2014, and many other similar solar eclipse observations).

As the middle quiescent corona appears to have an electron temperature around 1 MK (Seaton *et al.*, 2021; Boe *et al.*, 2020), it emits a range of coronal lines from the X-rays (above 20 Å) to the near infrared, mostly from highly ionized atoms. The strongest coronal lines are allowed transitions in the EUV/UV, between 170 and 1100 Å, and forbidden transitions in the visible and near infrared. The modeling of most of the allowed transitions is relatively simple, as their emissivity mainly depends on the local electron density and temperature, as well as chemical abundances and ionization states. The main populating mechanism is excitation by electron collisions (collisional excitation), and the observed radiance is proportional to the square of the electron density. However, there are cases where photo-excitation by the disk radiation in the visible/near infrared affects the ion populations, as in the case of Fe XIII (see, e.g. Dudík *et al.*, 2021), which somewhat changes the predicted emission of the allowed transitions. Measurements of the density from line ratios are available for the inner corona.

There is a range of allowed transitions from neutrals or ionized atoms which become very strong by direct resonant photo-excitation from the disk radiation. Examples are lines from H I, He I, He II, and O VI, which are the strongest in the lower and middle corona. Such atoms produce a very strong solar disk emission from the chromosphere/transition region, and naturally produce little emission at coronal temperatures/densities. Hence, a large fraction of their coronal emission is produced by resonant photo-excitation. Their modeling is complex as it depends strongly on the distribution of the disk radiation, which is highly variable and, in the case of He, also controls the charge states via photo-ionization. Modeling the Helium emission has several extra complications, as discussed in the first coronal model by Del Zanna *et al.* (2020). Lines from these

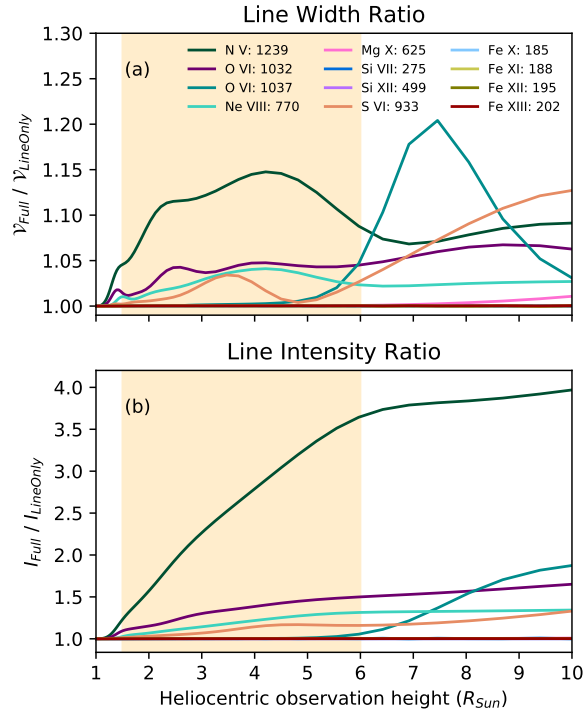


Figure 10. Ratio of modelled ion line properties as a function of height from (Gilly and Cranmer, 2020). (a) Excess width caused by including continuum. (b) Excess intensity caused by including continuum. The shaded orange region indicates the Middle Corona.

ions offer several diagnostics, the most widely used one being Doppler Dimming, to measure the outflow velocity (see, e.g. Noci, Kohl, and Withbroe, 1987).

Doppler effects must be considered when forward modelling the corona, or the calculation will be truncated. Figure 10 shows the difference between two runs of the GHOSTS code (Gilly and Cranmer, 2020), which simulates both collisional excitation and resonant scattering along lines of sight over the North solar pole. The only change between the two runs is the choice of incident light profile in the resonant scattering calculation: The “Full” case uses a window that contains realistic continuum out to the edge of the Doppler-shifted scattering window, while the “Line Only” case simply uses a model Gaussian spectral line. Panel 10(a) shows the change in the full width half maximum of the lines produced in each case, which can be as much as 15% in the middle corona. The effect on line intensities is much greater: Panel 10(b) demonstrates that some lines can be brightened by a factor of 1.5 - 4. Because of these effects, it is important to include a sufficient range into and out of the plane of the sky along the line of sight, and the incident light profile used in the scattering calculations must be wide enough and include a realistic continuum component such that the scattered light profile doesn’t artificially truncate.

