Predicting the Corona for the 21 August 2017 Total Solar Eclipse

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The total solar eclipse that occurred on 21 August 2017 across the United States provided an opportunity to test a magnetohydrodynamic model of the solar corona driven by measured magnetic fields. For the first time we used a new heating model based on the dissipation of Alfvén waves, and a new energization mechanism to twist the magnetic field in filament channels. We predicted what the corona would look like, one week before the eclipse. Here we describe how this prediction was accomplished, and we show that it compared favorably with observations of the eclipse in white light and extreme ultraviolet. The model allows us to understand the relationship of observed features, including streamers, coronal holes, prominences, polar plumes, and thin rays, to the magnetic field. We show that the discrepancies between the model and observations arise from limitations in our ability to observe the Sun's magnetic field. Predictions of this kind provide opportunities to improve the models, forging the path to improved space weather prediction.

Background

Eclipses have long been a source of wonder and fascination, but they also have a unique place in the scientific discovery process. On 21 August 2017, a celestial spectacle delighted millions of people across the United States, as a total solar eclipse swept across the country. It provided an opportunity to test our understanding of the physics of the solar corona[1–3], the region of the Sun's atmosphere where the gas is heated to over a million degrees by processes that are still not fully understood[4–6]. During totality a solar eclipse reveals the faint corona that is normally hidden from view, exposing intricate structures that are shaped by the magnetic field, including streamers, polar plumes, rays, and prominences. The coronal magnetic field is the source of the energy that is released during the solar flares[7] and coronal mass ejections that can damage Earth-orbiting satellites and cause power outages. It dominates the structure and dynamics of the corona, but is difficult to observe above the photosphere and chromosphere. It is of intense scientific interest to understand how the magnetic field emerges from beneath the Sun's surface, how it evolves, when it is about to erupt, and how such ejections travel through interplanetary space. These eruptions have the potential to trigger a geomagnetic storm when they interact with the Earth's magnetic field.

It is only through detailed three-dimensional (3D) modeling of the solar corona that we can link ob-

servations of the Sun's magnetic field in the photosphere to the coronal structures that are unveiled during an eclipse. Complementary measurements of extreme ultraviolet (EUV) and X-ray emission from space offer an additional perspective. White-light observations of the corona are made routinely from ground-based observatories and spaceborne coronagraphs, but neither can image the lowest layers of the corona, or capture the finest details that are observed during eclipses (though future space coronagraphs promise to narrow this gap[8]). Consequently, even with today's detailed space measurements of the Sun, eclipses play a unique role in this discovery process[9–11], especially since the expense of the instrumentation required is relatively modest.

It has been said that prediction is the ultimate test of a scientific theory. It was during the 1919 eclipse that Eddington and colleagues verified Einstein's theory of general relativity to great acclaim, confirming a prediction for the shift in the apparent position of stars by warping of space by the Sun[12] (though the accuracy of the measurement is not without controversy[13–15]). Our group has made routine predictions of the eclipse corona for over two decades[16–18], during which time our models have improved steadily as a result of dramatic advances in computing power, but also through enhancements in the physics of the models. These improvements were driven in part by comparisons with eclipse predictions. In the future, these and similar models are expected to improve the forecasting of solar storms. In this article, we describe a prediction of the solar corona using a computer model that tests recent advances in theory and modeling with modern observations. The model employs two key innovations: a physics-based formulation that describes the heating of the corona over a broad range of conditions, and a novel approach for energizing the coronal magnetic field on global scales. A related prediction of this eclipse with a different model has also been made[19], and is discussed below.

Predicting the Eclipse Corona

We predicted the structure of the corona one week prior to the eclipse, using a 3D magnetohydrodynamic (MHD) model to compute the interaction of the solar wind with the Sun's magnetic field (see Methods). It tracks the exchange of energy between coronal heating, radiative losses, and thermal conduction along the magnetic field, and is fed by measurements of the magnetic field in the photosphere[20–22]. We used spaceborne measurements of the photospheric magnetic field from the Helioseismic and Magnetic Imager (HMI)[23] aboard the Solar Dynamic Observatory (SDO)[24], and a wave-turbulence-driven (WTD) model to heat the corona via low-frequency Alfvén waves launched in the chromosphere[25–27]. A fraction of the outward-directed waves interact with reflected waves[28] and dissipate, heating the corona.

Eclipses reveal the lowest regions of the solar corona, where prominences are often seen, embedded at the base of coronal streamers and pseudostreamers[29]. Several prominences were observed during the 21 August 2017 eclipse, as is typical during this declining phase of the solar cycle. These dense, cold structures are believed to be supported by magnetic fields in filament channels[30–32]. When a prominence is present within a streamer, it tends to produce an "inflated" appearance because of the extra magnetic pressure from the magnetic field (see Supplementary Figure 6). To model these features, we implemented a technique to introduce highly sheared magnetic fields in these channels, at locations that were determined by examining animated images of EUV emission observed by the Atmospheric Imaging Assembly (AIA)[33] on SDO (see Supplementary Figure 5). This process increased the free magnetic energy, "energizing" the corona, as described in the Methods section.

As a boundary condition on our model we used photospheric magnetic fields derived from synoptic HMI measurements of the longitudinal (line-of-sight) component of the magnetic field, including data from Carrington rotation (CR) 2192, starting on 16 July 2017, combined with "Near Real Time" data from CR 2193, measured up to 12:00 UT on 11 August 2017, ten days prior to totality. (The composite

synoptic chart is shown in Supplementary Figure 2.) The parameters for the model, including the driving Alfvén wave amplitude, were selected based on runs made during the previous two months (as discussed in the Methods section, and summarized in Supplementary Figure 1). The calculation was begun on 11 August 2017, starting from one of these previous solutions. The corona was relaxed towards equilibrium by advancing the model for 60 hours of solar time in a dedicated queue at NASA's Advanced Supercomputing Center. At the final stage of our calculation, we introduced magnetic shear in filament channels, relaxing the corona for another 8 hours. These runs took a total of 54 hours of real time to advance 68 hours of solar time.
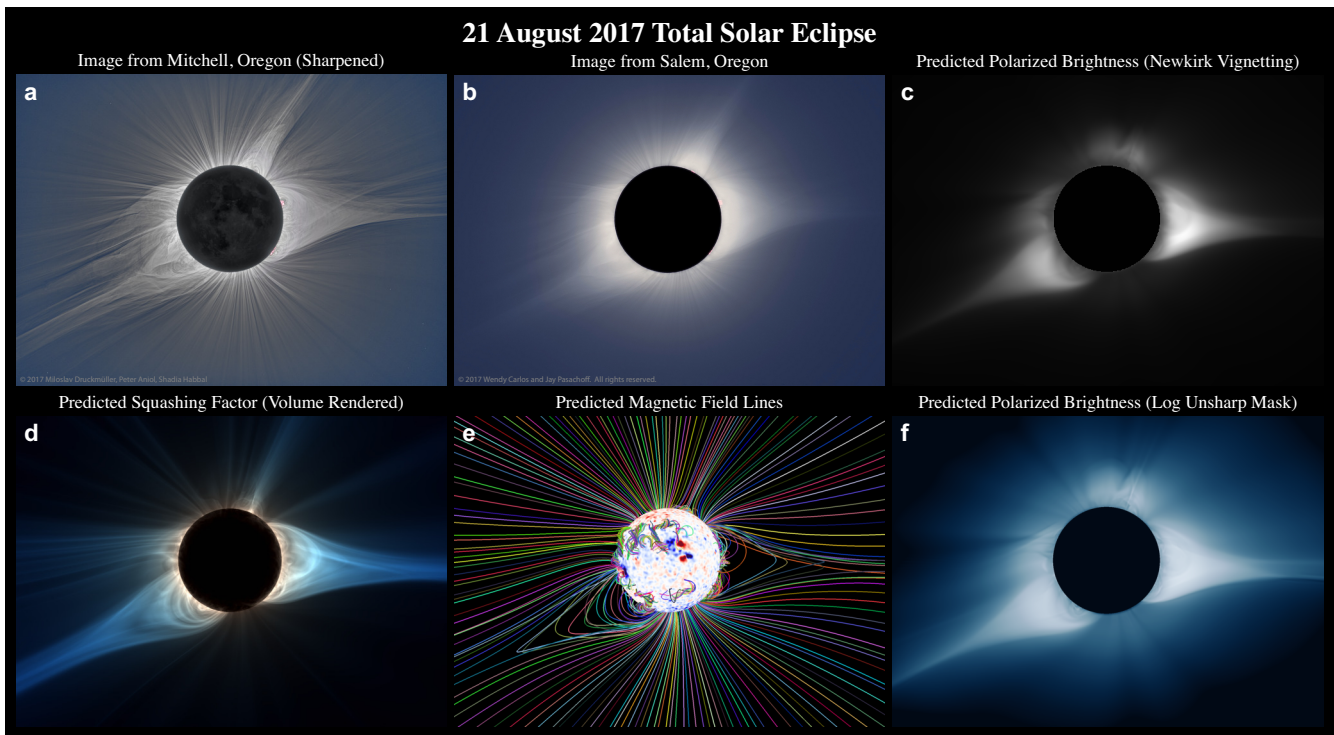
Since the corona responds to changes in the photospheric magnetic field, the accuracy of a prediction deteriorates over time. We would expect better accuracy during this declining phase of the solar cycle, when the Sun's magnetic field changes more slowly than at solar maximum, and this was indeed the case. Flux transport models have promise in improving the accuracy of the evolving photospheric magnetic field. Indeed, the Surface Flux Transport (SFT) model has been used in conjunction with a potential field source-surface (PFSS) model to predict the structure of the coronal magnetic field for this eclipse[19]. While this simpler model does not predict coronal density and temperature, and does not produce non-potential coronal magnetic fields, it can be carried out rapidly. The flux transport model that we used to identify energized filament channels (see the Methods section) employs a magnetofrictional model in the corona, and produces nonpotential coronal fields[34].

After completing the calculation, we synthesized observables that can be compared directly with observations taken during the eclipse. From the predicted electron density we computed the total and polarized brightness in white light[35], quantities that are principally measured during eclipses. Polarized brightness can be useful in separating the significantly polarized K-corona, of solar origin, from the largely unpolarized fainter outer F-corona, whose main contribution is from interplanetary dust[36]. Using the distribution of temperature, we computed the EUV emission expected in various channels of the AIA telescope, as well as soft X-ray emission[18,22,37]. We also visualized the squashing factor[38] Q that emphasizes the fine spatial scales in the magnetic field, as discussed in the Methods section.

Comparison with Eclipse Observations

Our prediction was tested against photographs of the eclipse and spaceborne observations. Overall, the model predicted the general appearance of the corona, though many details were different. The principal large-scale streamers that visually dominate the eclipse corona were predicted accurately. Figure 1 shows a comparison between two eclipse images and several predicted quantities from the MHD simulation. A series of photographs taken at different exposures by the Solar Wind Sherpas eclipse expedition in Mitchell, Oregon, were combined digitally and enhanced[39] to emphasize the finest details in the corona (Fig. 1a). A different series of 14 photographs taken in Salem, Oregon, by the Williams College expedition, were assembled digitally (Fig. 1b) as described in the Methods section. It is difficult to produce a simulated image of what the eye sees during an eclipse, because of the accommodation of the eye to the wide range of brightness in the corona, but in our personal experience, it is likely to between Fig. 1a and Fig. 1b.

