The Sun’s dynamic extended corona observed in extreme ultraviolet

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The ‘middle corona’ is a critical transition between the highly disparate physical regimes of the lower and outer solar corona. Nonetheless, it remains poorly understood due to the difficulty of observing this faint region (1.5–3 R☉). New observations from the Solar Ultraviolet Imager of a Geostationary Operational Environmental Satellite in August and September 2018 provide the first comprehensive look at this region’s characteristics and long-term evolution in extreme ultraviolet. Our analysis shows that the dominant emission mechanism here is resonant scattering rather than collisional excitation, consistent with recent model predictions. Our observations highlight that solar wind structures in the heliosphere originate from complex dynamics manifesting in the middle corona that do not occur at lower heights. These data emphasize that low-coronal phenomena can be strongly influenced by inflows from above, not only by photospheric motion, a factor largely overlooked in current models of coronal evolution. This study reveals the full kinematic profile of the initiation of several coronal mass ejections, filling a crucial observational gap that has hindered understanding of the origins of solar eruptions. These new data uniquely demonstrate how extreme ultraviolet observations of the middle corona provide strong new constraints on models seeking to unify the corona and heliosphere.

The solar corona is the primary driver of almost all plasma dynamics throughout the solar system. However, the precise nature of the connection between the corona and the heliosphere remains surprisingly poorly understood. Recent solar and heliospheric observations taken by Parker Solar Probe, well within Mercury’s orbit, revealed a highly structured environment shaped by flows and ejecta interacting with the corona’s complex magnetic field. The influence of these flows on the heliosphere, and the structural evolution of the global coronal topology, are both modulated by magnetic connectivity and physical transitions in the ‘middle corona’ between 1.5 and 3 solar radii (R☉, as measured from disk centre). However, critical extreme ultraviolet (EUV) observations of this region needed to characterize its plasma properties and dynamics are lacking, and so important gaps in our understanding persist. Even just predicting the appearance of the middle corona has been a major hurdle because ‘as we are dealing with an unexplored region, we really do not know how the fundamental plasma parameters vary with radial distance. Even considering the simplest case of a streamer in the quiet Sun, very different estimates of densities and temperatures have been published.”

Here we present new long-duration observations of the middle corona in EUV. These observations directly address key questions about the characteristics of the middle corona and how processes within it influence the global structure of the corona–heliosphere system. This includes the initiation and driving of eruptive solar flares and the acceleration of the solar wind. We discuss how these observations can provide much-needed constraints for theory and models of the corona on global scales. Such models provide the only way to connect measured observables with the physical processes at their origins because comprehensive direct measurements of the corona are infeasible. However, models that use the observed photospheric magnetic field as their primary boundary condition are known to systematically underestimate the resulting interplanetary magnetic flux compared to in situ measurements. Because changes in the polar surface fields also frequently manifest as changes in structure of the middle corona, our new observations promise to provide valuable constraints for these global models.

The lack of direct measurements of the middle corona—particularly in the EUV—stems largely from historical biases, technical limitations and optimization choices, but not from the physics of this region itself. EUV telescopes have focused primarily on the low corona, only to heights below 1.7 R☉, because of a commonly held misperception that EUV emission in the middle corona is too dim to observe with practical instrumentation. Recently, limited EUV imaging studies at a single wavelength with PROBA2/SWAP extended these observations somewhat, revealing unexpected structure and transient dynamics to about 2 R☉. However, existing EUV observations do not cover the full spatial extent of the middle corona or provided temperature diagnostics over sufficiently long timescales to systematically characterize dynamics in this region.