Calculations of the collisional excitation rates, which started in the 1970s, have now reached, for a few key ions, an accuracy of the order of 10–20%. (For a

recent review of a series of calculations for astrophysical ions see Badnell *et al.* (2016). Calculations of the decay rates for spontaneous emission now have an even better accuracy (see e.g. the review by Jönsson *et al.*, 2017). The atomic rates for the coronal ions in the EUV/UV are relatively complete and accurate, as a series of benchmark studies has shown (see Del Zanna, 2020, 2019; Del Zanna and Mason, 2018, and references therein), although significant improvements in the soft X-rays are still needed (Del Zanna, 2012). The latest set of atomic rates made available to the community are included in CHIANTI version 10 (Del Zanna *et al.*, 2021). The database also includes some approximate treatment of resonant scattering.

The ionization state is controlled by collisions with free electrons. The ionization and recombination rates, which are needed to calculate the ion abundances, either in equilibrium or not, are somewhat more uncertain. Fortunately, the modeling of the ionization state is relatively simple as most of the ion populations are in their ground state, hence it only depends on the electron temperature. Note, however, that there can be cases when photo-ionization from the disk can affect the ion balance in the corona and the solar wind (Landi and Lepri, 2015).

In summary, to model the radiances of the allowed transitions not affected by resonant photo-excitation, knowledge of the electron density and temperature is needed. Estimates of the averaged density in the middle corona are widely available via the pB measurements and the van de Hulst (1950) inversion. However, direct measurements of the electron temperature have been lacking (Del Zanna and Mason, 2018). This is one of the major problems when modeling the middle corona.

Therefore, modeling usually relies on the temperature obtained from line ratios assuming that ionization equilibrium holds i.e. the ionization temperature. That is usually a reasonable assumption in the low quiescent corona but not necessarily in the middle corona, where the ionization state needs to be calculated taking into account estimates of local flows, densities and temperatures.

Strong emission in the middle corona is also produced by forbidden lines in the visible/near infrared by highly-ionized atoms, see the review by Del Zanna and DeLuca (2018). There are also many weaker forbidden lines in the UV. As in the case of the allowed transitions by neutral or low-charge ions, these lines are photo-pumped by the disk radiation. The advantage of such transitions is that they are visible out to great distances (cf. Habbal *et al.*, 2011). However, they are also complex to model and use for diagnostic purposes.

Firstly, accurate collisional excitation rates for these forbidden lines are difficult to obtain as they require large-scale scattering calculations. Such calculations for iron ions have shown significant increases (50–100%) in the predicted emissivities of some key transitions (cf references in Del Zanna and Mason, 2018). However, not all ions have accurate atomic rates available. Also, large-scale models that are not currently available in CHIANTI are needed to account for all the cascading effects from high-lying states.

Secondly, as any atom affected by resonant photo-excitation, accurate estimates of the disk radiation are needed. For the visible and near infrared lines this is achievable as the disk radiation has little variability, but is more challenging for UV lines, where disk irradiance is both variable and inhomogeneous

(Vernazza and Reeves, 1978). Thirdly, an accurate knowledge of the local density is needed, to calculate the relative contribution of the collisional excitation and resonant photo-excitation processes. Obtaining densities from e.g. line ratios of forbidden lines is not trivial: the plane of the sky approximation is reasonable for the allowed transitions not affected by resonant photo-excitation, but the lines affected have a significant long-range contribution (see, e.g. Yang *et al.*, 2020). As a consequence, measurements of the ionization temperature from the resonant photo-excitation lines becomes strongly dependent on the distributions of the electron densities. The same issues apply when measuring chemical abundances.

Detailed knowledge of the emission mechanisms that act in the middle corona has led to the development of a variety of forward models and modeling frameworks (e.g., FORWARD; Gibson *et al.*, 2016). However, as knowledge of the nature of emission from the middle corona is quickly evolving, the terrain for modeling of this region is also shifting rapidly. Such forward models have been used both to characterize middle corona structure and improve understanding of the emission sources themselves, which is critical for developing more robust plasma diagnostics.

The best known examples of forward models that include the middle corona are probably the *Predictive Science Inc.* eclipse predictions, which capture global coronal structure extending out through the middle corona, in an attempt to predict the corona’s appearance across a variety of wavelengths, prior to a total eclipse (Mikić *et al.*, 2018)². These predictions leverage the Magnetohydrodynamic Algorithm outside a Sphere (MHD-MAS; see additional discussion in Section 5.3) global coronal model, which has also been used to extensively characterize the topology and thermodynamics of the corona, addressing a number of open questions about the nature of the corona’s large-scale magnetic structure, including within the middle corona (e.g., Riley *et al.*, 2019). Examples of forward modeling from these simulations are shown in Figure 11, which highlight how both broadband K-corona signatures as well as photo-excited coronal emission lines can be synthesized from MHD models. Such diagnostics can be used to tease out information about the K and F corona from eclipse observations (Boe *et al.*, 2021) as well as benchmark the temperature, densities, and charge-state distributions predicted by the MHD models through comparison to narrowband emission lines (Boe *et al.*, 2022).