These two images show features that resemble those in the predicted white-light polarized brightness (pB) (Fig. 1c). We detrended pB radially using the Newkirk vignetting function to bring out the faint intensity in the outer corona. This mimics the effect of a radially-graded filter that was used in past decades during a time when eclipse photography employed analog techniques[36,40]. The radial variation of intensity between the processed photographs and this pB image is therefore arbitrary, and should not be considered when comparing these images—only a latitudinal comparison of intensity is meaningful.

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a — Image from Mitchell, Oregon (Sharpened)
b — Image from Salem, Oregon
c — Predicted Polarized Brightness (Newkirk Vignetting)
d — Predicted Squashing Factor (Volume Rendered)
e — Predicted Magnetic Field Lines
f — Predicted Polarized Brightness (Log Unsharp Mask)

Figure 1. Comparison between the observed and predicted eclipse corona. The images are oriented with terrestrial north up; solar north is 18.2° counterclockwise from the vertical.
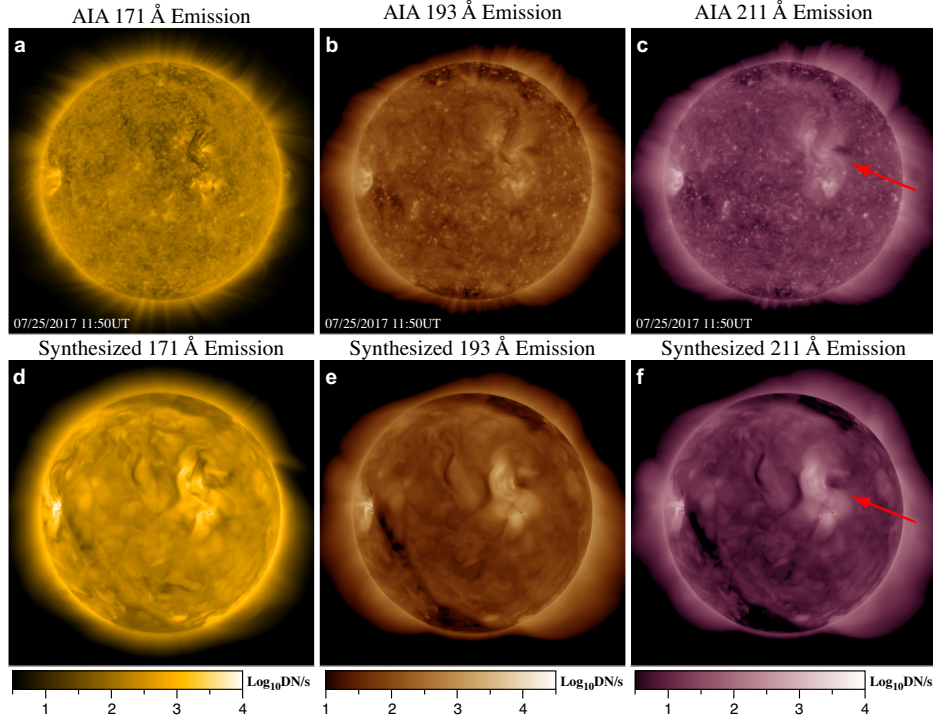
For an animation of pB at different longitudes see Supplementary Video 1. An alternate depiction of the coronal structure is obtained by using an "unsharp mask" on pB and displaying the result using a logarithmic scaling (Fig. 1f).

Polar plumes, which are visible in the polar regions (Fig. 1a), are seen to align with the magnetic field lines (Fig. 1e), as shown in Supplementary Video 2, an animation that fades between the two images. The fine-scale features in the white-light corona (Fig. 1a) are believed to be manifestations of the complexity of the underlying magnetic field. Although our calculations do not yet have enough resolution to resolve these spatial scales directly in the white-light corona, the magnetic field, as visualized by Q, does display similar fine-scale features (Fig. 1d). Many of the variegated, high-Q structures arise from the divergence of coronal field mappings as they approach the small-scale flux concentrations present in the photosphere. For an animation of Q at different longitudes see Supplementary Video 3. Animations that fade between an eclipse image and Q and pB are shown in Supplementary Video 4 and Supplementary Video 5. The complexity that is evident in the coronal magnetic field, and its associated topological consequences, including the presence of separatrices and quasi-separatrix layers (QSLs), has been termed the "separatrix web," or S-web[41–43]. It may provide the key to the origin of the slow solar wind, which has a distinctly different structure and composition from the fast wind. A key development of our model is to capture, self-consistently, the propagation of Alfvén waves, and the resultant coronal heating, in the backdrop of this magnetic complexity.

In addition to this comparison with eclipse observations, we compare with observations on other days to highlight interesting structures that are present in a three-dimensional model of the corona. In Figure 2 we compare predicted EUV emission on 25 July 2017 with AIA observations in the 171 Å, 193 Å, and 211 Å channels. This date falls within the range of magnetic field observations used for the prediction, one solar rotation prior to the eclipse. The predicted emission broadly matches the contrast and level

EUV Emission on July 25, 2017

AIA 171 Å Emission | AIA 193 Å Emission | AIA 211 Å Emission

Synthesized 171 Å Emission | Synthesized 193 Å Emission | Synthesized 211 Å Emission

Figure 2. Comparison between observed and predicted EUV emission. Observed EUV emission (**a**, **b**, and **c**) in the 171 Å (Fe IX), 193 Å (Fe XII and XXIV), and 211 Å (Fe XIV) AIA channels, deconvolved with the point-spread function, on 25 July 2017, one solar rotation prior to the eclipse, compared with simulated emission (**d**, **e**, and **f**) from the prediction. The images are oriented with solar north up. The red arrows indicate the diffused active region with a nonpotential character.

of observed emission across a wide variety of solar features, including coronal holes, which appear as extended dark regions, and active regions, which appear bright. There also are significant differences in the details, associated with temporal changes of the corona and the limited spatial resolution of the model, so the agreement must be considered qualitative. Coronal holes are locations with largely unipolar magnetic field in the photosphere, in which the magnetic field lines are open, and are believed to be the source of the fast solar wind. At this phase of the solar cycle the polar coronal holes are ubiquitous, and sometimes extend to lower latitudes. Since the level of emission is sensitive to the amount and distribution of coronal heating, this confirms that the WTD model performs well. The diffused active region at latitude 22°N, longitude 305°, indicated by red arrows in Figure 2, shows a significant nonpotential character, a consequence of the magnetic shear introduced along the polarity inversion line (PIL) passing through it (see Supplementary Figure 5).

Unraveling the Sun's Complexity

Although the agreement between the modeled features of the large-scale corona and observations is heartening, having a sophisticated model allows us to unravel the origin of interesting structures observed during the eclipse, and to examine theories in detail. To illustrate this, we describe the interpretation of several prominent thin rays[44] seen on the east limb (on the left side of the image) at near-equatorial latitudes in Figure 1a. These extended rays resemble polar plumes. Their origin can be traced by examining an animation of volume-rendered Q from different viewpoints (Supplementary Video 6). They
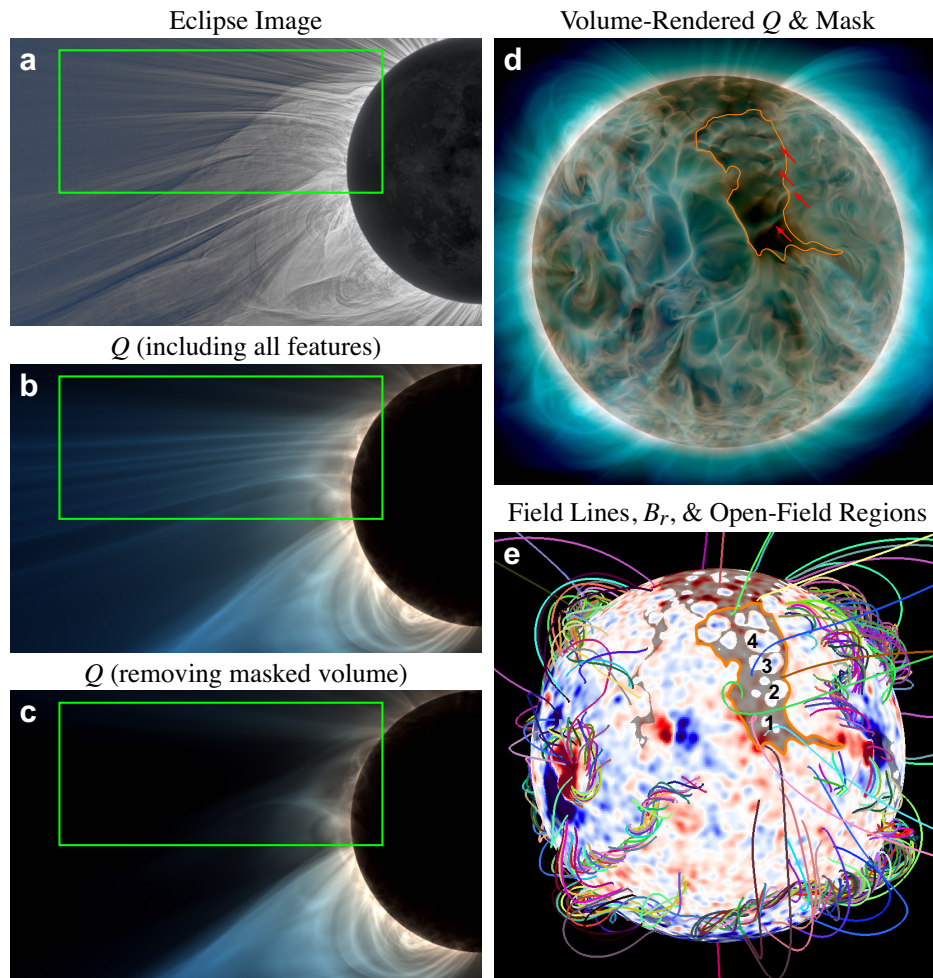
Figure 3. Investigating the origin of equatorial rays. The equatorial rays seen in the eclipse image **a** are present in the volume-rendered Q image **b** (within the green box). **c**, When the structures that connect to the low-latitude portion of the coronal hole are removed (within the volume that maps to the interior of the mask outlined in orange in **d** and **e**), the rays disappear, verifying that their source is within the coronal hole. **d**, A view of Q when the Sun is rotated by $117°$ about its axis to make the coronal hole visible. The red arrows point to the bases of 4 prominent rays. **e**, Open-field regions (transparent gray), B_r with blue (red) indicating negative (positive) values, and traces of magnetic field lines in arbitrary colors. The numbers 1–4 in **e** mark the parasitic polarity at the base of the rays. It is also evident from **d** and **e** that the polar plumes in the northern coronal hole emanate from locations with parasitic polarity.