Our EUV observations and the middle corona
Our new high-contrast EUV images from a 2018 deep-exposure wide-field mosaic campaign by the Solar Ultraviolet Imager (SUVI) on the Geostationary Operational Environmental Satellite 17 (GOES-17) spacecraft of the National Oceanic and Atmospheric Administration (NOAA) settle the debate over whether EUV emission is detectable in the middle corona by revealing structure and plasma dynamics throughout the region. The combination of our SUVI data with Large Angle Spectroscopic Coronagraph (LASCO) images at greater heights reveals complex relationships among phenomena in the lower corona, the evolution of coronal
morphology on global scales and the origins of discrete structure in the solar wind. This highlights, in particular, how outflows into the solar wind are frequently born in the middle corona and how feedback from the outer corona drives changes near the solar surface. This campaign demonstrates that deep-field EUV imaging provides a direct, experimental probe into coronal properties and dynamics that have previously been inferred only indirectly. These observations open a window into a generally overlooked region of the Sun–Earth system, resolving over a half-century of uncertainty. Our observations reveal three major classes of dynamic processes:

- Gradual bulk motions with speeds of a few km s\(^{-1}\) that continuously reshape the middle corona and that have not been systematically characterized before: gradual bulk motion that disrupts and reshapes the global coronal structure, manifesting as inflows and outflows of a few km s\(^{-1}\) traceable to heights of at least 4 \(R_\odot\); small-scale outflows with velocities of roughly 50–150 km s\(^{-1}\) that originate in cooler, plume-like features close to the solar surface and are visible to 2–3 \(R_\odot\); and impulsive eruptions that are linked to the interplanetary magnetic field.

The rate of fall-off is diagnostic of the EUV emission mechanism. Dashed lines in Fig. 1 show typical rates of fall-off (see Figure 1.4 in ref. 1) for emission due to collisional excitation (proportional to electron density squared) and resonant or Thomson scattering (linearly proportional to electron density). Comparison of the fall-off along the radial slice of the streamer suggests that emission from this structure is consistent with thermally driven collisional excitation below approximately 1.5 \(R_\odot\). Larger-scale features above 1.5 \(R_\odot\) are consistent with resonant scattering of emission originating elsewhere in the corona. Although this resonantly scattered emission is intrinsically faint, our processing overcomes this obstacle to enable visualization of coherent structure out to heights of at least 2–3 \(R_\odot\), where the magnetic field becomes primarily radial and connected to the interplanetary magnetic field. Our study confirms recent simulations\(^2\) that demonstrated that the fraction of resonantly scattered emission increases steeply at heights above 1.5 \(R_\odot\), including in the Fe emission lines observed in the 195 Å SUVI passband. Furthermore, these simulations highlight that observations of the ratio of resonant scattering emission to collisional excitation emission can serve as a novel probe of the previously unmeasured solar wind speed in this region.

**Dynamics**

Our observations reveal three major classes of dynamic processes that continuously reshape the middle corona and that have not been systematically characterized before: gradual bulk motion that disrupts and reshapes the global coronal structure, manifesting as inflows and outflows of a few km s\(^{-1}\) traceable to heights of at least 4 \(R_\odot\); small-scale outflows with velocities of roughly 50–150 km s\(^{-1}\) that originate in cooler, plume-like features close to the solar surface and are visible to 2–3 \(R_\odot\); and impulsive eruptions that are linked to...
Coronal mass ejections (CMEs) observed by LASCO, which rapidly alter coronal topology on global scales. Coronagraphic studies of the outer corona above \(5R_\odot\) detected largely uniform inflow and outflow with small but significant variations embedded within. By providing continuous single-instrument observations connecting the lower and middle corona, this campaign reveals that motion in the middle corona is much less homogeneous, which suggests a strong interdependence among structure, dynamics and the highly localized physical properties of their regions of origin.

The use of two simultaneous passbands, 171 Å and 195 Å, provides extended temperature diagnostics in the middle corona to \(>3R_\odot\). Figure 1 highlights the differences in observable structures between these two passbands. In the collisionally dominated regime, below \(\sim 1.5R_\odot\), emission in these passbands is generally from ions with characteristic temperatures around 0.8 MK and 1.5 MK, respectively. At greater heights this emission reflects only ionization state, which is influenced by, but no longer directly coupled to, temperature. The importance of this ionization selectivity becomes clearly apparent in Fig. 2 and the accompanying Supplementary Videos 1 and 2, in which the two passbands are overlain in false colour. For example, the large loop structure off the northwest limb (Fig. 2, label D; also visible in the separate co-temporal images in Fig. 1) is readily identifiable as a multi-thermal structure, potentially with complex three-dimensional geometry, in the composite image. The video reveals that this feature forms and retracts over a period of 12 h to 18 h, and its complex thermal structure is likely the result of reconnection-associated heating during the loop formation. By contrast, the polar plumes are cooler features predominantly visible in the 171 Å image, illustrating the difference in energetics for phenomena in closed versus open magnetic structures in the middle corona.

