**Fine Structures of the Inner Solar Corona and the Associated Magnetic Topology**

Yuan-Kuen Ko\(^1\), Guillermo Stenborg\(^2,3\), Jon Linker\(^3\), Micah J. Weber\(^5,6\), Roberto Lionello\(^4\), and Viacheslav Titov\(^4\)

\(^1\) Space Science Division, Naval Research Laboratory, Washington, DC, USA; yuan-kuen.ko@nrl.navy.mil
\(^2\) Johns Hopkins University Applied Physics Laboratory, Laurel, MD, USA
\(^3\) Formerly at Space Science Division, Naval Research Laboratory, Washington, DC, USA
\(^4\) Predictive Science Inc., San Diego, CA, USA
\(^5\) Department of Physics and Astronomy, George Mason University, Fairfax, VA, USA
\(^6\) Formerly NRC Fellow, Naval Research Laboratory, Washington, DC, USA

Received 2021 September 10; revised 2022 May 18; accepted 2022 May 20; published 2022 July 6

**Abstract**

We present the fine structure of the inner solar corona between 1.65 and 3.0 solar radii as revealed by the STEREO-A COR1 white-light coronagraph from 2008 June 20 to July 31. The COR1 imaging data were wavelet processed to enhance the intensity contrast of coronal features. The constructed limb synoptic maps at a range of altitudes show the evolution in time and altitude of these fine structures within the streamer belt, and equatorial and polar coronal holes during this period near the solar minimum. Distinct streamer-stalk structures are seen embedded within a diffuse background of the helmet streamer belt, which are preserved as they extend to higher heights. Pseudostreamers are also seen as multiple stalk structures, which also continue to higher heights. Various polar plume structures are seen to last from hours to days. Similar plume structures are also seen within the corona subtended by equatorial coronal holes. We compare the COR1 maps to that of the magnetic topology revealed by the modeled squashing factors, and discuss the relation between the two types of maps and its implications in the context of solar wind formation.

**Unified Astronomy Thesaurus concepts: Solar corona (1483)**

**1. Introduction**

The extended solar corona was first seen during total solar eclipses when the bright solar disk, whose intensity in visible light is more than 10\(^6\) times brighter, is fully blocked by the moon’s shadow as seen from Earth. This infrequent observation of the off-limb corona was changed when coronagraphs were invented. These instruments block the emission from the solar disk (Lyot & Marshall 1933) allowing only the faint coronal light to pass through the telescope. Since then, the extended solar corona can be routinely observed with coronagraphs at various wavelength ranges from both ground-based observatories (e.g., a series of white-light and infrared coronagraphs on the Mauna Loa Solar Observatory) and space missions. Coronagraphs flown in space missions include the Large Angle and Spectrometric Coronagraph (LASCO; Brueckner et al. 1995) and the UltraViolet Coronagraph Spectrometer (UVCS; Kohl et al. 1995) onboard the Solar and Heliospheric Observatory (SOHO; Domingo et al. 1995); the white-light COR1 and COR2 coronagraphs of the Sun Earth Connection Coronal and Heliospheric Investigation (SECHI; Howard et al. 2008) onboard the Solar Terrestrial Relations Observatory (STEREO; Kaiser et al. 2008); and Metis (Antonucci et al. 2020) on the recently launched Solar Orbiter mission ( Müller et al. 2020) in ultraviolet, among others. Coronagraphs have also been in sounding rockets, e.g., the HELium Resonance Scatter in the Corona and HELiosphere (HERSCHEL; Moses et al. 2020).

The white-light emission from the corona is produced by scattering of the solar visible light by free electrons in the corona via Thomson scattering (the K corona) and dust particles in orbit around the Sun (the F corona; Kouchmy & Magnant 1973; Kimura & Mann 1998). Therefore, the electron density in the corona can be inferred from the white-light intensity of the K corona (e.g., van de Hulst 1950; Saito et al. 1977; Hayes et al. 2001; Thernisien & Howard 2006; Kramar et al. 2009; Wang et al. 2017) and hence reveal the coronal structure and dynamics. The coronal structure was first crudely categorized into two main features: faint coronal holes and bright streamers. As the spatial resolution and sensitivity of the instruments become higher and higher and state-of-the-art imaging processing techniques are developed, the fine-scale structure within the coronal features starts to be resolved, exposing a higher degree of complexity (e.g., Stenborg & Cobelli 2003; Druckmüllerová et al. 2011; DeForest et al. 2018). Plumes are prominent structures embedded within the corona above coronal holes (e.g., Fisher & Guhathakurta 1995; see review by Poletto 2015 and references within) with dynamical features such as jets and oscillations (e.g., Raouafi et al. 2008; Thurgood et al. 2014). Closed loops are envisioned within streamers and multiple rays/stalks are seen extending into the outer corona (e.g., Thernisien & Howard 2006; Morgan & Habbal 2007; Decraemer et al. 2019). The white-light observations are also heavily used to study flows in the corona (e.g., Sheeley et al. 1997, 2009; Wang et al. 2000; Viall et al. 2010) and coronal mass ejections (CMEs; see review by Webb & Howard 2012 and references within) as they propagate into the heliosphere. The solar corona is where the nascent solar wind is heated and accelerated by various mechanisms that are still an active area of research. Since the high-density helmet streamer stalks are the extension of the magnetic field neutral line into the outer corona, white-light synoptic maps are often used to indicate the location of the heliospheric current sheet and served as a ground truth in assessing the coronal and solar wind structures predicted by coronal field models (e.g., de Patoul et al. 2015; Poirier et al. 2021). One question arising from these fine coronal structures...
is their relation to the solar wind, such as the role of plumes versus inter-plume regions as the source of the fast-speed solar wind, the role of coronal hole/streamer boundary and streamer stalks as sources of the slow speed solar wind, and which structures channel the solar wind/open field.

