A Truly Global Extreme Ultraviolet Wave from the SOL2017-09-10 X8.2+ Solar Flare-Coronal Mass Ejection

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Abstract

We report Solar Dynamics Observatory/Atmospheric Imaging Assembly (SDO/AIA) observations of an extraordinary global extreme ultraviolet (EUV) wave triggered by the X8.2+ flare-CME eruption on 2017 September 10. This was one of the best EUV waves ever observed with modern instruments, yet it was likely the last one of such magnitudes of Solar Cycle 24 as the Sun heads toward the minimum. Its remarkable characteristics include the following. (1) The wave was observed, for the first time, to traverse the full-Sun corona over the entire visible solar disk and off-limb circumference, manifesting a truly global nature, owing to its exceptionally large amplitude, e.g., with EUV enhancements by up to 300% at 1.1R⊙ from the eruption. (2) This leads to strong transmissions (in addition to commonly observed reflections) in and out of both polar coronal holes (CHs), which are usually devoid of EUV waves. It has elevated wave speeds >2000 km s−1 within the CHs, consistent with the expected higher fast-mode magnetosonic wave speeds. The CHs essentially serve as new “radiation centers” for the waves being refracted out of them, which then travel toward the equator and collide head-on, causing additional EUV enhancements. (3) The wave produces significant compressional heating to the local plasma upon its impact, indicated by long-lasting EUV intensity changes and differential emission measure increases at higher temperatures (e.g., log T = 6.2) accompanied by decreases at lower temperatures (e.g., log T = 6.0). These characteristics signify the potential of such EUV waves for novel magnetic and thermal diagnostics of the solar corona on global scales.

Key words: Sun: activity – Sun: corona – Sun: coronal mass ejections – Sun: flares – Sun: oscillations – waves

Supporting material: animation

1. Introduction

Global extreme ultraviolet (EUV) waves (Thompson et al. 1998) are intensity disturbances expanding across a sizable fraction of the solar corona. They are one of the most spectacular manifestations of solar eruptions involving flares and coronal mass ejections (CMEs). After a decade-long debate with extensive observations (e.g., Patsourakos & Vourlidas 2009; Liu et al. 2010; Temmer et al. 2011; Nitta et al. 2013; Muhr et al. 2014; Long et al. 2017b) and modeling (e.g., Wu et al. 2001; Chen et al. 2002; Ofman & Thompson 2002; Ofman 2007; Downs et al. 2011, 2012), it was recognized that their physical nature embodies a fast-mode magnetosonic wave component, often accompanied or driven by another non-wave component due to CME-caused reconfiguration (see reviews by Wills-Davey & Attrill 2009; Gallagher & Long 2011; Zhukov 2011; Patsourakos & Vourlidas 2012; Liu & Ofman 2014; Warmuth 2015; Chen 2016; Long et al. 2017a).

We report here Solar Dynamics Observatory/Atmospheric Imaging Assembly (SDO/AIA) observations of an extraordinary EUV wave on 2017 September 10. This was the first detection of a truly global EUV wave that, with its exceptionally large amplitude, covered the full-Sun corona, including traveling in and out of both polar coronal holes (CHs). It produced significant thermal perturbations to the coronal plasma, lasting for hours. These characteristics allow waves of such extreme magnitudes to serve as probes to diagnose the solar corona on global scales, a yet under-explored subject (West et al. 2011; Kwon et al. 2013; Long et al. 2017c).

2. Observational Overview

The event of interest (SOL2017-09-10T16:06) occurred in active region (AR) 12673 at the west limb, associated with an X8.2+ flare and a fast CME, which themselves were extremely remarkable in many respects, including being the second largest flare and causing the second ground-level enhancement event (GLE) of Solar Cycle 24 (e.g., Gary et al. 2018; Gopalswamy et al. 2018; Guo et al. 2018; Kurt et al. 2018; Li et al. 2018; Omodei et al. 2018; Polito et al. 2018; Warren et al. 2018; Yan et al. 2018).