are embedded in a low-latitude coronal hole that extends from the northern polar coronal hole that was located on the east limb at the time of eclipse. To illustrate this explicitly, we artificially "mask out" these features in the model, as illustrated in Figure 3. The rays are shown in a zoomed-in region of the eclipse image (Fig. 3a), together with a volume rendering of Q (Fig. 3b), and a version in which the contribution to Q from all field lines emanating from the low-latitude portion of the coronal hole has been masked out (Fig. 3c). The rays are clearly missing in Figure 3c, leaving only the curved feature of the streamer cusp, verifying that they are located in the coronal hole. A tracing of the mask in the photosphere is shown in orange in Figures 3d and 3e, with the Sun rotated to visualize the coronal hole. We conclude that the

rays are indeed similar to plumes[45], since they connect at their base to locations in coronal holes with parasitic magnetic polarity (Fig. 3e). Even though the simulated rays qualitatively resemble the observed ones, their individual brightness and locations are different. These are likely to be transient features because they are associated with small regions of parasitic polarity that cannot be captured using synoptic data.
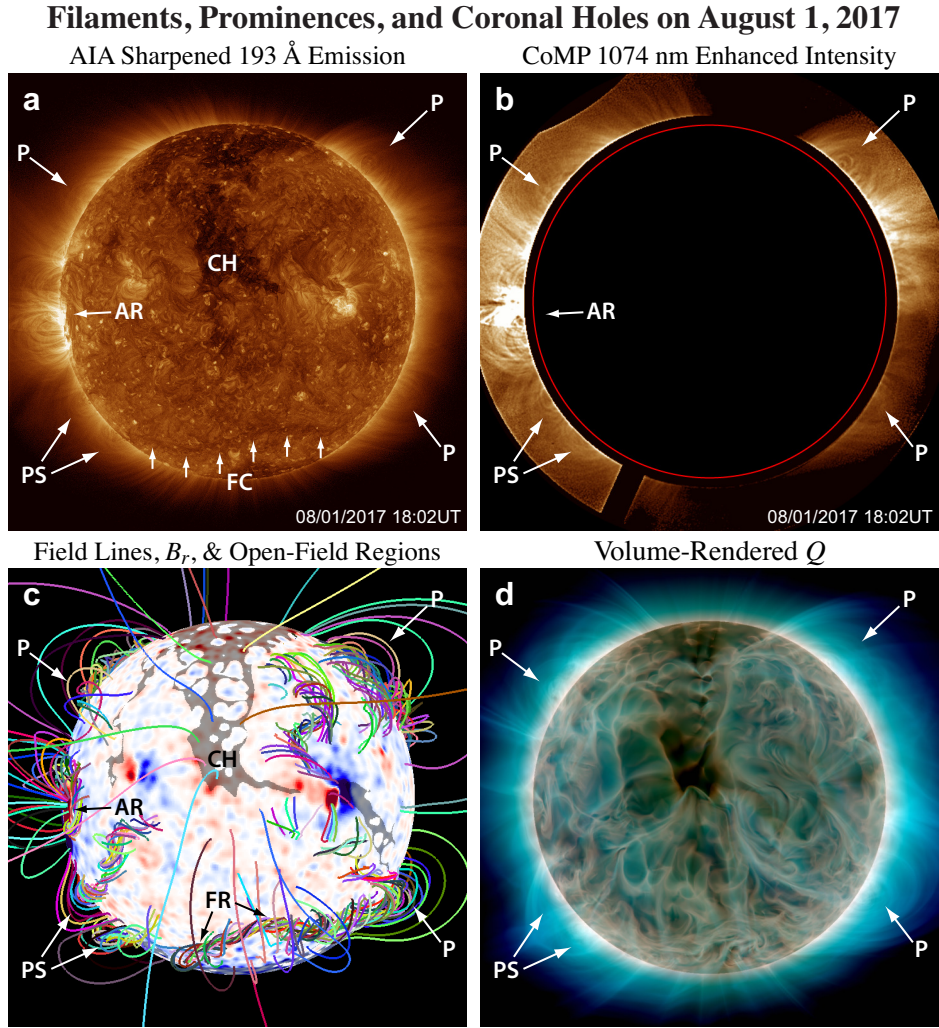
Figure 4. Comparison between observed features and model predictions. a, Sharpened AIA 193 Å EUV emission on 1 August 2017. **b**, Enhanced intensity of the 1074 nm Fe XIII coronal emission line from the MLSO CoMP instrument. **c**, Model predictions, including open-field regions (transparent gray), B_r with blue (red) indicating negative (positive) values, and traces of magnetic field lines in arbitrary colors. **d**, Volume-rendered squashing factor Q. Bright loops in an active region (AR) are visible on the limb (**a** and **b**). Dark coronal holes (CH) in EUV emission **a** correspond with open-field regions in the model **c**. Dark filament channels (FC) in emission **a** correspond with the location of a twisted flux rope (FR) in the model **c**. Cavities associated with prominences (P) and a pseudostreamer (PS) on the limbs in AIA and CoMP, **a** and **b**, agree with magnetic structures in the model, **c** and **d**.

Several large-scale features in EUV emission can be examined with the model. Global manifestations of twist in the coronal magnetic field are seen in filament channels that appear as narrow "dark lanes" in coronal EUV emission on the disk, indicating the presence of cooler material. At certain times these

locations are the sites of filaments, in which the coronal plasma condenses to chromospheric temperatures, which appear in Hα and in the 304 Å AIA channel. We illustrate these features in Figure 4, in which we compare observations with predictions on 1 August 2017. Figure 4a shows a 193 Å AIA image, sharpened[46] to emphasize fine details. The northern coronal hole (marked CH), which appears dark, can be seen to extend to equatorial latitudes. This area corresponds to locations with open field lines in the model (Fig. 4c), in a positive-polarity region (red), with small parasitic negative-polarity intrusions (blue). The twisted magnetic fields in a long flux rope (marked FR in Fig. 4c), correspond to a dark filament channel with the same shape in the EUV image (marked FC in Fig. 4a). Supplementary Video 9 compares the locations of energized filament channels with a synoptic map of AIA 193 Å emission.

On the limbs, prominences are associated with coronal cavities[47]. These are locations with reduced EUV emission that coincide with the flux ropes that magnetically support the cold and dense material in prominences. The 193 Å emission from AIA (Fig. 4a) and the enhanced intensity from the 1074 nm Fe XIII coronal emission line measured at Mauna Loa Solar Observatory (MLSO) with the CoMP instrument[48] (Fig. 4b) show the cavities associated with the flux ropes/prominences. A volume rendering of Q (Fig. 4d), which emphasizes the shape of magnetic structures on the limbs, shows good correspondence between the twisted flux ropes in the model that extend to the solar limbs and the cavities associated with prominences (marked P) in these images. In particular, a pseudostreamer[29] (marked PS), with two prominence cavities embedded in it, is clearly visible in AIA and CoMP on the southeast limb. The model shows the flux ropes that support these prominences in the same location (Fig. 4c), and these are clearly visible in Q (Fig. 4d). Animations of Q (Supplementary Video 6) and the magnetic field lines (Supplementary Video 7) versus longitude aid in following the 3D structure of these flux ropes.

The Missing NW Pseudostreamer

One notable disagreement between our prediction and the observed corona is the small pseudostreamer[29] that extends to large radius on the northwest limb (top center-right in Figs. 1a and 1b). The eclipse images show that it contains two prominences at its base, typical of pseudostreamers, which are associated with a double reversal (a "switchback") in the large-scale polarity inversion line (PIL)[29]. This structure is not seen in the predicted pB images (Figs. 1c and 1f), though the Q image (Fig. 1d) does show a tendency for an extended radial feature there. Careful analysis of the photospheric magnetic field synoptic chart used for the prediction (Supplementary Fig. 2) shows that the requisite PIL switchback is not present near the northwest limb (latitude 50°N, longitude 21°), precluding the formation of a pseudostreamer there. The magnetic field measurements in that neighborhood date from 16–20 July 2017, so they are over a month old by eclipse time. Newer observations, from 12–16 August 2017, show that the magnetic fields in that location are evolving, and the switchback now extends to the northwest limb (see Supplementary Figure 3), supporting the formation of a pseudostreamer. Interestingly, the SFT model correctly predicted a reversal at that location, as well as the associated pseudostreamer[19].

In Figure 5 we examine the PIL from different models at 21:52UT on August 14, 2017. This view is convenient to investigate the NW pseudostreamer because structures that were located at the west limb at eclipse time are at central meridian in this view. Fig. 5a shows photospheric B_r and the PIL (black line) for the synoptic HMI data used for our prediction (Supplementary Figure 2), compared to the PIL from the SFT model (magenta line). [The PIL from the SFT model is for the prediction[19] for 21 August 2017, obtained from their Fig. 3a]. Note that the tongue of negative polarity from the SFT model extends almost to the east limb (red arrows), and at central meridian it has the required switchback that allowed a pseudostreamer to form in the SFT model prediction[19]. The PIL in the map we used (black line), which used HMI data from July 16–August 11, does not reach central meridian (green arrows), explaining why

the NW pseudostreamer was absent in our prediction. Fig. 5b makes the same comparison, but now with updated HMI magnetic field data (July 20–August 16) corresponding to CR2193 (Supplementary Figure 3). The negative polarity (blue values) now reaches central meridian, implying that a prediction with this data would produce the NW pseudostreamer, an idea we intend to explore.

