Near-Sun Observations of an F-corona Decrease and K-Corona Fine Structures

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Remote observations of the solar photospheric light scattered by electrons (K-corona) and dust (F-corona/Zodiacal light) have been made from the ground during eclipses[1] and from space at 1 AU[2,3,4] and as close as 0.3 AU[5]. Previous observations[6,7,8] of dust scattering have not confirmed the existence of a theoretically-predicted dust free zone near the Sun[9,10,11]. The transient nature of the corona has been well characterized for large events, but questions still remain (e.g. initiation[12], production of solar energetic particles[13]) and for small events even the structure is uncertain[14]. Here we report on imaging the solar corona[15], from the Parker Solar Probe spacecraft[13], during the first two perihelion passes (0.16-0.25 AU), each of ten days duration. The view from these distances is qualitatively similar to the historical view, but there are some significant differences in the details. We have uncovered at short elongations a decrease in the intensity of the F-coronal intensity, which is suggestive of the long-sought dust free zone[9,10,11]. Also we have resolved the plasma structure of very small eruptions, which are being frequently ejected from the Sun. They take two forms - the commonly observed magnetic flux ropes[12,16] or the predicted, but not yet observed, magnetic islands[17,18] arising from the tearing mode instability in the current sheet. Our observations of the coronal streamer evolution confirm the large-scale topology of the solar corona, but they also reveal that, as recently predicted[19], streamers are composed of yet smaller sub-streamers channelling continual density fluctuations at all visible scales.

Parker Solar Probe (PSP) carries an imaging instrument, the Wide-field Imager for Solar Probe (WISPR)[14]. The inset in the left panel of Fig. 1 shows a WISPR inner telescope (WISPR-I) image taken on 6 Nov 2018 at the first perihelion. The Sun is 13.5° to the left of the image and the width is ~40°. The locus of points at the apex of the contours defines the photometric axis of the F-corona. While most observations of the F-corona/Zodiacal Light have been taken from the distance of Earth, two spacecraft, Helios A and B, each carrying the Zodiacal Light Experiment[5], orbited the Sun from 0.3 to 1.0 AU, one observing above the ecliptic plane and the other below. They measured the intensity of the zodiacal light from varying heliocentric distances and found[20] that it increases toward the Sun according to $I \sim R^{-n}$, where $n=2.3\pm0.1$. The upper and lower limits were recorded at small and large elongations from the Sun, respectively, and were independent of the ecliptic longitude of the observer. The Sun Earth Connection Coronal and Heliospheric Investigation[4] (SECCHI) heliospheric imagers HI-1[21], on-board the STEREO spacecraft[22] orbiting the Sun at ~1 AU, observed the corona at elongations ranging from 0.07 to 0.45 AU (5°-24°) from the Sun. An analysis of intensities[23] of the photometric axis of the F-corona from 2007 to 2014 found the exponent, for the entire elongation range covered by the HI-1 instrument, to be 2.31. Moreover, the analysis performed on restricted elongation ranges[23] showed an identical tendency to the Helios results for the intensity gradient to increase toward the Sun ($n=2.29\pm0.10$).