The flare occurred at 15:35 UT and peaked at 16:06 UT (Figure 3(b)). The impulsive phase (15:52–16:06 UT) started cotemporally with the onset of the rapid ascent (at an acceleration of 9.5 ± 0.7 km s−2; cf., Veronig et al. 2018) and lateral expansion of the teardrop-shaped flux-rope, giving birth to the CME and global EUV wave, which was observed...
Figure 1. SDO/AIA overview of the 2017 September 10 global EUV wave. (a) Composite tri-color image, 211 Å (red), 193 Å (green), and 171 Å (blue), showing the erupting flux-rope and notable structures, including ARs, North-polar/South-polar and on-Disk CHs (N-/S-, D-CH), bipolar regions (BP1, BP2), and a coronal cavity. (b)–(c) Simultaneous 171 and 193 Å running-ratio images showing the global wave. (d)–(i) Running-ratio tri-color images showing its evolution, with plasma heating (cooling) indicated in yellow or red (blue). Short white arrows in (f)–(i) mark wave fronts reflected/refracted from the polar CHs. An animation of this figure, covering 15:34–17:43 UT without annotations, is provided in the online Journal. The animation is of the four, synchronized SDO/AIA images: the composite tri-color original and running-ratio images (top), and the individual 171 and 193 Å running-ratio images (bottom). Individual, higher-resolution versions of the animations are available as data behind the Figure.

(An animation of this figure is available.)

by SDO/AIA, the Geostationary Operational Environmental Satellite-16/Solar Ultraviolet Imager (GOES-16/SUVI; Seaton & Darnel 2018; T. Podladchikova et al., in preparation), and the Project for On-Board Autonomy-2/Sun Watcher using Active Pixel System detector and Image Processing (PROBA2/SWAP; Goryaev et al. 2018). Its radio signatures were detected by the Low-Frequency Array (LOFAR; Morosan et al. 2018).

Figure 1 and its online animations give an overview of the EUV wave evolution. By 15:52 UT, it is clearly visible surrounding the eruption and starts to propagate in all directions. Off-limb, the wave travels both northward and
southward, traverses both polar CHs and a coronal cavity on the southeast limb, and finally arrives at AR 12680 on the east limb to the opposite end of the solar diameter from the eruption, covering the entire solar limb circumference. On-disk, the wave front begins with a circular shape, evolves into a reverse-C shape comprising the eastward primary wave and equatorward secondary waves reflected and refracted from the polar CHs, which eventually collide at low latitudes.

There are a variety of smaller-scale secondary waves due to reflections and/or refractions, wherever the primary or secondary wave encounters structures of differing magnetic-field strengths and thus fast-mode magnetoacoustic speeds. There are also ubiquitous stationary brightenings, dimmings (Zhukov & Veselovsky 2007), and oscillations, some lasting for more than two hours, e.g., at the coronal streamer and CH boundaries (Figures 1–2). Collectively, every corner of the full-Sun corona is essentially traversed by this wave. Its thermal effect is manifested in anti-correlated, large intensity variations between warm and cool wave compression and rarefaction, respectively.

3. Global Wave Characteristics

3.1. Off-limb Wave Propagation

To track the off-limb wave propagation, we selected three azimuthal cuts (A0–A2; cf., Liu et al. 2012) at constant heights above the limb over the entire global circumference. Figure 2 shows the resulting space–time diagrams, where the distance along the cut is radially mapped onto the limb and measured in the counter-clockwise direction from the eruption center. The left panels show original intensities, where bright ARs and (dark) CHs are identified. The rest of the panels show running ratios, where the EUV wave front is evident, generally as brightening at 193/211 Å and darkening (e.g., 171 Å) channels, indicative of adiabatic heating and cooling by wave compression and rarefaction, respectively.

One of this event’s novel features is the strong transmissions (cf., Olmedo et al. 2012) into both polar CHs, in addition to the commonly observed refractions (e.g., Gopalswamy et al. 2009). This, instead of apparent “transmission” by line-of-sight projection, is supported by the following evidence.