Other forward modeling efforts specifically focused on structures within the middle corona include those of Goryaev *et al.* (2014), who developed a forward model to simulate the coronal emission of a streamer in EUV and visible-light, using assumed distributions of the electron density and temperature. The distribution parameters were determined by the solution that best fit EUV observations from SWAP and Hinode/EIS, and visible-light observations from the Mauna Loa Mk4 Coronagraph. The streamer plasma temperature near the solar limb was found to be nearly isothermal from 1.2–2 R_{\odot} , at 1.43 ± 0.08 MK. They estimated the hydrostatic scale-height temperature from the determined density distribution and found it to be significantly higher, at 1.72 ± 0.08 MK.

²<https://www.predsci.com/corona>

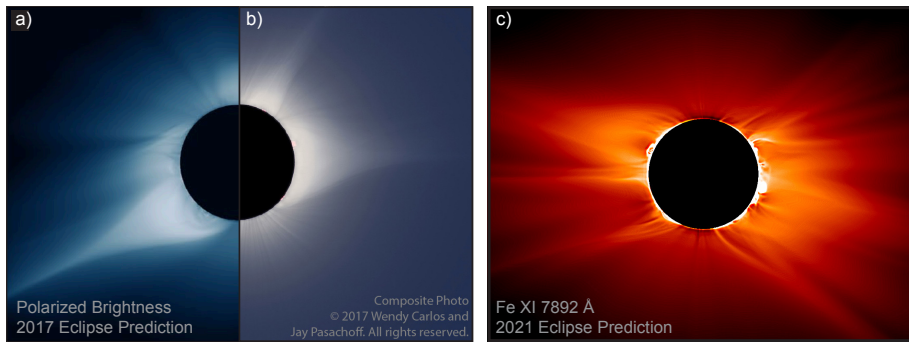


Figure 11. Two examples of forward modeling from the PSI eclipse predictions. Left panels: a merged image comparing the polarized brightness prediction for the August 21, 2017 total solar eclipse (a) to a processed eclipse photo (b, images adapted from Mikić *et al.*, 2018). Panel (c) shows radially filtered, sharpened radiances for the photoexcited Fe XI 7892Å emission line for the December 14, 2021 eclipse prediction (<https://predsci.com/eclipse2021>, see Boe *et al.*, 2022, for details on the method).

They suggested that an outward plasma flow along the streamer could be the cause of the discrepancy. They estimated that more than 90% of the observed EUV emission from the streamer was due to collisional excitation, whereas in the background corona above $2 R_{\odot}$, resonant scattering may become comparable to collisional excitation in its contribution.

Del Zanna *et al.* (2018) developed a cylindrical-symmetry model which reproduced SoHO/UVCS observations of the H I Ly α and coronal lines between 1.4 – $3 R_{\odot}$ in quiescent streamers. The radial profile of the electron density was close to what was obtained from pB measurements, and the ionization temperature was constant at 1.4 MK. The extrapolated densities at lower heights and the same temperature were successful in predicting the signal of the inner corona in near-infrared lines as measured during two solar eclipses in 2017 and 2019 by AIR-Spec, an Airborne Infrared Spectrometer, see Madsen *et al.* (2019); Samra *et al.* (2021).

5.2. Modeling the Energetic Events

The basic picture of slow energy build-up through magnetic field contortions and rapid energy release through magnetic reconnection is well established. However, the details of *how* that energy is released remain an area of active research. For CME energy storage and release alone, there are at least 26 review papers and ≥ 75 model papers spanning 18 physical mechanisms over the past 2 decades (Green *et al.* 2018 and references therein). A significant portion of that energy release is most clear in the middle corona, where CMEs experience the bulk of their acceleration (e.g., Bein *et al.* 2011; D’Huys *et al.* 2014).

Each of the numerous CME mechanism models can produce predicted kinematic profiles for the resultant CME (height–time, speed–time, acceleration–time), which have characteristic shapes that can be altered by varying the dependencies in the model. For example, the torus instability model (Kliem and Török, 2006) can be modified with an upward velocity perturbation whose

duration can be modified – an approximation for continued energy release powering the acceleration – and not only does the acceleration-time profile peak at earlier times with a longer velocity perturbation, it can change from a single acceleration peak to having two acceleration peaks (Schrijver *et al.*, 2008).