Polarity Inversion Line (PIL) on August 14, 2017
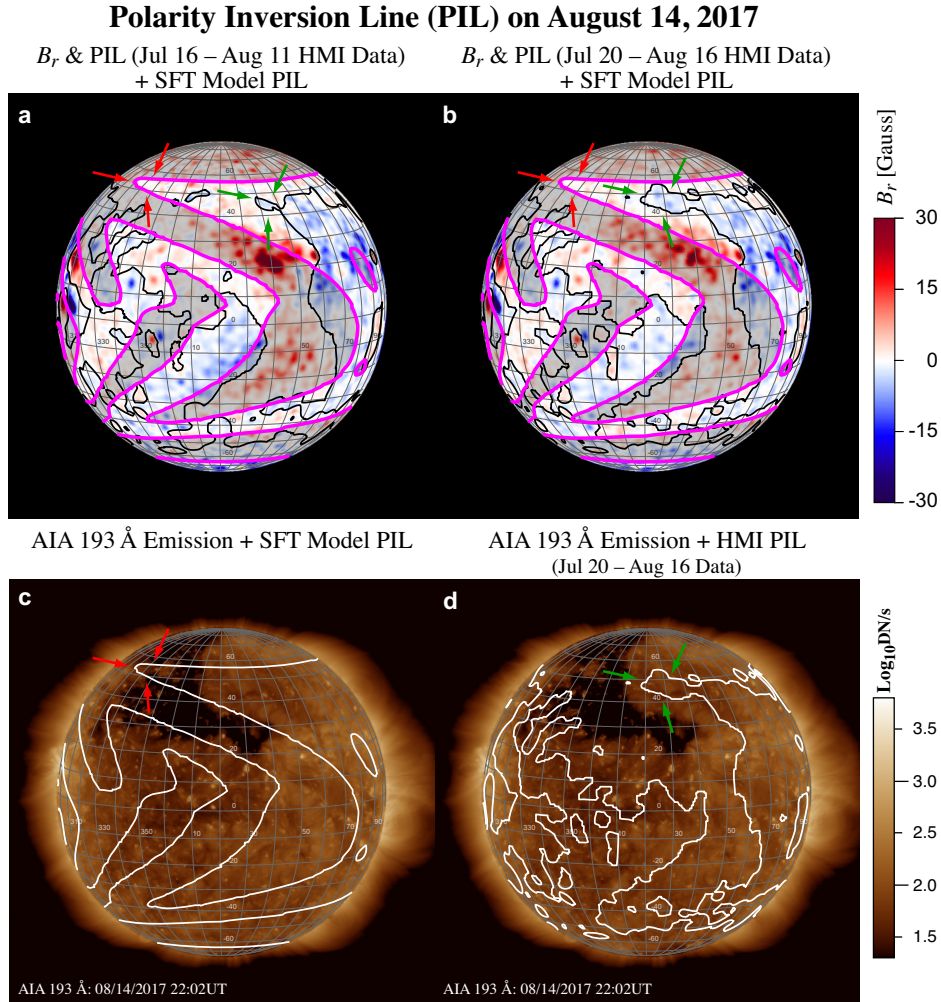
Figure 5. Polarity Inversion Line Comparison. a, B_r and the PIL (black line) from HMI data used for the prediction, compared with the PIL from the SFT model (magneta line). Positive (negative) B_r values from HMI are shown in red (blue). Positive-polarity regions in the SFT model are shaded a transparent gray. **b**, Same as **a**, but with updated HMI data (July 20–August 16). **c**, An overlay of the SFT model PIL (white line) on an AIA 193 Å EUV emission image. The extended dark region indicates a coronal hole. **d**, An overlay of the PIL from the updated HMI data on the same 193 Å image. In these views, the NW pseudostreamer that was on the west limb at eclipse time is at central meridian. The red arrows show the switchback in the SFT model PIL that allows the NW pseudostreamer to form; the green arrows show the switchback in the PIL from HMI synoptic data. These PILs are discussed in the text.

As already noted, coronal holes are unipolar regions, and therefore should not be crossed by PILs. Overlays of the PIL (white lines) from the SFT model and the updated HMI data on AIA 193 Å images are shown in Figs. 5c and 5d, respectively. A prominent coronal hole with positive polarity is seen to extend from the pole to low latitudes. It appears that the SFT model PIL (Fig. 5c) extends too far eastward:

the negative-polarity region (red arrows) encroaches into the positive-polarity coronal hole, leading to an inconsistency. On the other hand, the PIL from the updated HMI data (Fig. 5d) correctly stops short of the coronal hole boundary (green arrows).

Clearly, getting the most accurate representation of the magnetic field is of paramount importance when making predictions. As we have seen, synoptic magnetic field data, which are built up from observations from a single vantage point over a solar rotation, can lead to inaccuracies. An alternative is to use a flux-transport model that evolves the field over the whole Sun to predict the magnetic field into the future (making assumptions about the field that emerges in the intervening time). Because of the simplicity with which flux is added into the SFT model (i.e., in idealized bipolar active regions)[19], its predictions are subject to inaccuracies in active regions, and especially at lower latitudes. It has already been recognized that flux transport models that do not use data assimilation can introduce fundamental inaccuracies in high-latitude and polar fields[49]. It is likely that techniques that assimilate magnetograms into a flux transport model, such as the Schrijver & DeRosa model[50], the ADAPT model[51,52], and the Advective Flux Transport model[53], offer the best of both worlds, allowing for prediction of fields into the future while at the same time incorporating observations.

Prospects

Along with improved measurement techniques, computer models of the Sun have come of age. The sophistication of the models allows us to explore the details of coronal structures and the physics behind them. Our inability to measure the magnetic field instantaneously over the whole surface of the Sun limits the accuracy of our forecasts. Fortunately, this can be remedied by locating multiple spacecraft off the Sun-Earth line (e.g., at the L5 Lagrange point[49]). With improved data, a model such as the one we describe can be extended to track the continuous evolution of the Sun, similar to what is done in terrestrial weather models, with the potential to provide more accurate forecasts, including the initiation and propagation of coronal mass ejections. In the near term, detailed modeling will be crucial to provide the global context needed to interpret detailed measurements from the upcoming Parker Solar Probe and Solar Orbiter missions (to be launched in 2018 and 2020, respectively), which promise to give us new insight into the near-Sun environment.

Methods

Magnetohydrodynamic Model. The coronal eclipse prediction was performed using the MAS code, which solves the resistive MHD equations in spherical coordinates (r, θ, ϕ) on nonuniform meshes using a semi-implicit time-stepping algorithm. The method of solution, including the boundary conditions, has been described previously[54–58]. The model simulates the global corona and solar wind out to $15R_\odot$ and beyond[20,21,59,60]. A primary application of MAS is to simulate realistic magnetic configurations that are observed in the corona, which is achieved by using observational measurements of the radial component of the photospheric magnetic field, B_r, as a primary boundary condition. In this case, we used synoptic observations taken with the HMI magnetograph[23,61] aboard the SDO spacecraft[24] to specify B_r. The model includes a sophisticated treatment of the flow of energy, including thermal conduction along the magnetic field, optically thin radiative losses, and an advanced treatment of coronal heating[20,57,62], allowing the plasma density, temperature, and velocity to be computed in addition to the magnetic field. With this information we can accurately estimate EUV and soft X-ray emission that are observed from space[21,22,63], as well as white-light polarized brightness, which is best seen during eclipses, but can also be measured from the ground and in space.

Developing a model of the corona involves specifying parameters, including the Alfvén wave flux in the WTD model, the possible scaling of the photospheric magnetic field, and the abundance of elements in the corona. In general, the values of these parameters can be constrained by multiple observations, including EUV emission from AIA and spectrographs, scattered white light from coronagraphs, and additional observations that depend on the coronal magnetic field, such as radio emission, Faraday rotation, and the intensity in infrared spectral lines, and *in situ* measurements of plasma properties, magnetic fields, and charge states in the solar wind, among others. Comprehensive assimilation of these measurements into a model is a complex endeavor that is still in its infancy. We used an *ad hoc* procedure to constrain our parameters by considering a subset of these diagnostics. In the months leading up to the eclipse, we ran a series of 17 medium-resolution simulations (with $204 \times 148 \times 315$ mesh points) using the HMI B_r synoptic map for CR 2189 (2–29 April 2017). We made the following comparisons: 1) simulated EUV images were compared with AIA observations at three different periods during the rotation; 2) the size and morphology of coronal holes deduced from synoptic maps of observed AIA EUV emission[64] were compared with open-field boundaries from the model[65]; 3) the off-limb differential emission measure (DEM)-weighted temperature, deduced from fits to AIA emission[66], was compared with a similarly deduced temperature from the model; 4) simulated white-light polarized brightness and the morphology of streamers were compared with MLSO K-Cor coronagraph data[67]. We used these comparisons to fine-tune the heating in the model, expressed as the flux of Alfvén waves at the base of the corona. We eventually found a reasonable (though not perfect) agreement with all four diagnostics. This idea is summarized visually in Supplementary Figure 1, which compares the final prediction with some of these diagnostics on 25 July 2017, one solar rotation prior to the eclipse.

An important choice in our model was to specify the abundances of elements in the corona, which are not known precisely. For the final prediction we used coronal abundances, in conjunction with the CHI-ANTI 7.1[68] radiative loss function. For consistency, we used identical abundances to synthesize EUV emission. An alternate popular choice is to use photospheric abundances, which are generally lower. During our experiments, we found that, to zero order, changing the abundances in this way does not produce widely different coronal EUV emission, but it does affect the predicted plasma density in the corona (in a ratio that is inversely proportional to the square root of the abundances). From Supplementary Figure 1 it is apparent that our predicted pB is less bright than that inferred from MLSO K-Cor. Quantitatively, the predicted values are about a factor of 2 smaller. Since pB is proportional to plasma density, we could

have chosen to increase pB in our model by using photospheric abundances. This issue will be examined further in the future, possibly by comparing with other eclipse measurements.

Our final prediction was performed in two phases: a preliminary prediction, three weeks before the eclipse, and a final prediction, with updated magnetic field observations, one week prior to the eclipse, which was posted on our website (http://predsci.com/eclipse2017) on 15 August 2017. The timing of the synoptic magnetic field data we used is described in the main article. The high-latitude fields were fit using the procedure described in Supplementary Note 1. We multiplied the B_r inferred from HMI by the factor of 1.4 to account for the difference in magnetic field strengths measured by the HMI magnetograph and its predecessor, the MDI magnetograph on SOHO[69], since several of our previous eclipse predictions used MDI data, and our model parameters were benchmarked to MDI data. In general, photospheric magnetic fields measured by different instruments are qualitatively similar but differ quantitatively[70], and the true values are unknown[65]. Thankfully, the increase of B_r by this factor is not an essential aspect of the model. Similar results could be obtained by leaving B_r unchanged and using a different driving amplitude for Alfvén waves in the photosphere. The proper scaling of B_r must await confirmation by more reliable observations. Supplementary Figure 2 shows the photospheric radial magnetic field that was used in the calculation. Magnetic field data for CR 2193, which has updated measurements from 12–16 August 2017 at the location of the eclipse-day west limb (longitudes $0°$–$51°$), is shown in Supplementary Figure 3. This updated data relates to the inaccuracy in the prediction of the observed northwest pseudostreamer, as discussed in the Prospects section of the main article.

The simulation used a high-resolution mesh, with $295 \times 315 \times 699$ (r, θ, ϕ) mesh points, with a uniform angular resolution of $0.52°$ in longitude (corresponding to $6,300$ km at the Sun's surface), and a similar latitudinal resolution at the equator that increased to $1.23°$ towards the poles. The radial resolution was finer in the transition region ($\Delta r = 260$ km) to resolve the thermal conduction length-scale at low heights (which is artificially broadened using a special, solution-preserving technique[21,71]), and grows to match the horizontal resolution with radius, maximizing at $\Delta r = 290,000$ km at the upper boundary, $r = 15R_\odot$.

The calculation for the final prediction was run on 4,200 Pleiades CPU cores at NASA's Advanced Supercomputing facility. The first run simulated the relaxation of the corona for 60 hours of solar time (solution A), starting from the final state of a previous run (the preliminary prediction from 31 July, with magnetic fields updated to 8 August). A separate zero-beta simulation, in which the magnetic field was energized, was performed at the same time (solution B). The energization procedure is described below. The final magnetic field in this energized solution had the same B_r at $r = R_\odot$ as that in solution A. A third and final run then updated solution A with the nonpotential component of the magnetic field from solution B[72], relaxing the corona for an additional 8 hours to equilibrate the energized field with the large-scale corona from solution A. This end-state was used to produce the quantities for the prediction.