Since the coronal free electrons are essentially bounded by the magnetic field lines due to their small gyroradius, the coronal structure as seen in white light is closely related to the magnetic field structure (barring the effect of line-of-sight integration). The complex coronal magnetic field structure, with a forest of open and closed field lines, is the extension from the photospheric magnetic field where positive and negative magnetic elements are constantly moving, merging, emerging, and canceling. The early view of radial/non-radial open field lines out of the coronal hole and closed loops orderly oriented within a streamer is obviously oversimplified. The goal of our investigation here is to investigate how the fine coronal structure seen in white light relates to the coronal magnetic field structure, and how this can help our understanding of the solar wind formation. In this paper, we use observations from the STEREO-A COR1 white-light coronagraph from 2008 June 20 to July 31 to show the fine structure of the inner solar corona. The COR1 imaging data were processed with a multi-resolution technique to enhance the intensity contrast of the coronal features and hence reveal small-scale details. We then compare the COR1 limb synoptic maps to that of the magnetic topology revealed by the squashing factor $Q$, and discuss the relation between the two types of maps and its implications in the context of solar wind formation. In Section 2, we present the data selection rationale and processing, and the constructed white-light limb synoptic maps between 1.6 $R_\odot$ and 3.0 $R_\odot$. In Section 3, we show the corresponding $Q$ maps and simulated density maps, and relate the $Q$ maps to the fine structure seen in the white-light maps. In Section 4, we discuss our findings and the implications in the solar wind formation.

2. Methods and Observations

2.1. Data Selection and Processing

One objective of this work is to study the correspondence between white-light coronal structures and the topological structures of the coronal magnetic field, as depicted by the modeled squashing factor $Q$ (Titov et al. 2011). With that aim in mind, we selected a comprehensive set of observations that comprises the time period covered by the photospheric magnetic field synoptic map used for calculating the squashing factors in Titov et al. (2011). This photospheric magnetic field synoptic map was constructed for the 2008 August 1 total solar eclipse (Rušin et al. 2010). Therefore, here we exploit the white-light coronal observations taken by the COR1 instrument (Thompson et al. 2003) on the SECCHI-A suite onboard STEREO between 2008 June 20 (day of the year (DOY) 172), 01:00 UT and 2008 July 30 (DOY 213), 23:05 UT. During this time, STEREO-A covered the longitude range between 30°6 and 34°8 (HEE system), west of the Sun-Earth line.

The SECCHI-COR1 instrument is an internally occulted coronagraph, its field of view (FOV) ranging from 1.4–4 $R_\odot$. A linear polarizer is inserted in the optical path to capture the polarized brightness (pB) signal from the corona. The nominal observing program consists of a sequence of three images obtained in rapid succession with the polarizer at 0°, 120°, and 240°, these triplets being taken with a cadence of 5 minutes. The COR1 CCD detector has 2048 × 2048 pixels. The images are typically taken at full resolution and then binned onboard to 1024 × 1024, with a resulting pixel size of 7″/50 per pixel.

Each individual image of the sequence in the time period considered for this work has been calibrated and converted into Mean Solar Brightness Units using the SolarSoft (SSW) routine “secchi_prep.pro”. To obtain the total brightness (TB) we applied to each calibrated triplet the SSW “cor1_quickpol.pro” routine. The scene in COR1 TB images consists of (1) light scattered by the dust particles in orbit around the Sun (the F corona), (2) light scattered by free electrons in the corona (the K corona), (3) instrumental stray light, and (4) small point-like features such as, for example, stars and/or cosmic rays. In order to increase the signal-to-noise ratio (S/N), at the expense of diminishing the time resolution, we built up a data set where each image consisted of the average of all the images taken in 1 hr time intervals.