As another example, the helical kink instability tends to produce acceleration profiles with very strong jerks resulting from the magnetic flux rope twist exceeding a critical threshold of 448° (e.g., Fan, 2016). In these two cases, and many others, the acceleration profiles differentiate themselves in the middle corona. A comprehensive summary of all of the physical mechanisms is beyond the scope of this paper, but it has already been well covered by, e.g., Green *et al.* (2018) and Chen (2011).

Most of these models require magnetic reconnection to liberate the stored energy needed to accelerate CMEs and power their companion solar flares. Many reconnection models and observations also predict the formation of a large-scale plasma sheet associated with reconnection, extending from the low to middle corona. Though some models predict that reconnection itself occurs primarily in the low corona (Forbes, Seaton, and Reeves, 2018), both these models and observations of real events predict that upward-directed reconnection jets will dominate the dynamics of the middle corona in the wake of a CME (Yu *et al.*, 2020). Sophisticated numerical models now appear to capture the dynamics of eruptive CME reconnection itself and the supra-arcade downflows (SADs) which often accompany this process (Shen *et al.*, 2022). Since SADs often appear to originate from the middle corona (Savage and McKenzie, 2011) these new models help to explain one of the most important manifestations of energy release in this region in the wake of large eruptive events.

Importantly, both the limited observations we already have (Section 3) and the numerous models suggest that the middle corona is a key region for developing comprehensive understanding of CME energy release and acceleration. However, only with the next generation of high-sensitivity middle corona observatories are we likely to obtain sufficient observations to develop comprehensive, data-constrained models of eruptions, that include the global-scale processes that govern the early evolution of these events.

5.3. Global Coronal Models

Many studies have used PFSS extrapolations (Schatten, Wilcox, and Ness, 1969; Altschuler and Newkirk, 1969) to estimate the topology of the global coronal magnetic field, and hence consider the magnetic field of structures within the middle corona. For example, Goryaev *et al.* (2014) in estimating the magnetic structure of a coronal streamer and Seaton *et al.* (2013a) considering a coronal fan.

One parameter in a PFSS is the source surface height, R_{ss} , which is the height at which magnetic field lines become radial and are considered open. Many take the ‘default’ value of the source surface to be $R_{ss} = 2.5 R_\odot$, although some studies have shown that a lower source surface height may give a better fit to observations (e.g. Asvestari *et al.*, 2019). Sarkar *et al.* (2019) combined observations from the large FOV of SWAP and the LASCO C2/C3, to cover the

whole middle corona region, and by tracking the evolution of a cavity (EUV) into the three-part structure of the associated coronal mass ejection (visible-light), observed on 2010 June 13, captured the kinematics of the eruption. By applying successive geometrical fits they found that the cavity exhibited non-self-similar expansion in the low and middle corona, below $2.2 \pm 0.2 R_{\odot}$, indicating a spatial scale for the radius of the source surface.

A non-potential magnetic field model is a step up in complexity from a PFSS, allowing for free magnetic energy and electric currents within the volume. Meyer *et al.* (2020) investigated large-scale structures in the middle corona by comparing a data-driven, non-potential, global coronal magnetic field model with EUV observations from SWAP. The lower boundary condition for the model was a global photospheric magnetic flux transport simulation which incorporated observed active region magnetic field data derived from the SDO/HMI-driven AFT model (Upton and Hathaway, 2014), from 2014 September to 2015 March. The initial condition for the model was a PFSS extrapolation on September 1. The global coronal magnetic field was then evolved in time using a magnetofrictional relaxation method (van Ballegoijen, Priest, and Mackay, 2000; Mackay and van Ballegoijen, 2006), which produced a continuous series of non-potential equilibria in response to lower boundary motions from the flux transport simulation.

Meyer *et al.* considered the simulated coronal magnetic field from 2014 October onward, to allow sufficient time for the field to evolve away from its initially potential state. The model was found to reproduce the general structure of the global corona well. Discrepancies between the observed and model corona typically occurred off the east solar limb, caused by active regions having emerged on the far side of the Sun, which cannot be incorporated into the model until they are observed on the near-side. The simulated corona was found to self-correct within a few days, but only after the ‘late’ active region emergences were incorporated into the model. They followed the evolution of a particular coronal fan that was observed by SWAP over four Carrington rotations, from 2014 October to 2015 January. The model was able to reproduce the observed structure of the fan, particularly when observed off the west limb. The model indicated that the magnetic structure underlying the fan changed from a streamer to a pseudostreamer configuration during its evolution.