Coronal Heating Model. The heating of the corona was specified by using a wave-turbulence-driven (WTD) phenomenology to advance equations for Alfvén wave amplitudes along with the MHD equations. Our model is based on the idea that the interaction of outward and reflected waves is responsible for the dissipation of the waves, producing coronal heating[28]. This follows related works, where the general formalism for the propagation of Alfvén waves[73–75] is usually approximated to produce tractable equations for their propagation[28,76–86]. Our approach advances the amplitudes of the waves, rather than the energy densities, in terms of the Elsasser variables $\mathbf{z}_\pm = \delta\mathbf{v} \mp \delta\mathbf{B}/\sqrt{4\pi\rho}$, where $\delta\mathbf{v}$ and $\delta\mathbf{B}$ are the perturbed wave quantities. For incompressible transverse waves that are isotropic about the direction of the mean magnetic field, $\mathbf{B}$, the vector quantities $\mathbf{z}_\pm$ reduce to the scalar complex Fourier amplitudes z_+ and z_- for a wave with frequency ω. The amplitudes z_+ and z_- represent outward and inward propagating waves

along an open field line directed away from the Sun. Starting from equations for the evolution of z_+ and z_-, we take the zero-frequency limit of these equations to describe the propagation of low-frequency Alfvén waves, for which z_+ and z_- become real scalar quantities[79,87,88]. The following equations are advanced in MAS:

$$\frac{\partial z_\pm}{\partial t} + (\mathbf{v} \pm \mathbf{v}_A) \cdot \nabla z_\pm = R_1 z_\pm + R_2 z_\mp - \frac{|z_\mp| z_\pm}{2\lambda_\perp}, \tag{1}$$

$$R_1 = \frac{1}{4}(\mathbf{v} \mp \mathbf{v}_A) \cdot \nabla(\log \rho), \qquad R_2 = \frac{1}{2}(\mathbf{v} \mp \mathbf{v}_A) \cdot \nabla(\log |\mathbf{v}_A|), \tag{2}$$

where R_1 and R_2 are the diagonal (WKB) and off-diagonal (non-WKB) terms, respectively, and $\mathbf{v}_A$ is the Alfvén velocity. The self-reflection term, R_2, allows for the conversion of an outgoing wave into an incoming wave (and vice versa)—a crucial effect that is not captured in the WKB approximation. The last term in Equation (1) is a phenomenological wave dissipation term[89–93] that produces a volumetric heating rate in the energy equation,

$$H_{\text{WTD}} = \rho \frac{|z_-| z_+^2 + |z_+| z_-^2}{4\lambda_\perp}, \tag{3}$$

where $\lambda_\perp$ is the transverse correlation scale that varies with the flux tube area, $\lambda_\perp = \lambda_0 \sqrt{B_0/B}$, where λ_0 and B_0 are set to typical values at the solar surface. The waves accelerate the solar wind via the wave pressure, $p_w = \rho(z_- - z_+)^2/8$, that feeds into the MHD momentum equation[25,26].

This formalism provides a minimal description of coronal heating that is physically motivated, including a self-consistent treatment of the reflection and dissipation of Alfvén waves. The free parameters are the amplitude of waves at the inner boundary, z_0, and the factor $\lambda_0 \sqrt{B_0}$. Before implementing the WTD formulation into MAS we explored it extensively using a 1D hydrodynamic code, to gain intuition for parameter choices and the scaling of the model, and to ensure that it would be suitable for multi-dimensional MHD modeling. Our work has demonstrated the scaling and applicability of the WTD model to both open-field regions, where the solar wind is accelerated[25,26], and closed-field regions[27], where the corona is heated to several million degrees. The heating adapts automatically to local conditions, changing from low values with long scale lengths in open-field regions to large heating with short scale lengths in closed-field regions[27]. This ability for the model to adapt to both open- and closed-field regions without the need to track the open/closed field boundary makes it particularly suitable for 3D MHD models, where field-line connectivity changes in time.

To provide a visual sense for the overall heating and its variation in space, we show an equivalent heat flux map in Supplementary Figure 4. This map is generated by radially integrating the volumetric heating rate at every location on the surface of the Sun. The net heat flux deposited along a field line is directly related to the net Poynting flux of waves entering and leaving the domain at the inner boundary[27], but the radial integration gives a better sense of where it is actually deposited in the corona.

The WTD formalism and similar approaches[85] were developed by heuristically adapting the physics from one-dimensional models to three dimensions, so it is not surprising that they misbehave in certain situations. We have found that for realistic 3D magnetic fields, some regions, such as magnetic nulls or open field lines connected to weak-field regions, may not receive enough heating in the WTD model. Moreover, the wave-pressure force may develop unphysical behavior at these locations. In the future, these limitations will be improved as we gain more experience in using the WTD model. In the meantime, for this simulation we circumvented these problems by using the wave pressure from the WKB model[21], rather than that from the WTD model, in the MHD momentum equation, and we

added two small spherically symmetric heating terms of the form $H = H_0 \exp\left(-(r - R_\odot)/\lambda\right)$ to the coronal heating from the WTD model. The first term sets a minimum heating in the transition region and low corona ($H_0 = 2.7 \times 10^{-5}$ erg/cm^3/s, $\lambda = 21$ Mm), while the second ensures a minimum heating in open-field regions ($H_0 = 2.9 \times 10^{-8}$ erg/cm^3/s, $\lambda = 696$ Mm). These terms add equivalent heat fluxes of 5.9×10^4 erg/cm^2/s and 1.0×10^4 erg/cm^2/s respectively, which are considerably smaller than the average heat flux supplied by the WTD model, which is in the range $\sim 10^5$–10^7 erg/cm^2/s (Supplementary Figure 4).

Magnetic Field Energization. Filament channels are an observable signature of nonpotential magnetic fields in the low corona. These are regions along polarity inversion lines (PILs) in the photosphere, $B_r = 0$, where the magnetic field tends to be highly sheared, lying almost parallel to the PILs[32]. These filament channels are especially prevalent during this declining phase of the solar cycle, when the strong magnetic fields in active regions are confined to a limited number of locations. They consist of long, low-lying structures that sometimes have filament/prominence material that is visible in Hα and He 304 Å[94]. On occasion they erupt spectacularly. During the 21 August 2017 eclipse, a prominence was seen to erupt on the southeast limb in AIA images just before the eclipse. Quiescent prominences were seen on the west limb at the base of coronal streamers during the eclipse (appearing reddish in the white-light images, as seen in Figure 1). In order to capture these structures in our prediction we emerged sheared magnetic fields in these filament channels in our model, to "energize" the corona. The energization procedure is described in the section on the MAS model by Yeates et al.[95] The PIL at a height $r = 1.05 R_\odot$ was determined from the initial potential field. Segments of this PIL were selected for energization according to the presence of filament channels, determined by examining movies of EUV emission from the AIA instrument on SDO during the period 16 July–12 August 2017, in the 171 Å, 193 Å, and 211 Å channels, enhanced to emphasize filament channels[46]. Additional flux, ΔB_r, was added in the neighborhood of these segments; this flux is later cancelled in the final phase of the energization. The flux was added in channels that were $\sim 0.1 R_\odot$ wide, and amounted to between 10% and 30% of the existing flux in these channels. Transverse magnetic field, $\mathbf{B}_t$, was emerged along these segments, parallel to the PIL, by applying a transverse electric field $\mathbf{E}_t = \nabla_t \Phi$ at $r = R_\odot$, where ∇_t is the transverse gradient, with $\Phi = M B_r$, where M is a mask that localizes $\mathbf{B}_t$ to a neighborhood of the PIL.

The chirality of the magnetic field in filament channels (i.e., the direction of the transverse field along the PIL) was determined by running a separate calculation using a flux transport model, combined with the magnetofrictional model[34,96–98]. We simulated the nonpotential Sun continuously from 1 January–29 July 2017, by adding the active regions that were observed to emerge in HMI magnetograms, as assimilated into the Advective Flux Transport model[53]. This simulation was used to specify the direction of the emerged $\mathbf{B}_t$ in the MHD model by choosing the appropriate sign of M.

This process introduced a highly sheared magnetic field in the filament channels. Supplementary Figure 5 shows the location of the filament channels that were energized, as well as the potential Φ. This emergence phase was followed by a flux cancellation phase, in which the added flux, ΔB_r, was cancelled, by applying a transverse electric field $\mathbf{E}_t = \nabla_t \times \Psi \hat{\mathbf{r}}$ at $r = R_\odot$, with Ψ determined from $\nabla_t^2 \Psi = \Delta B_r / \Delta T$, where ΔT is the time interval over which $\mathbf{E}_t$ is applied. This cancellation tends to reconnect sheared magnetic fields, producing flux-rope-like structures, raising them slightly into the corona in the process. At the end of this phase the radial magnetic field B_r at $r = R_\odot$ matches the observed field. The correspondence between the location of the energized filament channels and those inferred from a synoptic map of observed emission in AIA 193 Å [data supplied by Nishu Karna[99]] can be seen in Supplementary Video 9, an animation that fades the energized channels on a background image of the synoptic emission. Supplementary Figure 6 shows a comparison of the corona before and after energiza-

tion, visualized by a volume rendering of the squashing factor Q, showing that the sheared magnetic fields inflate the streamers and pseudostreamers with flux ropes, with an appearance that resembles prominence cavities. Supplementary Video 8 shows a fade of Q between the unenergized and energized corona.

Squashing Factor of Magnetic Flux Tubes. To illustrate the complexity of the eclipse corona we developed a novel way to visualize the magnetic field structure using a composite, line-of-sight (LOS) rendering of the squashing factor[38, 100]. The squashing factor, Q, is a geometric characteristic of the magnetic field line mapping from one boundary to another. Conceptually it expresses how much an infinitesimal circle on one boundary is "squashed" into an ellipse as it is mapped along magnetic field lines to the other boundary[38]. Q becomes very large or infinite at locations where the magnetic structure experiences abrupt variation[101–103].

Visualizing the information contained in a 3D Q mapping is challenging, requiring the tracing of billions of magnetic field lines. It can be divided into two steps: the computation of Q, and the ensuing visualization of this quantity. We compute Q by exploiting the fact that it has the same value along a field line. We first compute Q at high resolution on the inner and outer radial spherical boundaries (at $4\times$ the resolution of the computation grid, using 16 points per simulation mesh point). The value of Q at each point in the 3D volume is obtained by tracing field lines from the point, in both directions, to their intersections with the inner and outer spherical boundaries, interpolating Q at these locations using cubic spline interpolation, and averaging the two values. We computed Q at 520 million locations inside the 3D volume, on a mesh that is $2\times$ the resolution (in each dimension) of the computation volume. To visualize the 3D Q mapping, we render color images in the plane of the sky, which are then animated with solar rotation to aid in the 3D visualization of Q. The three color channels of each image, red (R), blue (B), and green (G), each contain position-weighted integrals of $\log_{10} Q$ along the LOS, at each pixel, which are combined into a color RGB image. The R, G, and B color channels use different spatial weightings to give a sense of "depth" to the visualized Q, as described in Supplementary Note 2.