The average images show discrete K-corona features (e.g., streamers) embedded in a diffuse background. The brightness of the diffuse background has contributions from both the F corona and a diffuse component of the K-corona structures. Since we are interested in revealing the fine-scale structure of the discrete K-corona features, we implemented a customized procedure to remove the smooth component (in both the F and K corona), akin to a sophisticated unsharp-mask filter. The procedure is a simplified version of the wavelet-based technique devised and implemented in Stenborg & Corbelli (2003). As such, the technique is well suited to pick out discrete, small-scale features embedded within large-scale features. We note that the step of removing the F-corona component could be avoided by using the pB triplets rather than the TB images. However, the S/N is low in individual pB images. Since our main purpose is to capture the morphology of the structures, we work with the 1 hr averaged TB images where the S/N is much better for the purpose of this work.

In a nutshell, the whole procedure consists of several steps. First, we remove the point-like sources like bright stars and cosmic rays by applying a sigma filter as implemented in the IDL routine “sigma_filter.pro” in SSW. As employed, this routine simply replaces the pixels that deviate from their neighbors in an 11-pixel circular region by more than 2 standard deviations with the median value of that circular region. Once the point-like sources are removed, we transform each individual image into a polar representation, where the x-axis represents the position angle (from 0°–360°) and the y-axis the radial extent (from the occultor to the edge of the image FOV). This transformation of coordinates is motivated to avoid edge effects at the border of the occultor when applying the contrast-enhancement technique. The wavelet technique is then applied to each image in this polar representation to enhance the features at different spatial scales while removing the smooth background component. The procedure is built on a discrete implementation of the continuous wavelet transform where each spatial scale is simply computed in an iterative sequence as the difference between two consecutive low-pass filtered versions of the original image. The kernel of the low-pass filter is a 2D B3 spline as defined in Stenborg & Cobelli (2003). Finally, the enhanced images in the polar representation are converted back to the original Cartesian frame.
For illustration purposes, we show in Figure 1, (i) a 1 hr average COR1 TB image (left panel), and (ii) the resulting cleaned and enhanced version with the smooth component removed akin to an unsharp-masked image (right panel). The location of the solar disk is depicted with the white circle inside the occultor. The rather circular specks close to the bottom of the image are of instrumental nature. We note that in the wavelet-processed data, the relatively small brightness enhancements in the original non-processed signal are greatly enhanced. Hence, the detail of the small-scale structures becomes discernible, which would otherwise remain hidden in the direct TB images. The polar plumes and streamer-stalk structures are clearly seen after the cleaning and enhancing processing. Fine structures, resembling multiple streamer stalks, are observed embedded within the streamer structures at the east and west limbs. These distinct strands indicate locations where the electron density is enhanced, either intrinsically in the plane of sky or due to some structure extending away from the POS but along the same line of sight. The dark features that are seen beside the brightest coronal features are an artifact of the image processing applied to enhance the intensity contrast. Such dark feature at the boundaries of bright regions, the strength of the brightness contrast being in direct relationship to the strength of the brightness gradient at the boundary, is a well-known effect of any kind of unsharp-mask filtering approach.

2.2. White-light Limb Synoptic Maps

Limb synoptic maps at several heliocentric heights allow us to visualize the evolution of the coronal structures around the Sun in longitude and latitude as these structures rotate. The polar representation of the cleaned and enhanced 1 hr average COR1 TB images with the smooth component removed were used to construct such maps. Namely, for each time instance, data points were extracted along a slit at a given radial distance to the Sun center. This linear slit in the polar representation corresponds to a circular slit centered at the Sun’s center in the Cartesian representation of the images. Each cut is a stripe that contains 1536 data points, the full extent covering 360° in position angle. We emphasize that the offset of the image center from the Sun center has been taken into account when converting into the polar representation (see, e.g., Figure 1).

This procedure was repeated for 10 heliocentric heights, ranging from 1.65–3.0 R\textsubscript{\odot} for each of the 956 images that span the time period from 2008 June 20, 01:00 UT to July 31, 23:05 UT. For each height, the stripes from the 956 images were put together in time sequence to construct one limb synoptic map. In order to compare the limb structures between the east and west limbs, and with the central meridian disk synoptic maps, we calculate the time when the observed limb structure would be at the Sun’s central meridian as seen from Earth, based on the separation angle of 32°5 in longitude. This translates to 4 days, 8 hr and 18 min for the east limb structure seen by STEREO-A moving to the central meridian seen from Earth, and 9 days, 6 hr and 12 min for the central meridian structure seen from Earth moving to the west limb seen by STEREO-A.