Yeates *et al.* (2018) compared seven different global non-potential coronal magnetic field models, which were all used to model the solar corona during the 2015 March 20 total eclipse. Included in the comparison were a magneto-hydrostatic model (Bogdan and Low, 1986); non-linear force-free field models, including optimization (Wiegelmann, 2007), Grad-Rubin (Amari *et al.*, 2013), force-free electrodynamics (Contopoulos, Kalapotharakos, and Georgoulis, 2011) and the time-evolving magnetofrictional method (Mackay and van Ballegoijen, 2006); and MHD models including the AMR SIP-CESE Solar Wind model (Feng *et al.*, 2012) and MHD-MAS (Mikić *et al.*, 1999). All models produced static extrapolations of the corona on the day of the eclipse, with the exception of the magnetofrictional model, which simulated a continuous time-evolution of the global corona from 2014 September 1 to 2015 March 20.

Filament channel locations based on this magnetofrictional simulation were used to energize the MHD-MAS model. To evaluate their success, the plane-of-sky coronal structure of each model was compared with a stacked EUV image from SWAP and an Fe XIV 5305 Å image of the corona during the eclipse, and sheared magnetic field structures in the models were compared with filaments observed in an H α image from Big Bear Solar Observatory. Yeates *et al.* (2018) found that the models showed general agreement in magnetic topology and the ratio of total to potential magnetic energy, but showed significant differences in electric current distributions. Static extrapolations were found to best reproduce active regions, whilst the time evolving simulation could successfully recover filament channel fields. The authors recommended overall that a hybrid approach may be most suitable, using static extrapolations that are energized by a simplified evolution model, such as the MHD-MAS/magnetofrictional hybrid example they presented.

Indeed, Mikić *et al.* (2018) produced a prediction of the global corona for the 2017 August 21 solar eclipse using the MHD-MAS model, energized by filament channel information from a time-evolving magnetofrictional simulation in the months leading up to the eclipse. They compared the simulated corona with visible-light and EUV observations of the corona during the eclipse, finding that discrepancies between the model and simulations arose due to limitations in our current ability to observe the solar magnetic field, such as new active regions having emerged on the far side of the Sun.

Two observational constraints for global magnetic field modeling are that the open field regions in the model should approximately correspond to coronal holes observed in emission, and that the magnitude of open flux from the model should match that determined from in situ spacecraft. Linker *et al.* (2017) computed MHD and PFSS models from five different types of observatory magnetograms around 2010 July. They found that for all combinations of maps and models, the models which had open flux areas consistent with the observed coronal holes underestimated the interplanetary magnetic flux, and the models that matched the interplanetary magnetic flux had larger open flux areas than the observed coronal holes, hence raising an open flux problem.

Riley *et al.* (2019) investigated whether the “missing” open flux could be explained by adding flux to the polar regions, at latitudes too high to be resolved by ground-based observatories or Earth-based satellites. Through PFSS and MHD magnetic field modeling, they showed that this additional polar flux could partially address the open flux problem. These models were constructed to coincide with the 2010 July 11 total eclipse, so that plane of sky coronal structures could also be compared between the models and visible-light observations of the corona during the eclipse, where the global structure of the magnetic field becomes clear predominantly in the middle corona. Through this comparison, they concluded that the additional polar flux did not generate any new observational discrepancies, and indirectly demonstrated the value of middle corona observations as important constraints on global coronal models.

6. Open Questions and a Strategy to Answer Them

The middle corona is a region of critical transitions straddling the inner and outer corona, to the point where it has occasionally been labelled *the transition corona* (e.g. Masson *et al.*, 2014; Vourlidas *et al.*, 2020; Golub *et al.*, 2020). These transitions include the change from predominantly closed to open magnetic field structures, and the change from low to high plasma β in specific regions. The middle corona is implicitly 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 drive important effects in these regions and farther afield, including at the Earth and other celestial bodies, especially 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 , for example, varies widely within the middle corona. In general, however, $\beta \ll 1$ in the lower corona, and magnetic field dominates plasma dynamics almost everywhere, 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, these 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, particularly in streamers.

Ultimately the plasma kinetic energy dominates the magnetic field structure in the super-Alfvénic flow regime beyond 10–20 R_{\odot} , as seen in Parker Solar Probe (Fox *et al.*, 2016) in-situ data, even as plasma β varies across the unity threshold (Wexler *et al.*, 2021). In *open* field structures such as plumes (e.g., DeForest, Plunkett, and Andrews, 2001) or streamers it is believed that the release from low- β dominance occurs mainly in the outer corona, where plasma can flow freely outwards. However, the quiet sun and active region inner corona is dominated by closed field structures with more complex topology, where under certain conditions the plasma pressure can overwhelm the magnetic pressure, such as along magnetic neutral lines in streamers (Vásquez, van Ballegoijen, and Raymond, 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 under certain conditions can be released as eruptions and flares. The relative magnetic easing from very low β to a higher and variable role of gas pressure occurs largely in the middle corona. Understanding where the transitions occurs will help us better understand the plasma dynamics and how flows and eruptions are influenced.