The combination of these new wide-field EUV images with visible-light coronagraphy from LASCO (Fig. 3 and accompanying Supplementary Videos 3 and 4) reveals how the flows that SUVI observes from their inception are transformed by their passage through the turbulent and complex middle corona, establishing the outflows and structure observed in the outer corona and heliosphere. As these flows propagate outward, the plasma \(\beta\), which is the ratio of the gas kinetic pressure to the magnetic pressure, changes from low (magnetic field dominates) to high (gas dynamics dominate). It is not known exactly where this transition occurs, nor how it influences the flow evolution.

It has often been assumed that this \(\beta\) transition solely occurs high in the corona; in open structures such as polar plumes, where plasma can flow freely outwards, this \(\beta\) transition likely does occur beyond this campaign’s field of view (FOV). In closed structures such as loops, however, gas pressure can accumulate and can overwhelm the magnetic field in the middle corona. This allows fluid instabilities to drive runaway processes including large-scale outward and inward flows that drag the frozen-in magnetic field along with them, feedback back to drive evolution and changes in magnetic topology even in the middle and low coronae, within our FOV. The dynamics observed by SUVI strongly suggest that this transition occurs even below \(2R_\odot\) in closed structures, most obviously along the streamer belt (Fig. 3 F, G, and H, and co-temporal video frames). We visualize the temporal evolution of the three types of observed flows using height–time diagrams to track feature intensity along selected radial slices above the limb (Fig. 4).

**Gradual bulk inflows and outflows.** Figure 4 F and G show the dynamic evolution of the bulk inflow and outflow features highlighted by Fig. 3 F and G. This type of flow is characterized by relatively gradual evolution and velocities of only a few \(\text{km s}^{-1}\) and is continuously traceable from SUVI into the surrounding LASCO FOV. In SUVI, these flows are observed primarily in the warmer 195 Å channel, indicating a close relationship between plasma heating and the underlying flow acceleration process. Their emergence from closed-field regions requires reconfiguration of the underlying magnetic field, a process that liberates stored magnetic energy and heats the surrounding corona. The month-long SUVI campaign demonstrates how long-term systematic observations allow us to characterize the coupling between these flows and the likely role of closed-field reconnection in constantly reshaping the global morphology and connectivity of the corona across this region. Long-term tracking of these flows could help address the ‘missing heliospheric flux problem’ by providing constraints on the significance of time-varying processes in determining this magnetic connectivity.

Gradual flows that originate higher in the corona than impulsive eruptions have also been suggested to be a potential source of so-called ‘stealth CMEs’, that is, CMEs that are visible in coronagraphs but lack clear low-coronal sources. In general, the velocities of such events are also smaller than those of typical CMEs. With EUV observations of the middle corona unavailable in past studies, the sources of outflows that originate in this region could only very rarely be identified directly, but our new observations...
close that gap. Indeed, several of the gradual outflows observed during this campaign (for example, Fig. 3 G and H) may be candidate stealth CME sources.

Flows that begin in the middle corona and propagate inwards, such as those highlighted in Figs. 3 and 4 F, are particularly interesting. These flows can disturb and even destabilize existing structures when they arrive near the solar surface. Inflows in the outer corona have been extensively catalogued, but these flows have not generally been observed to originate in or propagate through the middle corona outside of specific events linked directly to solar eruptions. Thus, it has generally been assumed that low-coronal dynamics are driven primarily from below, that is, that the dominant driver of the low corona is emergence and subsequent motion of magnetic field lines. Our observations reveal that the middle corona is a significant and important influence on the low corona, as these inflows drive changes from above—an interaction that has gone largely untreated in the literature. In this case, the inflow observed in SUVI is associated with corresponding motions in LASCO. This may be an EUV manifestation of a ‘streamer detachment’ demonstrating the role of the middle corona in mediating feedback on the low corona by events initiated at much higher altitudes. These observations emphasize the need for further dedicated study and modelling of this mechanism driving low-coronal dynamics.