Figure 2 shows the limb synoptic map at the west limb at 1.80 R\textsubscript{\odot} with the time axis being the translated time (in DOY) as calculated above. Various coronal features are marked on the figure, namely:

1. A large, dark region (i.e., less intensity in white light) above the north and south polar coronal holes with polar plume structures of various lifetimes.
2. Dark equatorial coronal holes (EqCHs) that persisted in subsequent solar rotations (one centered around DOY 165 and DOY 193 for one, and the other centered around DOY 174 and DOY 202), exhibiting filamentary structures within.
3. A helmet streamer belt that would go along the neutral line/heliospheric current sheet. It is seen in the form of fuzzy patches indicating ubiquitous structure that cannot be resolved by the wavelet technique (e.g., loops of uniform density and closely spaced). Filamentary structures are seen overlapping such fuzzy patches. They could be closed loops within the streamer with higher density or groups of loops that happen to align along the
line of sight. Alternatively, they could be streamer stalks out of mini-streamers embedded within this large-scale helmet streamer belt. Most of these filamentary structures span tens of degrees in longitude and do not change significantly in position angle/latitude.

(4) Pseudostreamers are seen as streamer stalks due to their low-lying cusps (Wang et al. 2007). They resemble the fine structures within the helmet streamer but without the fuzzy patches. These pseudostreamers can be confirmed with the $Q$ maps (Section 3).

(5) Transient displacement of filamentary structure in a streamer due to deflection by a coronal mass ejection (CME).

(6) Movement in latitude/position angle of some high-latitude streamer stalks due to solar rotation (see polar rays, Li et al. 2002).

Figure 3 shows the limb synoptic maps at five heights for both the west (left panels) and east limb (right panels) structures, with the time axis being the translated time as calculated above. This period spans close to one and half solar rotations (42 days) at a time near the solar minimum. We see that the large-scale global coronal structures did not change significantly over this time. The helmet streamer belt (seen as swabs of fuzzy patches, e.g., DOY 170–195, also occurred before and after) and the two EqCHs remain similar in the two rotations. The helmet streamer belt becomes narrower in latitude as it converges toward higher heights. However, the filamentary structures within it persist to high heights. This indicates that they are likely substructures/substreamers within the streamer belt. At 3 $R_\odot$, the streamer stalk still consists of a number of filamentary rays.

The processing applied to the images enhances the intensity contrast of the K-corona features against the background. The trade-off is that the radiometric calibration of the images no longer applies. Therefore, topological studies such as the one in this work benefit from it, while studies involving the evaluation of dynamic quantities (e.g., mass, energies) do not. In the maps we notice, however, regions with higher intensity and contrast than others, as well as an overall intensity decrease of the features farther away from the Sun. Even if the photometry is not preserved, the relative intensity of the features with respect to the background is valid. Moreover, the interpretation of the cleaned and enhanced maps is straightforward, provided the calibrated images are inspected in parallel. For instance, in addition to the features described in Figure 2, we can note a few persistent horizontal features in the maps comprising an extended period of time. Back on the images, they correspond to features that persist in time at given position angles. Their nature can be either instrumental or a real coronal structure. Close inspection of the evolution of the wavelet-processed images with time shows that during particular time periods, at certain position angles, there are ray-like structures that persist at the same location as time evolves. In those cases, their behavior is translated into the horizontal stripes observed in the synoptic maps. On the other hand, a persistent feature in a fixed location is a typical signature of an instrumental artifact. Therefore, horizontal features in the map, if extending throughout the whole time range of the map, should be disregarded as a real physical entity.

The two polar coronal holes are prominent structures during this time of the solar cycle. The polar plumes shown in Figures 2 and 3 are seen as segments (mostly above 50° latitude) and do not change much in position angle with time. The various lengths of the segments correspond to a range of lifetimes of these plumes. The short lifetime of less than a few hours could be transient coronal jets that extend from bright points inside the coronal hole (Wang et al. 1998; Kamio et al. 2007) due to field cancellation of moving magnetic elements inside the coronal hole (Young & Mughach 2014). We will present a detailed study of the polar plumes from this data set in a separate paper (Weberg et al., in preparation).

There are two dark regions bounded between streamers, one centered around DOY 165 that reappears around DOY 193 on the next solar rotation, and the other centered around DOY 174 that reappears around DOY 202. The coronal areas subtended by these two EqCHs do not expand much from 1.65–3.0 $R_\odot$, as opposed to those above the two polar coronal holes. These two EqCHs are of opposite polarity and a neutral line (consequently the heliospheric current sheet) runs between them, separating...
the two magnetic sectors (see Section 3). As revealed by the coronal magnetic field model (see Section 3), the corona above both EqCHs is bounded at one side by a pseudostreamer (Figure 2). There are plume-like structures within the EqCHs, although some of them could be filamentary structures within the neighboring streamer that get in the line of sight.