Eclipse Observations. The Williams College Eclipse Expedition observed from the campus of Willamette University, in Salem, Oregon. The images used in the composite were taken with Nikon 400-mm and 800-mm lenses and Nikon D810 cameras controlled by the program Solar Eclipse Maestro (from Xavier Jubier). The images were assembled digitally, using a group of custom manual techniques to stack, merge, correct, and optimize them into a composite image that closely approaches the naked-eye appearance of the corona, within the limits of the medium.

Code availability. We have opted not to make the MAS code available at the present time because of the complexity involved in its use, and the expertise required to run it. The support that we would need to provide to users exceeds our current resources. A version of MAS is available for "runs on demand" at NASA's Community Coordinated Modeling Center (CCMC), at https://ccmc.gsfc.nasa.gov.

Data availability. The magnetic field data from the HMI instrument and the EUV data from the AIA instrument on SDO are publicly available at the Joint Science Operations Center (JSOC). The data from the Mauna Loa Solar Observatory (MLSO) are publicly available at their web site. The eclipse images are included in this published article. Some of the other images are publicly available at the Predictive Science, Inc. web site, http://predsci.com/eclipse2017. The other datasets generated during the current study are available from the corresponding author on reasonable request.

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Author contributions

Z.M. and C.D. wrote the text, developed and ran the MHD model, and analyzed the output. R.M.C. developed and ran the MHD model. D.H.M. ran the magnetofrictional model. L.U. analyzed data and provided model inputs. J.A.L., P.R., R.L., T.T., and V.S.T. contributed to the development of the MHD model. J.W., P.R., and Z.M. developed the web site. M.D. photographed the eclipse and produced an eclipse image. J.M.P. organized the 2017 eclipse expedition and its imaging, supervised the composition of an eclipse image, and contributed to the text. W.C. composed an eclipse image. All authors reviewed the manuscript.

Additional information

Predicting the Corona for the 21 August 2017 Total Solar Eclipse

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Supplementary Information:
Notes and Figures

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Supplementary Notes

Supplementary Note 1: Treatment of Polar Fields

The high-latitude radial magnetic field B_r estimated from HMI line-of-sight synoptic maps has inaccuracies due to projection effects. We therefore used a fitting procedure to specify B_r in the polar caps. The time interval during which the synoptic map was assembled from central meridian observations, 16 July–11 August 2017, includes a large part of Carrington rotation (CR) 2193 and a small part of CR 2192, as shown in Supplementary Figure 2. During that time, the solar B_0 angle varied between $4.4°$ and $6.4°$, implying that the north pole of the Sun was visible from Earth, and that the south pole was hidden. We used a geometrical fitting of the high-latitude field (in the latitude region $67°$–$79°$N for the north pole, and $53°$–$67°$S for the south pole) to estimate the polar field (Linker et al. 2013). We verified that this field was consistent with estimates made for previous rotations when the respective poles were maximally visible from Earth, since we keep a running record of the polar fields over time. Alternate schemes for estimating polar fields have also been developed (Sun et al. 2011; Sun 2018). The existing values of B_r from the HMI synoptic map were replaced in the region with latitudes between $80°$–$90°$N and $73°$–$90°$S as follows. To make the polar field less smooth the flux was concentrated into small localized flux elements (Tsuneta et al. 2008), using ~ 400 small flux patches in the north polar cap and ~ 150 in the south polar cap, picked randomly in strength from a Gaussian distribution whose mean matched the fitted values. The total flux in these caps was equivalent to a magnetic field of 2.9 G at the north pole, and -4.3 G at the south pole (before scaling of the overall field by the factor of 1.4, as explained in the Methods section). This field was spatially smoothed using a low-pass filter to blend it with the measured high-latitude field, to give the final result, as shown in Supplementary Figure 2. Flux transport models (e.g., Yeates 2014; Nandy et al. 2018) offer promising alternatives for estimating polar fields.

Supplementary Note 2: Volume Rendering of Q

The volume rendering of the squashing factor Q of magnetic flux tubes was performed as follows. For the large field-of-view images (Figures 1d, 3b, and 3c), the integral takes the form

$$\int_{LOS} e^{-s^2/(2r^2\sigma^2)}\, r^{-n} \log_{10} Q\, ds,$$

where the integration is along the LOS coordinate, s, which is perpendicular to the plane-of-sky, with $s = 0$ corresponding to the limb. The Gaussian term weights the integration to a certain angular extent away from the plane-of-sky, with σ chosen to give a FWHM of $40°$. The r^{-n} term influences the weighting of structures as a function of height in the solar atmosphere, with $n = 1$ corresponding to equal weighting. To separate low-, mid-, and large-scale coronal heights, we use

different powers of $n = 3$, $n = 2$, and $n = 1.5$ for the respective R, G, and B color channels. The signal for each channel is converted to image intensity using linear scaling.

The smaller field-of-view images (Figures 3d, and 4d, and Supplementary Figure 6) are designed to emphasize low coronal structures over the solar disk and off the solar limb. Here the integral uses simple exponential weighting,

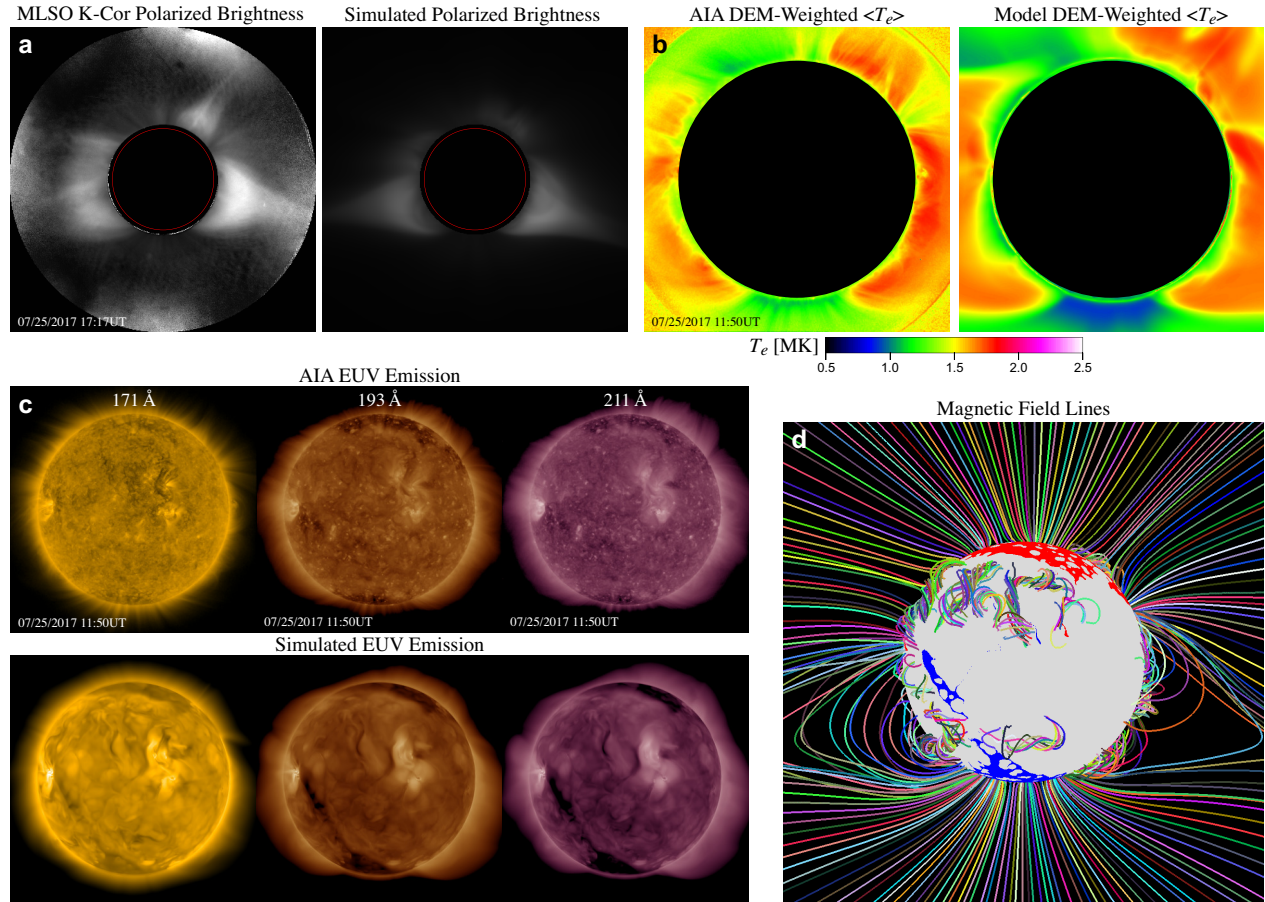$$\int\limits_{LOS} e^{-r/\lambda} \log_{10} Q \, ds,$$

where λ is a scale height. To separate features at different heights we choose $\lambda = 21\,\mathrm{Mm}$, $\lambda = 84\,\mathrm{Mm}$, and $\lambda = 140\,\mathrm{Mm}$, respectively, for the R, G, and B color channels. The signal for each channel is converted to image intensity using logarithmic scaling.

Supplementary References

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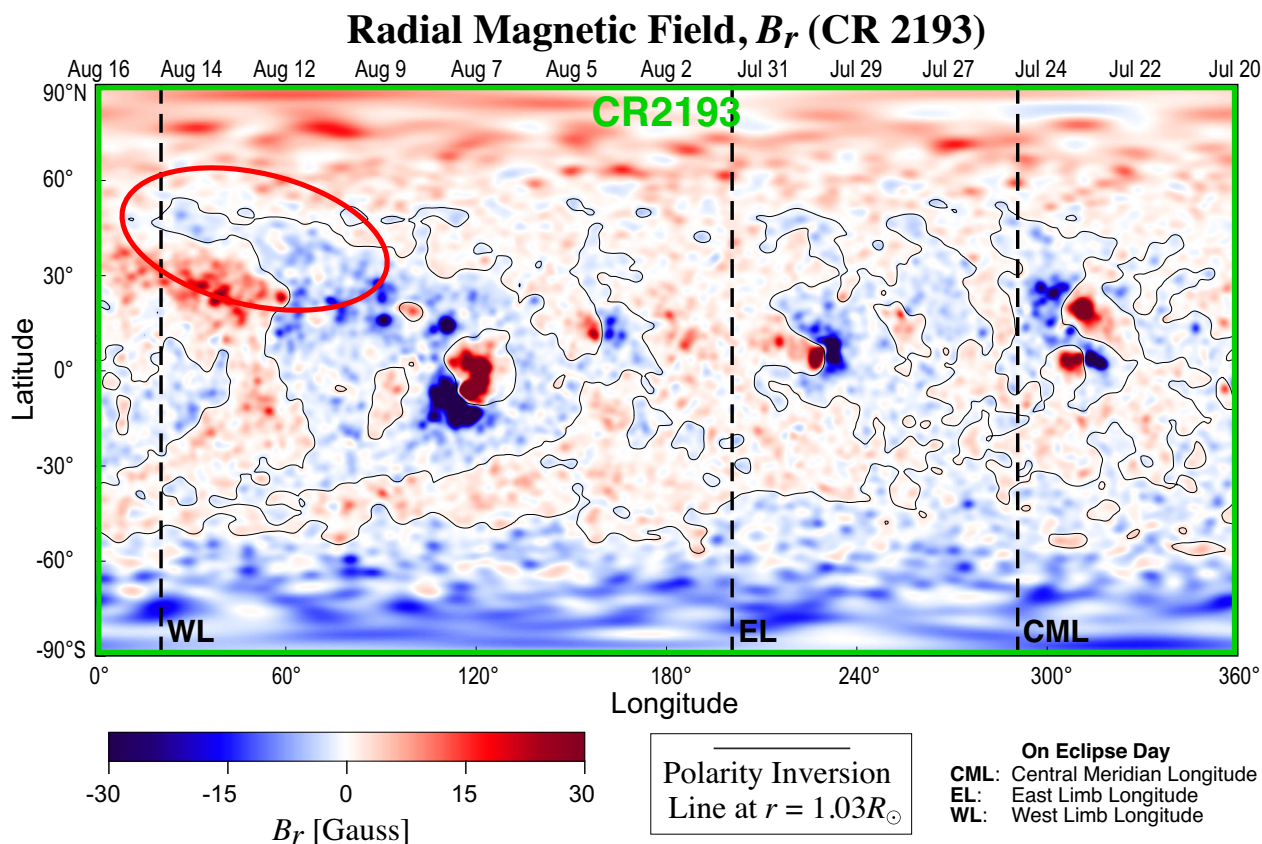
Supplementary Figures