In spite of these important transitions, however, remote sensing observations in both radio and shorter wavelengths have been insufficient to definitively characterize its global properties (see Sec. 3). Occasional instrumental off-points, eclipses (see Section 3.1.2), and radio imaging have helped bridge the gap, but only intermittently.

Importantly, the primary methods used to observe the inner and outer corona already create an artificial boundary between these regions (Byrne *et al.*, 2014). From an imaging perspective, the differing X-ray, EUV, and narrowband visible observations primarily sample line-of-sight *emission measure*, the amount of emitting material at the temperature the passband samples, while broad-band visible coronagraph observations sample electron density (at all temperatures) along the line-of-sight.

Reconciling large-scale, multi-thermal, three-dimensional bright structures, such as solar eruptions, across multiple passbands is difficult (see e.g., O’Hara *et al.*, 2019). The absence of continuous and self-consistent observations, and an incomplete understanding of the underlying plasma properties, (see Section 5), has exacerbated the challenge of developing a deep understanding of the middle corona and its properties and behavior. We are left with several important questions that must be addressed to close this knowledge gap. In the following section we discuss a few of these key questions before presenting a broad strategy that could help to address them in Section 6.2.

6.1. Open Questions Relating to the Middle Corona

6.1.1. Questions Concerning Transitions

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

The many transitions that occur within the middle corona include the change from predominantly *closed* to *open* magnetic field structures and the change from low to high plasma β in quiet sun regions. These changes will vary throughout the region depending on the underlying coronal structures and plasma properties. The lack of comprehensive, systematic, and self-consistent observations through the region, in particular those that can provide density, temperature, and magnetic field estimates, 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 (Section 4.2). 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. The height of freezing-in is still debated and can occur throughout the middle corona. New observations are required to constrain modelled plasma properties which are used to derive freeze-in heights.

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, the inner corona is composed primarily of closed magnetic structures, while the outer corona is almost entirely radial, open magnetic field. The transition between these two regimes occurs entirely within the middle corona, but neither existing observations nor models have been sufficient to fully characterize how this transition occurs or the important role it plays in determining the dynamics that occur here. Increasingly, simulations (Higginson, 2016) and observations (Chitta *et al.*, 2022) have revealed the ways in which the complex topology of this region and the interactions that occur in the S-web dictate structure embedded throughout the heliosphere, but much more work is needed.

*6.1.2. Questions Concerning Outflow and Inflows***How does the evolving structure of the middle corona drive the structures that shape outflow into the solar wind?**

Central to the understanding of solar wind formation is the knowledge of the connection between the solar corona and the heliosphere (Viall and Borovsky, 2020). The heliospheric magnetic field is composed of an open field anchored in the photosphere, while lower in the corona the field is dominated by closed structures. The boundary between the open and closed field, 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 a lack of sensitivity and coverage in the middle corona region. Understanding this feedback is critical for heliospheric studies since it determines how hot magnetized plasma enters interplanetary space. Furthermore, the open magnetic field and associated plasma 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, Altschuler, and Harvey, 1968; McComas *et al.*, 2007; Yeates, Mackay, and van Ballegooijen, 2008). These deviations from the radial field have implications for the large-scale energy storage in the corona. These implications have yet to be fully explored because of the lack of observations in the middle corona region.

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

Inflows have been shown to interact with structures in the inner corona, including large scale flows seen in EUV observations (Seaton *et al.*, 2021), SADs seen in the wake of solar eruptions (Savage, McKenzie, and Reeves, 2012), weaker inflows on many scales (Sheeley and Wang, 2014). Smaller or fainter downflows may also be ubiquitous in the less dynamic atmosphere but could trigger eruptions through mechanisms such as magnetic breakout (e.g., Antiochos, DeVore,

and Klimchuk, 1999). The exact nature of this interaction and the frequency of downflows are not fully known due to the weak signal in the far-field of EUV observations, and consequently a lack of observations. The lack of understanding of this feed-back also leaves gaps in unified coronal-heliospheric models.

6.1.3. 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). Likewise, interactions within the middle corona can sometimes alter the trajectories of mature CMEs (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). However, the lack of self-consistent observations of the region presents a barrier to comprehensive understanding of how the forces and structures that emerge here manifest to shape the evolution of solar eruptions. By fully characterizing CME kinematics from the inner corona through the middle corona, we can ascertain how the background solar atmosphere interacts with the eruption, which forces are dominating, and perhaps understand the background solar conditions.