To relate the structures seen at the limb to those seen on the solar disk, Figure 4 shows the SOHO Extreme-ultraviolet Imaging Telescope (EIT; Delaboudinière et al. 1995) λ195 central meridian map spanning CR 2071 and CR 2072 (2008 June 9, 18:52 UT, DOY 161.786 to August 3, 04:39, DOY 216.186). The map is constructed from the EIT Carrington
maps obtained from http://spaceweather.gmu.edu/projects/synop/EITSM.html with the x-axis being the time at central meridian instead of Carrington longitude. The low-latitude extension of the north polar CH at DOY 180–190, and of the south polar CH at DOY 180 and 206 for CR 2071 and 2072, respectively, can be seen in correspondence in the limb maps (Figures 2 and 3). The two EqCH systems per rotation extend into the corona at similar locations in the limb maps (one around DOY 165 and 193 and the other around DOY 175 and 202). The two EqCH systems of opposite polarity caused the neutral line to turn north–south-wise (see Section 3). Note that there were only three active regions (around DOY 167, 174, and 203) during these two Carrington rotations that produced only A-class X-ray flares.

3. Coronal White-light Structure versus the Magnetic Topology

To investigate how these fine coronal structures seen in white light reflect the complex coronal magnetic topology, we present the latter with the Q maps that were constructed using the same photospheric magnetic field synoptic map as that by the 3D magnetohydrodynamics (MHD) model (Mikić et al. 2007) for the 2008 August 1 total solar eclipse prediction (Rušin et al. 2010; Titov et al. 2011). The input photospheric magnetic field synoptic map for CR 2072 (2008 July 6, 23:37—August 3, 04:39 that contains the eclipse date of August 1) was constructed with the SOHO/Michelson Doppler Imager (Scherrer et al. 1995) line-of-sight magnetograms up to July 22, 7 UT (CR longitude 157°5 of CR 2072) when the MHD simulation was last run for the prediction. The resulting magnetic synoptic map was therefore constructed from July 6 (DOY188), 23:37 UT to July 22 (DOY 204), 7 UT for CR longitude 360°–157°5, and those for CR longitude 157°5–0° were filled with the previous Carrington rotation data from June 25 (DOY 177), 2 UT to July 6, 23:37 UT. To match this constructed magnetic synoptic map, we also constructed modified COR1 limb maps for CR 2072 with the same time frames above using the time when the east/west limb structures seen by COR1 are expected to be at the central meridian seen from Earth (see Section 2 and Figure 3).

The magnetic topology was described in the same way as in Titov et al. (2011) using the analytical expression for the squashing factor Q defined in spherical coordinates (Titov et al. 2008). The squashing factor Q characterizes the divergence of the neighboring magnetic field lines on the way between their footpoints. High-Q regions define separatrix surfaces and quasi-separatrix layers (Priest & Démoulin 1995), which delaminate qualitatively different flux volumes that can reconnect with one another. Figure 5, left panels, show the signed logQ (slogQ) Carrington maps at five heights (see Figure 7 in Rušin et al. 2010 and Figure 10 in Titov et al. 2011). slogQ is defined as sign(B)log[Q/2 + (Q^2/4 − 1)^{1/2}] (Equation (15) of Titov et al. 2011) and practically coincides in absolute value with log Q but has the advantage of showing the sign of the local radial magnetic field, which significantly facilitates the interpretation of the resulting slogQ maps made by using the blue-red palette. The neutral line is situated where the two opposite polarities meet. These slogQ maps show that:

1. During this near solar minimum period, the complex magnetic topology is mainly within a latitude of ±30° around the equatorial streamer belt, with the highest Q values along the neutral line that would extend out to form the heliospheric current sheet. At the lowest height shown here (1.65 R_☉), there are a few bipolar/high-Q features outside of the neutral line (e.g., at CR longitude/latitude of 190°/−20°, and 300°/+15°), which are likely from localized low-lying closed loops such as from an active region (see Figure 4).

2. The magnetic topology is similar between 1.65 and 3.0 R_☉. The main difference is that the spatial (latitudinal) extent of the complex structure surrounding the neutral line decreases with altitude as the helmet streamer converges toward the cusp. Most of the Q structure maintains its appearance to high coronal height.

3. The magnetic topology inside the equatorial/low-latitude coronal holes is more complex than that in the two polar coronal holes. The lack of Q structure in the polar coronal holes could be partly due to mostly radial field and partly due to the low resolution of the magnetic synoptic map used in this simulation. Simulations with a magnetic synoptic map of much higher resolution reveal complex magnetic topology inside the polar coronal holes as well with moderate Q values (Downs et al. 2020).