Small-scale rapid outflows. In contrast to the above, flows that occur in open-field regions (Figs. 2 and 4 C) propagate unimpeded by overlying magnetic forces and therefore have relatively little influence on global coronal dynamics. They are rapid and cool, and have nearly constant profiles as they travel outwards. Such small-scale jets are apparently ubiquitous in the low corona and have been associated with narrow, intermittent outflows observed by coronagraphs. Our new SUVI observations directly track these features through the middle corona and highlight how future extended studies can quantify the role that such flows play in carrying energy, structure and magnetic flux from the low corona, where they are initiated, into the solar wind throughout the heliosphere.

Impulsive eruptions. Our campaign occurred near the nadir of the solar activity cycle, when the global field is very nearly dipolar and little free magnetic energy is available to drive eruptions. Nonetheless, we observed several modest CMEs (Fig. 2 A, B and E; Fig. 3 B; and Fig. 4 A, B and E) that reached speeds of a few tens of km s\(^{-1}\). Two of these CMEs (Figs. 2 A, B and E) highlight how these observations permit us to identify the precise locations of impulsive acceleration and infer the temperatures throughout the events. For example, the faster CME on 2018 September 6 (Fig. 4 A and B) clearly warms during acceleration, visible as a dimming in (cooler) 171 Å and simultaneous brightening in (hotter) 195 Å. (Although the 171 Å dimming occurs at the seam between the Sun-pointed and off-pointed images in the mosaic, contemporaneous observations from PROBA2/SW AP and the Sun-pointed SUVI on GOES-16 confirm that the dimming trend begins in the low corona and is not an instrumental artefact.)

By contrast, the slow, weak CME on 2018 September 9 stays cool throughout (Fig. 4 E), with no noticeable emission in 195 Å (Fig. 4; note the region marked \(E\)), which is an indication—coupled with its smaller velocity—that this event is less energetic overall. The height at which impulsive acceleration begins, visible as the knee from small to large slope in the height–time profile, also differs between these two events. The differences between these two representative examples occurring in essentially the same location on the Sun—and between these and others in the dataset (not shown here)—illustrate the clear need for systematic studies that can sufficiently sample the broad range of physical conditions under which CMEs manifest and the processes that initiate them.

Although eruption initiation has been extensively modelled, specific predictions about CME acceleration and magnetic reconnection-driven energy release have not been sufficiently validated due to the lack of appropriate observations in the middle
Fig. 4 | Height-time diagrams showing radial evolution of features as a function of time at selected positions, wavelengths and time ranges. Dashed lines highlight coherent flows for visual reference. Velocities are indicated near the location where they were measured. Features delineated by letters are discussed in the text and correspond to the equivalent labels in Figs. 2 and 3.

corona. Many models predict that CME acceleration occurs primarily below 2R☉. Only a handful of observations have captured complete CME trajectories to track their acceleration through this region or the associated impulsive expansion of the CME as it rises. Likewise, models of reconnection in eruptions predict the formation of current sheets that drive flows and heating in the middle corona, but these have been observed only infrequently and often the reconnection site lies outside the FOV of low coronal imagers. Although the few, weak CMEs we observed in this campaign are not optimal to directly address these questions, they prove that dedicated wide-field, multi-wavelength EUV observations during periods of greater activity can extend our existing capabilities to provide the necessary constraints to fully validate CME initiation models. Such observations would also greatly benefit space weather forecasting by helping to refine the predictions of propagation speeds and potential geoeffectiveness of major CMEs.

Discussion

Globally, space agencies have recently prioritized missions to observe and connect the outer corona and heliosphere through their dynamic interface, with both remote sensing and in situ measurements. These include current missions Parker Solar Probe and Solar Orbiter, the upcoming Polarimeter to Unify the Corona and Heliosphere (PUNCH) and Aditya-L1, along with new missions dedicated to space weather operations at multiple vantage points in the heliosphere. New ground-based coronagraphs that can probe the coronal magnetic field through spectropolarimetry, to heights of about 2R☉, are also in development. Although these missions are expected to provide groundbreaking insight into the physics of their respective domains, a comprehensive understanding of the intertwined corona–heliosphere system as a whole requires observations that can capture the pivotal physics in the middle corona.