The left panel of Figure 1 displays a log-log plot of a sample of F-coronal intensity profiles in units of mean solar brightness (MSB) along its photometric axis as measured by WISPR-I between 15° and 50° elongation from Sun center. The sample comprises data from five different heliocentric distances of the PSP spacecraft (0.336 AU to 0.166 AU) obtained during the orbit inbound to the first perihelion. Color is used to distinguish the plots. For clarity we only plot these five positions, but all the profiles during the encounter are similar. These five profiles are normalized to the maximum intensity at 30° elongation to reveal the behavior of the profiles for the various PSP heliocentric distances. Clearly, at larger elongations, the curves have exactly the same slope, and at shorter elongations (<20°), the intensity decreases with decreasing PSP distance, with the top plot (pink) being when PSP is the furthest from the Sun and the bottom plot (dark green) the closest. The right panel shows the intensity profiles at the same five PSP distances for both telescopes, but plotted against elongations converted to Rs. The conversion to Rs was performed by dividing the elongation by ½ the angular size of the Sun at the respective PSP distance. Note that the curves all overlie each other now – even the decreases seen in the left panel. The small upward ticks are due to bright stars. The dashed blue line shows the linear fit to the F-coronal intensities for elongations between 20 and 77 Rs ($n=2.31$), a result identical to that obtained from both earlier observations[20,23]. For comparison, historical data[3,24,25] have been added. The dashed green line depicts the linear fit to the LASCO-C3 data[3] (light green dots) for elongations greater than 13 Rs, extrapolated down to 4 Rs. The exponent, n, in this case is also 2.31 (note the match between the blue and green dashed lines). The LASCO-C3 data have been normalized to the WISPR value at 20 Rs. For WISPR the absolute calibration has been determined by analyzing the intensity of stars in the field, which resulted in an error of 12%. The relative accuracy and repeatability of the WISPR are excellent, which gives us high confidence in the turnover of the intensities below 17 Rs. The historical measurements represented by the black dots[24] and green dots[3] both have absolute errors of 20%. On the other hand, no error was given for the data represented by the red dots[25].

Figure 2 shows the K-corona from both telescopes on 6 Nov 2018, after removal of the brighter background from the dust scattering. Supplemental Videos 1 and 2 provide background-removed videos of the images taken during the first two encounters. The grid lines for both Figure 2 and the Supplemental Videos are in the HPLN-ARC coordinate system[26,27]. The videos show the evolution of a coronal streamer during the two encounter periods of PSP observations. On the large scale, the agreement with model predictions by our team (Extended Data Figure 1) is very good, validating the model assumptions about the configuration of the magnetic field and the mass flux of the equatorial solar wind. The representation of WISPR-I images in a latitude versus time format (Extended Data Figure 2a) reveals that near perihelion WISPR suddenly imaged faint coronal rays that are distinct from the main streamer rays. We note that fine structure along the streamer belt has been observed before[19,28]. High-resolution simulations of the corona reproduce these brightness features. We interpret their displacement to higher apparent latitudes to the spacecraft motion (Extended Data Figure 2b). This striated 'texture' of the background corona is born in our model by the spatial variability of coronal magnetic flux tubes along which the plasma is heated and accelerated to form the slow solar wind.

Supplemental Video 1 shows a series of ejecta along the streamer. A particular event characterized by a big magnetic flux rope followed by several smaller ones is shown in Fig. 3. The first one (yellow arrows) has an elliptical high-density envelope surrounding a quasi-circular density depletion at its center and a striated envelope. While similar structures have been observed by LASCO, they could not always be resolved. The Encounter 1 images were binned 2x2, giving an effective 2-pixel spatial resolution[15] of 60 arcsec (at 0.21AU) for WISPR-I, which is about 2x finer than the LASCO-C3 observations of this event. On the other hand, LASCO-C2 tracked this structure when it was much closer to the Sun for a few images only, but with about 2.5x better spatial resolution. The event was also recorded by WISPR-O with an effective 2-pixel spatial resolution of 96 arc sec, extending the coverage of the event. Such density features have been interpreted as the boundaries of magnetic flux ropes[12,16]. We have combined the spatially resolved density information with modeling to locate the structures corresponding to the internal toroidal and poloidal magnetic fields and study their interactions with the ambient plasma as the structure expands inside the streamer rays. Preliminary work demonstrates (Extended Data Figure 3) that the structures are indeed consistent with a force-free magnetic flux rope propagating along the heliospheric current sheet which is quite flat during this period. The heliospheric current sheet (HCS) flatness may be the reason for detecting the fine-scale structure of the event. Such behavior is extremely rare in 1 AU observations[29].