The right panels of Figure 5 show the simulated plasma density Carrington maps at the same five heights from the corresponding MHD simulation. The density scale is shown on each panel. The 3D MHD model was first developed by Mikić et al. (1999), then subsequently improved with a sophisticated energy equation replacing a polytropic one (Lionello et al. 2009; see Rušin et al. 2010 for a more detailed description of the model). The specific simulation here for the 2008 August 1 solar eclipse used the same photospheric magnetic map as in the calculation of Q (Rušin et al. 2010; Titov et al. 2011). Therefore, the Q and density structures...
Figure 5. Left panels: $slogQ$ Carrington maps at 1.65, 1.80, 2.10, 2.55, and 3.00 $R_S$. The red/blue colors represent positive/negative polarity. Right panels: corresponding simulated plasma density Carrington maps. The density is in units of $10^6$ cm$^{-3}$. Time goes from right to left.
Figure 6. Scatter plots of $|\text{slog}Q|$ vs. simulated plasma density at 1.80 $R_\odot$ (left panel) and 2.55 $R_\odot$ (right panel) for all values within ±45° in latitude. The corresponding linear Pearson correlation coefficients calculated in linear space are shown on each panel.

The SECCHI/COR1A observations from the time period between 2008 June 20 and July 31 processed with the wavelet-based methodology applied in this work reveal the fine coronal features within large-scale structures in the inner corona from 1.65–3.0 $R_\odot$. These observations fill the gap between the

can be consistently compared. We see that there is much similarity between the $Q$ and density structures. Locations with the highest density are along the neutral line where the $Q$ values are also among the highest. The enhanced density structures outside of the neutral line are often colocated with enhanced $Q$ values of the same polarity (e.g., CR longitude range of 50°–100° at around +25° latitude, 160°–230° between about −20° and +10° latitude, and 250°–360° at around +25° latitude). Figure 6 shows a scatter plot between the magnitude of $\text{slog}Q$ and density at 1.80 and 2.55 $R_\odot$ for all values within ±45° in latitude. Both the $Q$ and density values are mapped to the same 720 uniform longitude grids from 0°–360° and 360 uniform latitude grids from −90° to +90°. There is indeed a non-negligible correlation between the two, albeit with significant scattering. We note that the correlation plots at all five heights are very similar with similar correlation coefficients ranging from 0.50–0.61.

Figures 7 and 8 show the corresponding COR1 Carrington maps at 1.65 and 2.10 $R_\odot$ at the west limb and east limb, respectively, overlaid with the $\text{slog}Q$ map at the same heights (see Figure 5). Here we focus on comparing the overall large-scale coronal structures observed by COR1 with those depicted by the magnetic topology ($\text{slog}Q$ map). The helmet streamer belt/neutral line coincides in location where the $\text{slog}Q$ magnitude is large and its structure is most complex. The helmet streamer belt/neutral line is mostly flat (heliospheric current sheet lying edge-on) except at the CR longitude of around 250° where it turns north–southwise (heliospheric current sheet lying face-on). Note that the CR longitude of 250° corresponds to DOY 170.1 for CR 2071 and DOY 197.3 for CR 2072, which is right between the two EqCH systems of opposite polarity (see Figures 2–4). Since the observed white-light intensity is an integration along the line of sight, we expect lower white-light intensity along the streamer belt when the neutral line is oriented north–southwise, even though the $\text{slog}Q$ magnitude and the intrinsic electron density are large. As mentioned above, there are enhanced simulated density structures outside of the neutral line with enhanced $Q$ values of the same polarity. These structures are also seen in the COR1 map as pseudostreamer stalks. The dark EqCHs at Carrington longitudes of 200° and 300° in the COR1 map (see Figure 2) are where $\text{slog}Q$ and simulated density are low. However, the fine structures inside as depicted in both the $\text{slog}Q$ and COR1 map are no less complex. The polar plume structure is not caught by $\text{slog}Q$, partly due to insufficient resolution of the input magnetic field synoptic map (Downs et al. 2020).

The white-light pB of the corona in the plane of the sky can be simulated from the MHD solution by integrating the 3D electron density structure (see Figure 5, right panels) along the line of sight for each given Carrington longitude and latitude grid. This is done by convolving the electron density profile with a scattering function (Billings & Guide 1966), and filtering the output with a radially graded filter to mimic the effect of instrument vignetting (Mikić et al. 1999). Figure 9 shows the resulting east limb pB Carrington map at 1.65 $R_\odot$ as an example. In the left panel we show the straight map from the simulation, and in the right panel an unsharp-masked version of it, which was obtained as the ratio of the map to the map convolved with a uniform kernel of size equivalent to 3 pixels. Even with the low resolution of the pB map (2° grid in longitude and 1° grid in latitude), multiple streamer-stalk-like structures can be seen along the helmet streamer belt in the unsharp-masked version. There are many similarities in such multi-streamer-stalk structures to those exhibited in the COR1 TB map (Figure 8, top panel). The movement of high-latitude streamer stalks can be seen in both the simulated pB map and the COR1 TB map (e.g., at longitude/latitude around 300°/+25°, 150°–25°, 230°–35°). The pB map does not show plume structures within the solar coronal holes and EqCHs, likely due to the low spatial resolution in the model. Future investigations similar to this work but with high spatial resolution photospheric magnetic field map and MHD simulation could reveal more coronal fine structures, lending further support to the close relationship between the fine magnetic field structure (as exhibited in the $\text{slog}Q$ map) and the observed fine coronal density structure (as exhibited in the COR1 TB map).