Our observations address long-persistent questions about the transition from the magnetically dominated low corona to the gas-dynamics-dominated outer corona. They strongly indicate that the middle corona indeed encompasses the transition from low to high β in closed structures, as well as a topological shift from magnetic loops to predominantly radial structure. This campaign reveals directly how this region mediates the outward flow that gives rise to the solar wind and its embedded magnetic field, in addition to the multidirectional flow of information as the global corona adjusts to perturbations at particular locations. The observations demonstrate that EUV emission in the middle corona, whether collisionally excited or from resonant scattering, can provide valuable diagnostics of the temperature, density, connectivity and dynamics of this region.

Direct observations of the time-dependent evolution of the middle corona such as these provide important new constraints on—and validation of—model results, and can help reconcile inconsistencies between existing predictions and in situ measurements of the conditions in the outer corona and heliosphere. Our exploratory, long-duration, deep-field SUVI campaign captured a variety of phenomena that demonstrate the complexity and importance of this region, even during solar minimum. This pathfinding campaign, together with two follow-on campaigns in late 2019 and April 2021 using improved procedures, lay the foundation for future observations dedicated to high-sensitivity, long-term, wide-FOV EUV observations that will lead to a holistic understanding of the Sun’s entire outer atmosphere.

Methods

SUVI is a solar EUV telescope with six wavelength channels producing 1,280 × 1,280 pixel images with a 2.5 arcsec pixel scale, and is primarily intended for space weather operations. For this campaign we used SUVI in an east–west rastering mode to construct three-panel mosaic images in three passbands, 171 Å, 195 Å and 304 Å, from 2018 August 7 to September 13. Only the first two channels yielded sufficient statistics for analysis. We used 10 s full-resolution exposures for the Sun-pointed central panel and 20 s × 2 rebinned exposures for each of the side panels, at each wavelength. These images were normalized by exposure time, co-aligned on the ground and assembled into complete images of the EUV corona that extend to approximately 5R☉ in the horizontal direction. The full observation sequence, including all three passbands and repointing between offset positions, required a little over 6 min per cycle. Our observations coincided with the GOES eclipse season, meaning that brief data gaps appear around local midnight (about 05:30 UT) throughout the campaign.

SUVI is on the Sun-pointing platform mounted on the solar panel on the GOES spacecraft. Because the GOES spacecraft makes terrestrial observations from geostationary orbit, the solar array must rotate normal to Earth’s equatorial plane to maintain a constant view to the Sun. As such, SUVI’s horizontal imaging
axis is parallel to the Earth’s equatorial plane, which is generally not parallel to the solar equatorial plane. In our campaign images, the horizontal axis is rotated ~16–23° clockwise from the solar equator, depending on relative orientations of Earth and Sun.

We improve the signal-to-noise ratio in the Sun-pointed central field by rebinning that image 2×2 on the ground, resulting in a uniform platescale of 5 arcsec per pixel across the full mosaic. To further improve the signal-to-noise ratio in these mosaics, we median-stack sets of three composite images in time, yielding an effective imaging cadence of just under 20 min for the observations used in this analysis.

SUVI was intended to be operated with the Sun at the centre of the FOV. Consequently, when used in off-pointed mode, the internal telescope baffles do not fully mitigate off-axis light, and a strong glint contaminated the off-pointed panels throughout this campaign. This glint is largely invariant on short timescales and is superimposed on the normal solar signal. To remove this stray light, we computed a running boxcar minimum for each pixel with a time window of ±16 h around each frame and subtracted it after smoothing to suppress artefacts.

The relatively high flux of low-energy electrons in geostationary orbit contaminates most SUVI observations, producing spikes that are especially problematic in the long-duration side-panel exposures. A de-spiking step before image assembly suppresses the strongest transient noise resulting from these particles, but is ineffective in removing weak events. In the off-pointed panels, these weak events, coupled with photon counting (shot) noise, can be of the same order of magnitude as the true solar signal, and another strategy is required. Therefore, we further remove transient noise by applying a three-dimensional Savitzky–Golay filter, which works by locally fitting polynomials to small data windows tilted over the entire data cube. This polynomial serves as a locally tunable smoothing function that suppresses weak transient noise. Lower-degree polynomials preserve only the coarse structure in the data while suppressing high frequency variation, whereas higher-degree polynomials preserve more fine detail at the risk of preserving more noise. For these data we used a 9×9×9 pixel window with a 5×5×5 degree polynomial, which provided the best balance between removing noise and preserving fine structure based on visual inspection of the data.