The event shown in Figure 3 also shows two additional smaller flux ropes (red arrows) following the northern boundary of the main flux rope that are likely by-products of the interaction between the main event and the ambient corona. The quasi-circular shape and faint striations within the feature suggest strongly that it is an idealized magnetic flux rope. Smaller features, with similar morphologies, are also seen following the main ejection. The yellow arrows follow the first, main event. The red arrows follow the two following events, until they become merged in the background, but which are still visible in the Supplemental Video 1. These structures were not detected by either LASCO or SECCHI, although both have observed many small ejecta[14]. Small dense features caused by interaction of a Coronal Mass Ejection (CME) with its environment have proved difficult to identify positively[30]. Further studies will be necessary to test that idea.

Observations during the second perihelion (Supplemental Video 2) again show new dynamics in a coronal streamer. In this case, the observations capture the formation of oblong structures consistent with magnetic islands. Magnetic islands are, in two dimensions, a collection of roughly elliptical magnetic field lines which close on themselves; or, in three dimensions, helical field lines wrapping around a central (guide) field, again with a roughly elliptical cross section. These island structures are predicted to form via the tearing mode instability[17] from magnetic reconnection in a current sheet, such as the one within this streamer, where oppositely directed magnetic fields meet. Figure 4 shows several snapshots of this streamer and the formation and evolution of one of these oblong structures. This structure first appears at the inner edge of the image around 6 April 2019 20:00 UT and propagates out, within the current sheet, as an expanding, highly elliptical shape with a high intensity (dense) ring of emission surrounding a low intensity core. The final panel of Figure 4 shows a measure of the aspect ratio (ratio of minor axis to major axis) of the ellipses fit to this structure in each of the 33 frames from time 6 April 2019 19:57 UT to 7 April 2019 02:54 UT. Each ellipse was fit to a set of points placed by hand on the high-density ring of the oblong structure in each frame. The corresponding ellipse is shown as a green curve in the five snapshots here, with a red dot at the center of the ellipse. The plot indicates that the structure expands with a slightly increasing aspect ratio until 23:45 UT on 6 April and then it increases more quickly until the entire structure fades into the background. This evolution, including the increase in aspect ratio, is consistent with simulations of the tearing mode formation of islands in an expanding coronal wind[18]. These simulations show the un-reconnected guide field collecting at the center, forming this low emission core, with the reconnecting field forming the high-density ring around the core. While such an island ejection from a coronal streamer has been reported previously[31], these earlier observations were not sufficiently resolved to show this internal ring and core structure.

WISPR imaged a variety of interesting structures in the corona/solar wind during the first two PSP orbits about the Sun. The departure from linearity of the F-corona intensity profiles below about 17 Rs, is opposite to that found in both Helios and STEREO data. Although this behavior could be leading to the predicted dust-free zone close to the Sun, the intensity decrease could be due to a change in the properties of the dust scattering, or a combination of the two. WISPR has certainly not observed the dust free zone. Theoretical analyses of the plausible existence of a dust free zone predict[8,9,10,11] the formation of circumsolar dust bands that could be observed by their thermal emission. In a compilation of the 30 observations[6] made at various wavelengths from 0.8 to 3.6µ during eleven solar eclipses from 1966 through 1998, about half indicated an enhancement and the other half, including the two latest eclipses, 1991 and 1998, did not. The resolution of whether this WISPR finding represents dust depletion or something else will have to wait until PSP steps down to lower perihelia.