4. Summary and Discussion

The SECCHI/COR1A observations from the time period between 2008 June 20 and July 31 processed with the wavelet-based methodology applied in this work reveal the fine coronal features within large-scale structures in the inner corona from 1.65–3.0 $R_\odot$. These observations fill the gap between the
on-disk EUV imaging observations (that seldom extend above 1.5 \(R_\odot\)) and observations from other space-based white-light coronagraphs such as SECCHI/COR2 and LASCO/C2 whose FOV starts at above 2 \(R_\odot\). The COR1 limb synoptic maps created with these processed images for different heliocentric heights reveal the evolution in both time and altitude of the fine-scale features within the streamers and the equatorial and polar coronal holes. During this time period near a solar minimum, the prominent large-scale coronal structures at the covered altitude range include a helmet streamer belt that embeds the neutral line/heliospheric current sheet, the north and south polar coronal holes, and a couple of EqCHs that are bounded by a helmet streamer and a pseudostreamer. There were few active region emergences and CME events that would affect the appearance of these large-scale structures over this period. Distinct streamer-stalk structures are seen embedded within a diffuse background of the helmet streamer belt at low heights and are preserved as they extend to higher heights. Pseudostreamers are already seen as multiple stalk structures at 1.65 \(R_\odot\) that are also preserved to higher heights. Polar plumes are seen to appear all the time and last from hours to days. Similar plume structures and characteristics are also seen within the corona subtended by the EqCHs.

These fine structures should reflect the complex coronal field structures therein. We thus constructed Carrington maps of the squashing factor (slog\(Q\)) and compared with the corresponding COR1 Carrington maps. Even though these \(Q\) maps, which were constructed with a single photospheric magnetic field Carrington map (see Section 3), do not show dynamical features such as appearance/disappearance of polar plumes or latitudinal movement of streamer stalks, we can still make a meaningful qualitative comparison between the two types of maps. We find that the helmet streamer belt overlaps with regions having the most concentrated high-\(Q\) values (Figures 7 and 8), with \(Q\) among the highest at the neutral line and streamer-stalk locations (Figure 5). The corona subtended by the EqCHs exhibits a web of moderate \(Q\) values. Inside the polar coronal holes the \(Q\) values are among the lowest, which is reasonable since the coronal field within would be largely close to radial.
The derived $Q$ structure here is a snapshot of the coronal manifestation of the underlying photospheric magnetic field. The quiet Sun as well as the coronal hole are like a ubiquitous magnetic carpet (Title & Schrijver 1998) with networks of positive and negative magnetic elements constantly emerging, moving, merging, and canceling. Some of the field lines from these magnetic elements reach out to the corona and form a complex web of coronal field structures that translate with height, as manifested by the $Q$ maps presented here (see the S-Web, Antiochos et al. 2011). The diffuse background inside of the helmet streamer belt seen by COR1 (Figures 2 and 3) indicates strands of magnetic field lines that are closely packed together with similar density (thus white-light brightness), and therefore cannot be distinguished by the wavelet processing. They could be overlapping closed loops of various orientations, some of which straddle the neutral line. Closed loops are not radial field structures and often meet with neighboring ones to form quasi-separatrix layers. This is in line with the high concentration of high-$Q$ structures within the helmet streamer belt (Figures 7 and 8). The multiple filamentary structures embedded within, as seen in white light, could be ministreamers and/or pseudostreamers with low-lying cusps. Some of these filamentary/stalk features survive to higher heights (Figure 3) and extend into the inner heliosphere. In addition, higher $Q$ locations tend to be where divergent field lines meet with one another (whether streamer stalk or not), which could result in higher density there (see Morgan 2011). This would explain why the $Q$ and simulated plasma density values are somewhat correlated (Figure 6).