Model Benchmarking (July 25, 2017)

MLSO K-Cor Polarized Brightness   Simulated Polarized Brightness   AIA DEM-Weighted $\langle T_e \rangle$ Model DEM-Weighted $\langle T_e \rangle$

a

07/25/2017 17:17UT

b

07/25/2017 11:50UT

T_e [MK]   0.5   1.0   1.5   2.0   2.5

AIA EUV Emission

c   171 Å   193 Å   211 Å

Magnetic Field Lines

07/25/2017 11:50UT   07/25/2017 11:50UT   07/25/2017 11:50UT

d

Simulated EUV Emission

Supplementary Figure 1. Comparison of predicted and simulated quantities during model benchmarking. An example of a comparison with observations on 25 July 2017, one solar rotation prior to the eclipse. **a**, A 30-minute average of MLSO K-Cor pB compared with simulated pB; the same scaling and (Newkirk) radial filter is used for both images. **b**, Average DEM-weighted off-limb electron temperature for the observed and simulated data, derived by integrating over the 6-channel AIA DEM fit. **c**, Comparison of AIA 171 Å, 193 Å, and 211 Å EUV emission with simulated images. **d**, Selected magnetic field lines from the model, highlighting the streamer structure in the plane of the sky, and showing open-field (blue and red) and closed-field (gray) areas in the photosphere.

Radial Magnetic Field, B_r (CR 2192 + 2193)
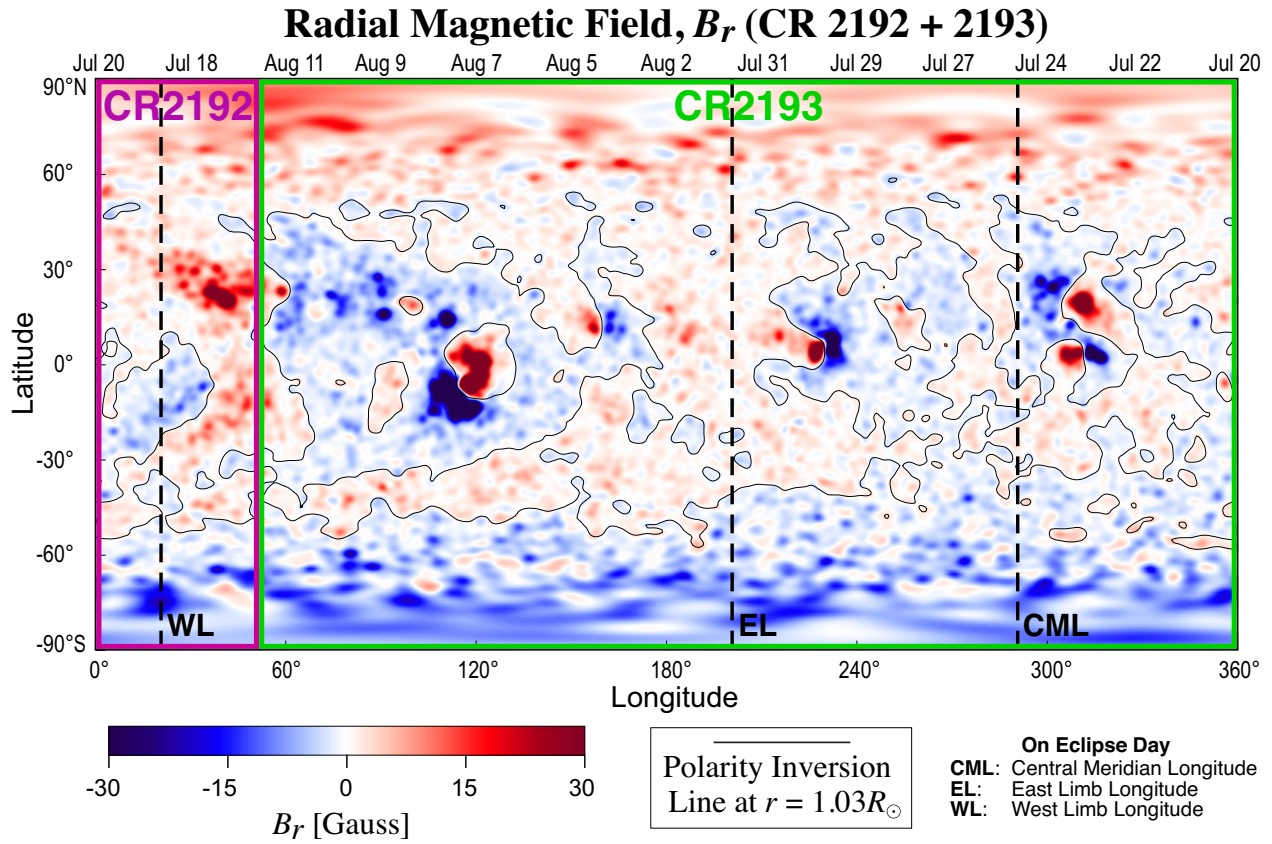
Supplementary Figure 2. Photospheric magnetic field. Synoptic chart of the radial component of the photospheric magnetic field, B_r, for CR 2192 + 2193, measured by HMI and scaled by the factor 1.4, that was used for the final prediction. The dates at the top of the image show the time when the data was measured at central meridian. The dashed vertical black lines show the longitudes of the central meridian (CML), the east limb (EL), and the west limb (WL) at eclipse time.

Radial Magnetic Field, B_r (CR 2193)