The near corotation of PSP allows us to observe the radial outflow of the solar wind, without the confusing impact of solar rotation. The observations suggest that many small ejecta, commonly called "blobs," may indeed be magnetic flux ropes but are usually too small to identify as such from 1 AU[32]. Structures larger than these are generally interpreted as CMEs, but the physical mechanism of formation may not be the same. This finding, particularly with the anticipated measurements of the same structures by PSP's in-situ payload, may finally clarify the evolution of the CME magnetic structure in the heliosphere, opening new avenues of research on internal CME dynamics. As PSP steps closer to the Sun over the next five years, these observations together with the modelling will certainly provide new insights and opportunities to study and separate the spatial from the temporal variability of the solar wind near its source and will likely increase the performance of Space Weather prediction schemes. This will benefit a wide range of communities from basic physics research to space situational awareness to even astrophysics through exoplanet habitability applications.

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Sequential Figure Legends

Figure 1. **Intensity plots along the photometric axis of the F-corona.**

Left Panel: Observed intensities from WISPR-I for 5 heliocentric distances as a function of elongation (degrees) scaled to the same value at 30^{o} elongation. The inset in the left panel shows an image of the F-corona taken on 6 Nov 2018. Right Panel: Observed intensities from both telescopes for 5 heliocentric distances as a function of elongation (solar radii). See text for further explanation.

Figure 2. **Combined images from the inner and outer telescopes of WISPR on 6 Nov 2018 at 01:44UT.**

After removal of an empirical model of the F-corona, the faint solar wind structures are revealed. Visible is a faint streamer outlining the heliospheric current sheet, and faint, radial and rather diffuse rays all with apparent origin on the Sun. The image also reveals the dust trail along the orbit of the asteroid 3200 Phaethon (delineated by the white dots). The Galaxy dominates the scene in the inner part of the outer telescope accompanied by two bright objects - Jupiter (to the upper right) and the star Antares (a little below to its left) in the Scorpius constellation.

Figure 3. **The propagation of a coronal mass ejection**.

Shown are five cropped frames from Supplemental Video 1 at different times in the same coordinate system as Fig. 2. The radial range is shown at the top, and the latitudinal range is 0°±10° for each panel. The yellow and red arrows are pointing to structures described in the text.

Figure 4. **Formation and propagation of an island-like structure within a streamer.**

The first five panels show snapshots from WISPR-I during the second perihelion. An ellipse (green line) is fit to the high-density ring of the structure in each panel. The final panel shows the aspect ratio (minor axis / major axis) of these ellipse fits versus time. The red and blue solid lines show a linear fit to this aspect ratio from 20:00 UT to 23:45 UT on 6 April 2019 (red) and from 00:00 UT to 02:40 UT on 7 April 2019 (blue). The pairs of dashed lines on either side of these fits show the 1-sigma values.

Supplementary Video 1. Video of the combined WISPR telescopes for the first PSP encounter period. The encounter 1 observations from 1-10 Nov 2018, encompass the period when PSP is within 0.25 AU from the Sun. The cadence of the video is at the cadence of the outer telescope which is longer than that of the inner telescope. The cadence varies throughout the encounter due to the number of images per day that were taken. The background, consisting mostly of the F-corona, has been removed. The grid lines are in the HPLN-ARC coordinate system[26,27]. The radial range of the video extends from 13.5° to 108°.

Supplementary Video 2. Video of the WISPR-I telescope for the second PSP encounter period: 1-10 Apr 2019. The encounter observations encompass the period when PSP is within 0.25 AU from the Sun. The background, consisting mostly of the F-corona, has been removed. The cadence varies throughout the encounter due to the number of images per day that were taken. The grid lines are in the HPLN-ARC coordinate system[26,27]. The radial range of the video extends from 13.5° to 108° from the Sun.