A final processing step is required to equalize the dynamic range for optimal display, as discussed (Fig. 1). To do this, we generate an azimuthally varying radial filter, that is, a polar-coordinate normalizing function that samples the radial fall-off and smooths the azimuthal intensity over a 25° window, derived uniquely for each individual frame. The filter is then apodized to avoid over-enhancing noise at the radial extrema and over-suppressing brightness at the limb, which helps to preserve a more natural appearance. Each image is then renormalized by its unique filter. This is similar to—but less sophisticated than—the well-known Fourier normalizing-radial-graded filter. This filtering process can, occasionally, generate a small ring-like artefact in regions of the limb where there is limited brightness (for example, polar coronal holes), and such an artefact does appear in the videos and figures on occasion. Additional details on this method will be described in a forthcoming paper (D.B.S., manuscript in preparation).

This processing compensates for the four-orders-of-magnitude fall-off in coronal brightness globally, while preserving the intrinsic luminosity on local scales to retain coherent spatial features. All of the SUVI images and videos in this paper make use of the same background subtraction, noise reduction and radial filter techniques, except where noted in Fig. 1. To enhance the visibility of features in the two-colour display in Fig. 2, we further increase the contrast using an unsharp mask; this processing is not required in the simpler single-channel SUVI component of Fig. 3.

The LASCO data presented in Fig. 3 were prepared using the standard LASCO data reduction tools distributed by the LASCO team in the Interactive Data Language (IDL) SolarSoftWare (SSW) package. To improve the signal-to-noise ratio in these images, we stacked them in time to a 1 h effective cadence. We removed stray light and F-corona from the stacked images by computing a minimum-value image from the entire campaign and subtracting it from each frame. An additional de-spiking step suppressed both cosmic rays and stars in the images to isolate the degraded K-corona signal. We applied a single azimuthally isotropic and temporally invariant radial filter to each frame, derived from a median image calculated over the entire campaign, to equalize the dynamic range similarly to SUVI.

**Data availability**

Standard SUVI observations are available for download via the NOAA National Centers for Environmental Information (NCEI) GOES-R archive. Preliminary data products from this campaign, as used in this paper, as well as additional documentation and observations from subsequent campaigns, are available at the same website. Fully processed SUVI observations will be made public as they become available.

**Code availability**

The data processing and analysis discussed in this paper leveraged publicly available software packages in Python and SolarSoft IDL. The specific processing steps that generated figures and videos presented in this paper used an iterative process that spanned several platforms and multiple languages, and therefore publication of the code in a single, self-contained processing package is not straightforward. However, all processing codes will be provided on request.