Supplementary Figure 3. Updated photospheric magnetic field. Synoptic chart of B_r for CR 2193. The magnetic field data near the west limb (longitudes 0°–51°) is updated to 12–16 August 2017, compared to the data in the chart for CR 2192 + 2193, which was measured during 16–20 July 2017 at those locations, shown in Supplementary Figure 2. Note that the negative polarity region (blue) near latitude 50°N (inside the red oval) now extends to the west limb (WL), supporting the formation of a pseudostreamer there. A comparison between the polarity inversion line (PIL) for this data and the data for CR 2192 + 2193 is shown in Figure 5.
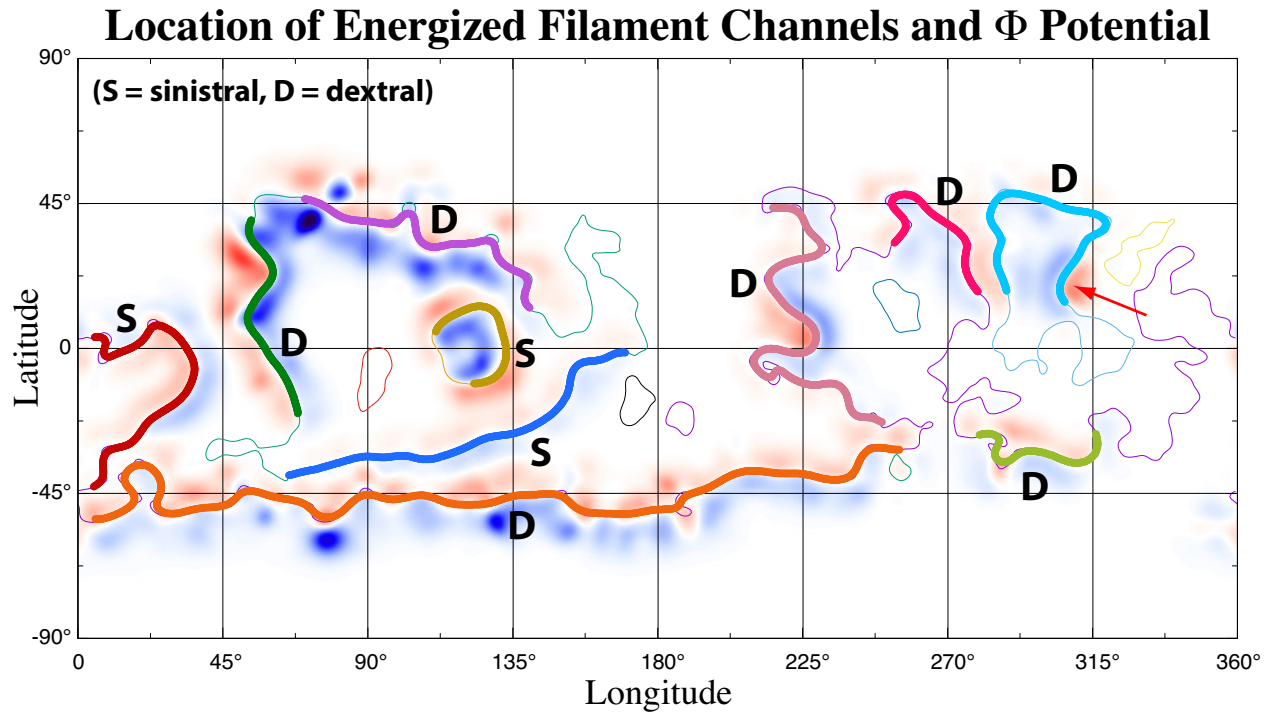
Equivalent Heat Flux at $r = R_\odot$
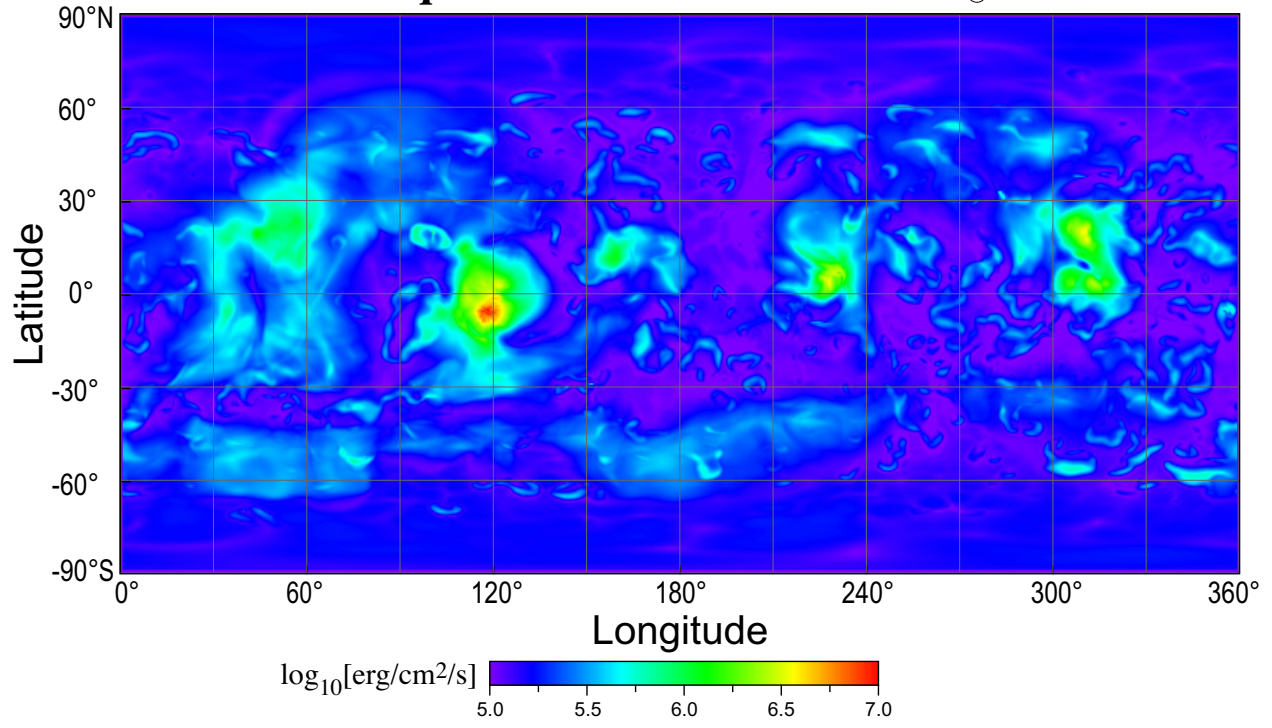
Supplementary Figure 4. Equivalent heat flux. A synoptic map of the equivalent heat flux at $r = R_\odot$, using a logarithmic scale, for the final eclipse prediction.
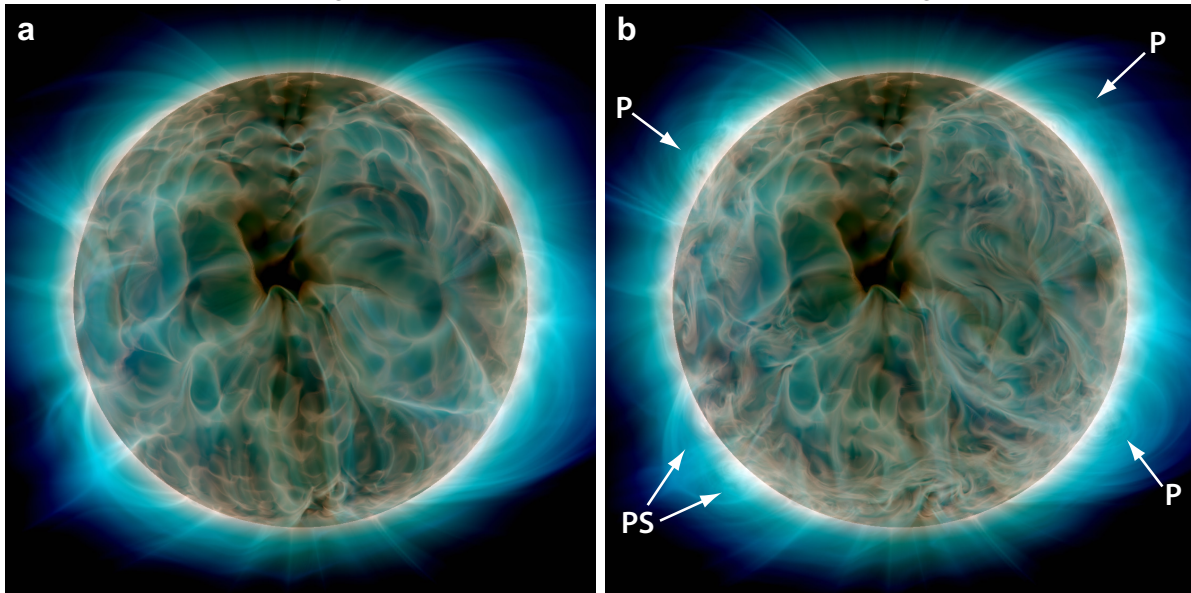
Supplementary Figure 5. Locations of energized filament channels. The synoptic map shows the Φ potential that was used to energize the magnetic field, with blue (red) indicating negative (positive) values. The thin line shows the PIL at $r = 1.05R_\odot$, and the colored segments show the locations of the filament channels that were energized, as determined from AIA observations. The chirality of the magnetic field (sinistral or dextral) was determined from a separate run of the magnetofrictional model. The red arrow near latitude 22°N, longitude 305° indicates the section of the PIL that passes through the active region that appears in the northwest of the solar disk on 25 July 2017, shown in Figure 2. An animation that fades the locations of the energized filament channels on a background image of a synoptic map of observed AIA 193 Å emission is shown in Supplementary Video 9.

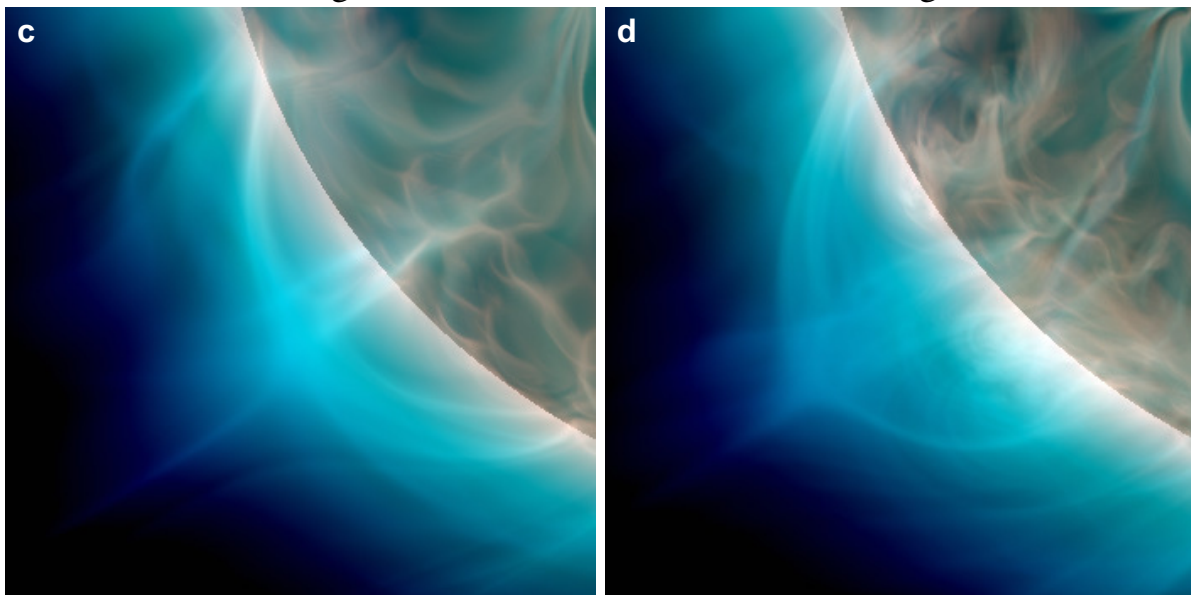# Effect of Energization: Volume-Rendered Q

Before Energization · After Energization

Zoom: SE Pseudostreamer

Before Energization · After Energization

Supplementary Figure 6. Energization of the magnetic field. Volume-rendered squashing factor Q at 18:02 UT on 1 August 2017, before energization of the magnetic field, **a** and **c**, and after energization, **b** and **d**. The twisted flux ropes in the energized model visibly inflate the streamers on the limb at locations of prominences (P) and in the pseudostreamer (PS). This is the same view as that shown in Figure 4. Supplementary Video 8 shows an animation that fades between images **a** and **b**.

Supplementary Videos

- **Supplementary Video 1.** An animation of the simulated polarized brightness versus central meridian longitude, showing the 3D structure of the streamers around the Sun. The time of eclipse in Oregon corresponds to a central meridian longitude (CML) of 290.7°. (For the best effect, when viewing this movie, set your video player to loop continuously.)

- **Supplementary Video 2.** An animation that fades between an observed eclipse image (Fig. 1a) and the magnetic field lines (Fig. 1e). (For the best effect, when viewing this movie, set your video player to loop continuously.)

- **Supplementary Video 3.** An animation of the large field-of-view squashing factor Q versus central meridian longitude, showing the 3D structure of the large-scale magnetic field around the Sun. (For the best effect, when viewing this movie, set your video player to loop continuously.)

- **Supplementary Video 4.** An animation that fades between an observed eclipse image (Fig. 1a) and the squashing factor Q (Fig. 1d). (For the best effect, when viewing this movie, set your video player to loop continuously.)

- **Supplementary Video 5.** An animation that fades between an observed eclipse image (Fig. 1a) and the simulated polarized brightness pB (Fig. 1c). (For the best effect, when viewing this movie, set your video player to loop continuously.)

- **Supplementary Video 6.** An animation of the small field-of-view squashing factor Q, showing the 3D structure of the magnetic field in the inner corona. (For the best effect, when viewing this movie, set your video player to loop continuously.)

- **Supplementary Video 7.** An animation of the magnetic field lines as the Sun rotates, showing the open- and closed-field regions, as well as the twisted flux ropes in the filament channels. (For the best effect, when viewing this movie, set your video player to loop continuously.)

- **Supplementary Video 8.** An animation that fades between the squashing factor Q in the inner corona for the unenergized (Supplementary Fig. 6a) and energized (Supplementary Fig. 6b) corona on 1 August 2017. Note that the twisted flux ropes in the filament channels (in the energized model) visibly inflate the streamers and the pseudostreamer. (For the best effect, when viewing this movie, set your video player to loop continuously.)

- **Supplementary Video 9.** An animation that fades the locations of the energized filament channels (colored lines from Supplementary Fig. 5) on a background image of a synoptic map of observed AIA 193 Å emission for CR 2192 + 2193 (16 July–12 August 2017). (For the best effect, when viewing this movie, set your video player to loop continuously.)