Extended Data Figure 1. Comparison of Observations and Synthetic Observations from MHD Model

Panel a: An image from the inner WISPR telescope taken on 3 Nov 2018 at 06:55:41UT. The field of view (of both panels) is 40°x40° with the Sun 13.5° to the left. Two distinct sets of bright streamer rays are marked by red arrows. They are separated by a darker region marked by a blue arrow. The technique employed to remove the background F-corona in the WISPR image has artificially enhanced this dark region. The streamer rays located northwards of the dark region (top red arrow) are brighter than the rays situated southwards of the dark region (bottom red arrow). **Panel b:** a synthetic white-light image produced from 3-D simulations of the solar wind by the MULTI-VP MHD code using a Wilcox Solar Observatory photospheric magnetogram[33]. The 3-D density cubes produced by running the MULTI-VP code were processed by a white-light rendering code computing the brightness of the corona in the WISPR field of view from the heliocentric position of Parker Solar Probe. The MULTI-VP numerical model and the procedure to produce white-light images have been detailed[33]. The star field from the new Hipparchus astrometric catalog[34] was added to the simulated image in panel **b)** for comparison with the WISPR image in panel **a)**.

Extended Data Figure 2. Latitude vs Time Maps – Observations and Modeling

Panel a: A representation of WISPR inner telescope images in the form of a latitude versus time map. This map provides a summary of the temporal and spatial variability of coronal rays observed during the first encounter. We note that such fine structure along the streamer belt has been observed before[19,28]. We identify in these maps the main streamer rays already seen in Extended Figure 1 (the same blue and red arrows are shown here). During the period of super and corotation (5 to 9 Nov 2018), bright coronal rays drift in latitude away from the equator (green arrows). This is also visible in video given in Supplemental Video 2. **Panel b:** An equivalent map to Panel a obtained from the WISPR synthetic images based on the MULTI-VP 3-D density cubes shown in panel b of Extended Figure 1. These medium resolution simulations reproduce the time-varying aspect of the main streamer including their fading during perihelion (5 to 7 November). **Panel c**: MULTI-VP high-resolution simulation results for the period 5 to 9 Nov 2018 based on 2-degree resolution magnetograms produced by the *Air Force* Data Assimilative Photospheric Flux (ADAPT) model[35]. The color table has been saturated in these maps to enhance the features. The solar wind simulations reveal the finer striated structure of the corona and the coronal rays migrating poleward as observed by WISPR (green arrows). A search in the simulation data cubes reveals that these faint rays are separate from the brighter streamer rays. They form in the simulation as a result of considerable variability in the properties of the magnetic fields along which the slow solar wind forms. Since the prescribed coronal heating is scaled to the magnetic field properties this drives different mass flux along different flux tubes. We interpret the coronal rays marked by the top red arrows as resulting from the main streamer and the rays situated southwards (bottom red arrow) as resulting of a pseudo-streamer.

Extended Data Figure 3. Modeling of a CME as a 3D Flux Rope

Panel a: an image from the inner WISPR telescope taken on 1 Nov 2018 at 19:30:50UT during the passage of a pristine CME. Clear substructures are discernible in the WISPR image. The field of view is 40ºx40º with the Sun 13.5º to the left. A bright ring at the outer contour/boundary of the CME is indicated by a blue arrow. A striking feature of this CME event is the presence of a dark circular core located at the center of the CME event and indicated by a red arrow. **Panel b:** the same image as in panel a but the results of a 3-D flux rope fit superimposed. This figure proposes an interpretation for the different features observed by WISPR based on our current understanding of the appearance of CMEs imaged in white light. The magnetic field lines (computed from solutions of the Grad-Shafranov equation) of the CME are traced inside this flux rope. The bright ring (blue arrow) corresponds to plasma located on the boundary of the flux rope where the poloidal magnetic field lines of the CME are adjacent to the ambient solar wind plasma. The dark core (red arrow) marks the location where strong toroidal (axial) magnetic fields dominate the plasma locally. Detailed modelling of the event will be presented in a future dedicated publication.