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?

Theoretical predictions suggest the magnetic reconnection that powers eruptive solar flares should occur relatively low in the corona (Forbes, Seaton, and Reeves, 2018), but only a few observations, such as those by Yu *et al.* (2020), have successfully isolated this location. Other manifestations of reconnection, such as SADs, can originate much higher – well into the middle corona – posing a mystery: what is the relationship between SADs and reconnection, and what do they have to teach us about one another? Likewise, other types of reconnection, like magnetic breakout, may occur high above pre-eruptive structures (Lynch and Edmondson, 2013), potentially within the middle corona, but such processes have only rarely been observed. Still other types of CMEs, including so-called “stealth CMEs,” originate from unknown processes even higher in the middle corona (D’Huys *et al.*, 2014), but may be driven by reconnection in streamers. Better observations of the middle corona are needed to provide important into the role of magnetic reconnection in all of these disparate situations.

How do CME-driven waves and shocks influence the middle corona, particularly to accelerate particles? What can these tell us about CMEs themselves?

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, and includes: through through the aforementioned down-flows generated in the wake of eruptions (SADs); the movement 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, Mancuso, and Bemporad, 2020). Understanding these interactions are particularly important for the space-weather community.

6.2. A Strategy to Maximize our Understanding of the Middle Corona

Figure 2 presents a summary overview of the past, present, and near-term future of middle corona observations, highlighting the patchwork nature of our coverage of this important region. The systematic observations of the solar disk and inner corona over the past few decades have been extraordinarily successful in addressing the longstanding questions that the instruments were optimized for. However, while middle-corona-optimized missions presently in development or proposed for the future are likely to lead to some progress towards more systematic observations of the region, we remain a long way from the structured, well-coordinated observations needed to resolve the questions outlined in Section 6.1.

In particular, numerous studies, such as those of Byrne *et al.* (2014) and 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 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. This observational gap must be closed.

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. Missions like SunCET (in development) and ECCCO (proposed) can serve as important pathfinders, so the technologies and strategies that follow them can lead to a generation of imagers that can fully connect the inner, middle, and outer coronae in a single field of view.

In contrast, from the visible light perspective, the inner edge of the necessary coronagraph occulters must be reduced to lower heights. This can only be achieved with instrumentation incorporating improved stray-light rejection. The PROBA-3, Aditya VELC, UCOMP and COSMO coronagraphs again serve as key pathfinders, but require complementary observations to extend the FOV to the outer edge of the middle corona. Future strategic planning is required to ensure the availability of co-temporal observations from all types of instruments discussed above.

Spectral observations are a crucial part of any middle corona observation program, and they are required to help derive detailed understanding of the plasma properties of features captured in traditional images. Optical, UV and

EUV spectra provide unique diagnostics for densities, electron temperatures, ionization states, elemental compositions, kinetic temperatures and temperature anisotropies, Doppler shift velocities along the line of sight, and velocities radially away from the Sun. Except for optical observations during eclipses, spectral observations of the middle corona have been largely limited to the UV spectra from UVCS, which operated from 1996 to 2013. These UVCS observations were severely hampered by SOHO’s low telemetry rate as well as a limited instantaneous spectral range and low sensitivity, all of which can easily be overcome by modern instruments and spacecraft. Closer integration of spectral and imaging observations, as designed for the Large Optimized Coronagraphs for Key Emission line Research (LOCKYER) mission concept (Laming and Vourlidas, 2019) would greatly enhance the effectiveness of both.

While multiple radio facilities are available around the globe, there is no solar-dedicated radio instrument that provides true broadband dynamic imaging spectroscopy in the $\sim 0.4\text{--}1$ GHz spectral range, which is critical to producing observations in support of key open questions about the middle corona, including CME initiation and acceleration, understanding the CME-accelerated electrons, and perhaps most importantly, to provide unique measurements of the evolving magnetic field of CMEs in the lower portion of the middle corona ($\sim 1.2\text{--}2 R_{\odot}$).

CMEs are faint and diffuse structures, which necessitate radio interferometers with a large number of antennas (several 10s to 100) to achieve sufficiently high-dynamic-range imaging ($>10^3:1$) and high surface-brightness sensitivity. In fact, 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 is envisioned to provide high resolution, high dynamic range, and high fidelity dynamic imaging spectroscopy over a wide frequency range from 0.2–20 GHz.