Received: 24 July 2020; Accepted: 11 June 2021; Published online: 2 August 2021

**References**

1. Schwenn, R. Space weather: the solar perspective. *Living Rev. Sol. Phys.* 3, 2 (2006).
2. Cranmer, S. R. & Winebarger, A. R. The properties of the solar corona and its connection to the solar wind. *Ann. Rev. Astron. Astrophys.* 57, 157–187 (2019).
3. Howard, R. A. et al. Near-Sun observations of C-corona decrease and K-corona fine structure. *Nature* 576, 232–236 (2019).
4. Kiefer, J. C. et al. Alfvénic velocity spikes and rotational flows in the near-Sun solar wind. *Nature* 576, 228–231 (2019).
5. McComas, D. J. et al. Probing the energetic particle environment near the Sun. *Nature* 576, 223–227 (2019).
6. Bale, S. D. et al. Highly structured slow solar wind emerging from an equatorial coronal hole. *Nature* 576, 237–242 (2019).
7. DeForest, C. E., Howard, R. A., Velli, M., Viall, N. & Voruridas, A. The highly structured outer solar corona. *Astrophys. J.* 862, 18 (2018).
8. Chhiber, R., Usmanov, A. V., Mattheeus, W. H. & Goldstein, M. L. Contextual predictions for the Parker Solar Probe. I. Critical surfaces and regions. *Astrophys. J. Suppl. Ser.* 241, 11 (2019).
9. Del Zanna, G., Raymond, J., Andretta, V., Telloni, D. & Golub, L. Predicting the COSIE-C signal from the outer corona up to 3 solar radii. *Astrophys. J.* 865, 132 (2018).
10. Vásquez, A. M., van Ballegooijen, A. A. & Raymond, J. C. The effect of proton temperature anisotropy on the solar minimum corona and wind. *Astrophys. J.* 598, 1361–1374 (2003).
11. Masson, S., McCauley, P., Golub, L., Reeves, K. K. & DeLuca, E. E. Dynamics of the transition corona. *Astrophys. J.* 787, 145 (2014).
12. DeForest, C. E., Hassler, D. M. & Schwadron, N. A. On the magnetic correspondence between the photosphere and the heliosphere. *Sol. Phys.* 229, 161–174 (2005).
13. Gilly, C. R. & Cranmer, S. R. The effect of solar wind expansion and nonequilibrium ionization on the broadening of coronal emission lines. *Astrophys. J.* 901, 150 (2020).
14. Linker, J. A. et al. The open flux problem. *Astrophys. J.* 848, 70 (2017).
15. Riley, P. et al. Can an unobserved concentration of magnetic flux above the poles of the Sun resolve the open flux problem? *Astrophys. J.* 884, 18 (2020).
16. Schrijver, C. J. & Mullanen, R. A. A case for resonant scattering in the quiet solar corona in extreme-ultraviolet lines with high oscillator strengths. *Astrophys. J.* 531, 1121–1128 (2000).
17. Winebarger, A. R., Warren, H. P. & Mariska, J. T. Transition Region and Coronal Explorer and Soft X-Ray Telescope active region loop observations: comparisons with static solutions of the hydrodynamic equations. *Astrophys. J.* 587, 439–449 (2003).
18. DeForest, C. E., Martens, P. C. H. & Wills-Davey, M. J. Solar coronal structure and stray light in TRACE. *Astrophys. J.* 690, 1264–1271 (2009).
19. Seaton, D. B., De Groof, A., Shearer, P., Berghmans, D. & Nicula, B. SWAP observations of the long-term, large-scale evolution of the extreme-ultraviolet solar corona. *Astrophys. J.* 777, 72 (2013).
20. Goryaev, F., Slementz, V., Vainshtein, L. & Williams, D. R. Study of extreme-ultraviolet emission and properties of a coronal streamer from PROBA2/SWAP, Hinode/EIS and Mauna Loa Mk4 observations. *Astrophys. J.* 781, 100 (2014).
21. O’Hara, J. P., Mierla, M., Podladchikova, O., D’Heuys, E. & West, M. J. Exceptional extended-field-of-view observations by PROBA2/SWAP on 2017 April 1 and 3. *Astrophys. J.* 883, 39 (2019).
22. Tadokoro, S. K. et al. Coronal imaging with the Solar UltraViolet Imager. *Sol. Phys.* 294, 28 (2019).
23. Seaton, D. B. & Darnell, J. M. Observations of an eruptive solar flare in the extended EUV solar corona. *Astrophys. J. Lett.* 852, L9 (2018).
24. Vasudevan, G. et al. Design and on-orbit calibration of the ultra violet imager (SUVI) on the GOES-R series weather satellite. *Proc. SPIE* 11180, 11180F7P (2019).
25. Brueckner, G. E. et al. The Large Angle Spectroscopic Coronagraph (LASCO). *Sol. Phys.* 162, 357–402 (1995).
26. Strachan, L. et al. Latitudinal dependence of outflow velocities from O VI Doppler dimming observations during the Whole Sun Month. *J. Geophys. Res.* Re2, 2345–2356 (2009).
27. Parker, E. N. Dynamics of the interplanetary gas and magnetic fields. *Astrophys. J.* 128, 664–676 (1958).

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