Methods

WISPR contains two telescopes and measures the intensity of the visible light corona in addition to stellar and galactic sources. The two telescopes slightly overlap and have a combined field-of-view (FOV) of 13.5° to 108.5° from the Sun, corresponding to approximately 9 to 78 solar radii (Rs; 1 Rs = 696,000 km) at 35.6 Rs perihelion. The visible light corona consists of two components – light scattered by free electrons (the K-corona) and light scattered by interplanetary dust (the F-corona). The F-corona of each WISPR image is removed using a technique[36] similar to that developed for the SECCHI/HI-1. The primary difference is that for the HI-1 images the initial step in the procedure analyzed the horizontal lines in the image, whereas here, the initial step uses vertical lines in the images.

All of the data presented here have been calibrated into Mean Solar Brightness (MSB) units. The calibration details will be published in a future paper, but include the removal of geometric distortion, vignetting, instrumental artifacts (stray light, etc) and then applying the photometric calibration of the system. The vignetting is caused by two sources: the projection of the image onto the 2D plane of the Advanced Pixel Sensor detector and for WISPR-I the obscuration of the objective lens of the sunward side of the image by a series of baffles (including the PSP heat shield) which are used to block the solar disk illumination and block diffraction from the edges of the preceding baffles. The absolute calibration is confirmed on-orbit by measuring the intensity of stars passing through the field. The intensity of the stars as they transit across the image is also a check on the vignetting correction.

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Author Contributions

All authors contributed to writing the manuscript. R.A.H., A.V., N.R., and G.S. designed and collected the data. N.R., P.H., R.C.C., B.G., and G.S. performed the data processing and calibration. G.S. developed the technique to compute the background models. R.A.H., A.T., G.S. and P.L.L. performed the analysis of the dust scattering. A.V., C.E.D., M.L., P.H., P.C.L., A.R., N.P., A.K., N.V., G.S., A.H., N.E.R., V.B., P.R. and R.A.H. carried out the analysis of the K-corona. J. L. assisted in the observation planning by providing MHD model predictions. A.H. and N.E.R. coordinated the data acquisition and downlink. P.C.L., J.R.H. and P.P., assisted with data calibration, observation planning, and analysis. R.A.H., N.R., A.V., P.L.L, S.P.P., C.M.K, R.C.C., and D.G.S. assisted with design, calibration and instrument checkouts.

Competing Interests

The authors declare that they have no competing interests.

Author Information

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Data Availability

The PSP Science Data Management Plan (https://sppgway.jhuapl.edu/docs/data/7434-9101_Rev_A.pdf) requires that all science data from the first two orbits with calibrations, must be released to the public within 6 months of downlink of the first orbit. In addition to this data type, we will be releasing background subtracted images, videos, and lists of events. Furthermore, the data must be delivered to the appropriate NASA/GSFC facility and integrated into the Virtual Observatory (VO). Thus, the date for the data availability is Nov 12, 2019. A complete archive will be maintained at NRL (https://wispr.nrl.navy.mil) and publicly available at least during the full mission lifetime. A copy of the WISPR data will be located at the NASA/GSFC SDAC facility (https://umbra.nascom.nasa.gov) and integrated into the Virtual Solar Observatory (VSO).

Supplementary Information

Supplementary Video 1. Video of the combined WISPR telescopes for the first PSP encounter period: 1 – 10 Nov 2018. The encounter observations encompass the period when PSP is within 0.25 AU from the Sun. The cadence of the video is at the cadence of the outer telescope which is longer than that of the inner telescope. The cadence varies throughout the encounter due to the number of images per day that were taken. The background, consisting mostly of the F-corona, has been removed. The grid lines are in the HPLN-ARC coordinate system[26,27]. The radial range of the video extends from 13.5° to 108°.

Supplementary Video 2. Video of the WISPR-I telescope for the second PSP encounter period: 1-10 Apr 2019. The encounter observations encompass the period when PSP is within 0.25 AU from the Sun. The background, consisting mostly of the F-corona, has been removed. The cadence varies throughout the encounter due to the number of images per day that were taken. The grid lines are in the HPLN-ARC coordinate system[26,27]. The radial range of the video extends from 13.5° to 108° from the Sun.