Structures throughout the corona are defined by the underlying magnetic fields; however, very few instruments can probe coronal magnetic fields at all, and only the Upgraded Coronal Multi-channel Polarimeter (UCoMP; Landi, Habbal, and Tomczyk 2016, still under development) will be able to measure them anywhere close to the middle corona. Techniques to ascertain the coronal magnetic field are restricted to extrapolating magnetic fields from photospheric magnetograms and inferring them from density/temperature models. However, future instruments that leverage the Hanle effect, particularly in Lyman- α measurements (Raouafi *et al.*, 2016), will be able to much more directly ascertain the strength and orientation of the coronal magnetic field. Coupled with radio measurements, these observations can provide strong constraints on global models. Such new observations will significantly improve our ability to understand the topology, evolution, and global scale effects of the middle corona’s complex magnetic field.

All of these individual measurements are important in their own right, but the middle corona in particular is a dynamic, three-dimensional environment that cannot be fully understood if only observed from a single, Earth-bound, perspective. Thus, developing true understanding requires $360^{\circ}/4\pi$ views of the Sun, including both the photospheric magnetic field and multiple lines of sight

through coronal features and magnetic field structures. Such observations, coupled to global magnetic field models and advanced 3D reconstruction techniques (e.g., Plowman, 2021) would facilitate comprehensive understanding of the entire middle (and inner) corona. Such multi-perspective observations are required especially to characterize the highly structured and complex interfaces between middle corona structures and the inner and outer coronae. Given the exotic solar orbits required to achieve these 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, e.g., expanded opportunities within NASA’s CubeSat and LCAS programs.

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. $360^\circ/4\pi$ observations – including out-of-ecliptic perspectives – should prioritize measurements that cannot be made from the Earth or ecliptic perspective, or that facilitate significant research or space weather forecasting progress using additional vantage points.

Coupling all of these new observations to global models is a major challenge, particularly determining how new magnetic field and three-dimensional 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. Further investments in models and model data assimilation are required, and important lessons could be drawn from Earth and atmospheric science communities, which already have extensive data–model integration capabilities (Lahoz and Schneider, 2014).

7. Conclusion

The middle corona, the region roughly spanning heliocentric heights from 1.5 to $6 R_\odot$, encompasses almost all of the influential physical transitions and processes that govern the behavior of coronal outflow. These transitions include the change from predominantly closed to open magnetic field structures, and the change from low to high plasma β in specific regions. As a consequence of these transitions, the region is generally the location of primary solar wind acceleration, ionization state freezing-in, composition anomalies in long-lived structures, supersonic flow where the dynamical pressure exceeds the thermal pressure, and eruption and flow (and associated shock) kinematic shaping.

In spite of the important transitions that occur here, the middle corona remains poorly understood compared to both the inner and outer corona, primarily because it has been much more poorly observed than these regions. Remote sensing observations, both in radio and shorter wavelengths, have been insufficient to definitively characterize its global properties. Occasional imaging opportunities,

along with radio imaging and spectroscopic observations, have helped bridge the gap, but only intermittently and not self-consistently. Developing deep understanding of the large-scale multi-thermal structures from which the middle corona is predominantly composed has therefore proved difficult. We are left with numerous important questions that must be addressed to close this knowledge gap.

The object of this paper has not been simply to invent another naming convention, but rather to help define the new discovery space that is the middle corona. In particular, we aimed to highlight the deficiencies in our sporadic observations of the region and the numerous important open questions that follow from this. It is our hope the paper will serve as a valuable summary and reference for what we know about important middle coronal properties at the present time.

Acknowledgments The need to define the middle corona, and consequently the need for this paper, emerged from an ever increasing community interested in exploring the region. The seeds of the community were planted in a series of AGU and other conference sessions that began in Washington, DC, in 2018. The conveners and presenters of those sessions, and the conversations they sparked within our informal middle corona working group, have strongly contributed to and influenced the narrative of this paper, for which we are extremely thankful.

During the COVID-disrupted AGU conference of 2020 the middle corona session was driven online in a video-conference format, and in this remote format we discovered that meaningful, wide-ranging discussion was much easier. From these early conversations, a monthly, free for all, community led meeting was born. Through this series of meetings and the broad and inspiring discussions at the online Heliophysics 2050 Workshop, we decided that a clearer, more focused definition of this region was needed to help motivate studies that focused on the region and highlight its importance to the Sun-Heliosphere system. This paper is the outcome of that decision. Many people contributed to its genesis, development, and writing – more than just those who appear on the author list, and more than we can name briefly here. Nonetheless, we thank everyone who has engaged with this community over the years, from session attendees to discussion group members to participants in discussions hosted on our Slack workspace.

To get involved in the middle corona community, please reach out via our web page, where you will find additional information on our meetings and other opportunities to interact: <https://middlecorona.com>.

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