The question then arises concerning what these fine structures imply in the source of the solar wind. The locations with concentrated white-light fine structures and high-$Q$ values, prevalent along the streamer belt, tend to be where magnetic reconnection occurs when conditions are met, which would be induced by the constant field line shuffling from their footpoint motion. Magnetic reconnection occurring at these locations could be between closed field lines, between closed and open field lines (interchange reconnection), and between open field lines (pinching). The latter two scenarios (Wang et al. 2000) could form plasmoids seen as white-light streamer blobs that

Figure 8. COR1 east limb Carrington maps at 1.65 $R_{\odot}$ (top panel) and 2.10 $R_{\odot}$ (bottom panel) overlaid with the $\log Q$ map at the same heights (see Figure 5).
are released into the solar wind (Sheeley et al. 1997, 2009; Viall et al. 2010; DeForest et al. 2018) and have been proposed to be one source for the slow wind formation (Wang et al. 2000; Suess et al. 2009; Abdo et al. 2016; Ko et al. 2018). Time-dependent MHD simulations also provided such mechanisms as the formation of plasmoids/blobs and source of variability in the slow solar wind (Higginson et al. 2017; Higginson & Lynch 2018). Note that high-$Q$ values should only be a necessary condition for plasmoid production.

Polar plumes are prominent, higher density structures against the dark polar coronal hole seen off the solar limb (see review by Poletto 2015 and references therein). The COR1 maps presented here clearly show that the polar plumes have a range of lifetimes and are not just transient coronal jets. Both plume and the so-called inter-plume regions should be sources of the fast solar wind, but which one is the dominant source is still an open question (e.g., Gabriel et al. 2003; Teriaca et al. 2003; Wilhelm et al. 2011; Poletto 2015). The simulation by Downs et al. (2020) with an ultra-high resolution magnetic map is able to reveal high-$Q$ structures within the polar coronal hole that resemble plumes. Based on the correlation between the $Q$ magnitude and simulated plasma density (Figure 6), perhaps some polar plumes are associated with converging non-radial open field lines that are oriented irregularly from their footpoint network elements. However, this does not address how the plumes are formed, which is a dynamic process (e.g., Wang & Muglach 2008; Raouafi & Stenborg 2014; Wang et al. 2016).

Plume structures are also seen inside the equatorial/low-latitude coronal holes (Figures 2 and 3; e.g., Del Zanna & Bromage 1999), and the magnetic topology inside is more complex than that in polar coronal holes, as depicted in the slog$Q$ maps. This indicates that size matters, i.e., we would expect more and more complex magnetic topology with smaller and smaller coronal holes/open field regions, approaching that at the coronal hole boundary. This in turn indicates that the open field lines inside small coronal holes would be largely non-radial and nonuniformly oriented, thus resulting in more complex s-log$Q$ structures. A common prediction from the coronal field models is that a non-radial field is associated with large expansion factors and slower speed solar wind (e.g., Wang & Sheeley 1990; Arge & Pizzo 2000; Riley et al. 2015). Therefore, small EqCHs are expected to be sources of only the slow-speed solar wind. Only when an EqCH has a sufficiently large area could it be a fast solar wind source like the polar coronal holes (e.g., Rotter et al. 2012).

Interchange reconnection is proposed as one of the scenarios to explain the magnetic field switchbacks detected in the solar wind (e.g., Balogh et al. 1999; Bale et al. 2019; Kasper et al. 2019; Drake et al. 2021). In this scenario, one would expect that locations with a large concentration of high-$Q$ structures (where interchange reconnection tends to occur) would have a higher probability of producing switchbacks. As we show in this paper, the regions around helmet streamer and pseudostreamer stalks (neighboring a coronal hole boundary), as well as in small coronal holes, are places with a concentration of high-$Q$ structures. Should the trajectory of a spacecraft (such as Parker Solar Probe and Solar Orbiter) magnetically connect to footpoints at the Sun that cross a sufficiently large EqCH, where there are significantly fewer high-$Q$ structures (Figures 5, 7, and 8), perhaps there would be fewer switchbacks and more inter-switchback structures (Griton et al. 2021). Whether this could be an indicator for or against this scenario for slow solar wind formation by interchange reconnection remains to be seen.

We thank the referee for his/her detailed and constructive comments and suggestions that greatly improved this paper. Y.-K.K. acknowledges support from the NASA LWS program (NNX10AO82I) and the Office of Naval Research. G.S. acknowledges support from the NASA STEREO/SECCHI program (NNG17PP27I). R.L. acknowledges support from the NASA LWS program (8NSSC20K0192).

ORCID iDs
Yuan-Kuen Ko @ https://orcid.org/0000-0002-8747-4772
Guillermo Stenborg @ https://orcid.org/0000-0001-8480-947X
Jon Linker @ https://orcid.org/0000-0003-1662-3328
Micah J. Weber @ https://orcid.org/0000-0002-4433-4841
Roberto Lionello @ https://orcid.org/0000-0001-9231-045X
Viacheslav Titov @ https://orcid.org/0000-0001-7053-4081

References
Abbo, L., Ofman, L., Antiochos, S. K., et al. 2016, SSRv, 201, 55
Antiochos, S. K., Mikic, Z., Titov, V. S., Lionello, R., & Linker, J. A. 2011, ApJ, 731, 112