1. The EUV wave captured on the off-limb azimuthal cuts has elevated speeds (by ×[2–3]) within the CHs, consistent with the expected higher fast-mode speeds. If the wave were to propagate around (in front of or behind) the CHs, the POS-projected wave speed would not increase but remain the same or smaller.

2. The vertical cuts within the polar CHs show clear continuation between the off-limb and on-disk waves, with different space–time slopes but without detectable time lag at the limb (Figures 3(d) and (h)). This suggests that the off-limb and on-disk waves are of the same front that travels primarily along the limb. The N-CH, in particular, extends substantially both off-limb and on-disk (down to latitude ~60°), throughout which the wave signal is present and has a steeper slope than its quiet-Sun on-disk counterpart.

3. Another indication that the EUV wave actually travels into the polar CHs is the wave-triggered transverse displacements (up to 60 km s⁻¹) of polar plumes within CHs that occur sequentially at increasing distances upon the wave arrival (Figure 1(a) animation) and appear as feather-like patterns in space–time plots (Figures 2(h)–(i)).

An interesting effect of CH transmission is the alteration of the wave propagation direction. As shown in Figures 1(f) and (g), the wave fronts emerging from the polar CHs are nearly parallel to latitudes, rather than longitudes (as one would expect for waves from a source at the west limb), and travel toward the equator. This is because the fast-mode speed increases toward the center of the CH, causing the wave to be refracted away from the center and travel nearly radially outward. This effect, as numerically demonstrated (Schmidt & Ofman 2010; Jin et al. 2016, their Figure 4(e)), makes each polar CH essentially serve as a new “radiation center” for the waves emerging from it.

We find multiple wave fronts, or “ripples,” leaving the polar CHs at quasi-periodic intervals in the 3–10 minutes range, marked by white open circles in Figures 3–4. As partly indicated in simulations (Schmidt & Ofman 2010; Afanasyev & Zhukov 2018; Plantschitsch et al. 2018), these pulses could result from a combination of: (i) direct reflection at the CH boundary in 3D space, (ii) refraction of the transmitted wave as noted above, (iii) multiple reflections/bounces within the CH between its two end boundaries, each producing its own...
Figure 2. Off-limb wave propagation. (a) Context AIA 211 Å image. (b)–(i) space–time plots from the three azimuthal cuts shown in (a) in original intensity (left) and running-ratio (middle/right) at 211/193 Å (top) and 171 Å (bottom). The horizontal dotted lines delineate the polar CH boundaries. In (c) and (d), 211 and 193 Å data are shown, respectively, between and beyond the two innermost horizontal lines near ±100″. Unless otherwise noted, cyan dotted lines starting with an open circle in all space–time plots of this article are linear fits to the wave front positions, labeled with fitted speeds in km s⁻¹, and are shifted back in time by −100 s here and by −500 s in Figures 3–4 to avoid obscuring the original data.
transmission out of the CH, and (iv) dispersive propagation of the primary fast-mode wave, which itself exhibits certain periodicities near the eruption (e.g., Figures 3(f) and 4(b)). Pulsed waves from CHs were reported before (e.g., Figure 6 in Yang et al. 2013), but the large number of pulses (up to six) in this event is remarkable.

3.3. On-disk Wave Propagation

To track the on-disk wave propagation and measure the so-called “ground speed” projected onto the spherical solar surface (e.g., Liu et al. 2010), we employed two sets of spherical sector cuts: one set (P0–P9) originating from the flare kernel at the limb and the other (P0–P9) from the POS-projection of the Sun’s south pole, whose selected space–time plots are shown in Figure 4 (top and bottom, respectively).

As shown in Figure 1, the initially circular-shaped on-disk wave front is interrupted by a cluster of strong magnetic-field regions to the northeast/east of the eruption, including ARs and bipolar regions. Only its southern portion advances substantially onto the quiet-Sun disk toward the east. This is also seen in Figures 4(b)–(d), where we find initial wave speeds of \( \sim 800 \text{ km s}^{-1} \) near the eruption, similar to the off-limb speeds (Figure 2). The speed generally decreases with distance, either gradually or abruptly upon encountering local structures, e.g., bipoles BP1 and BP2. The increased speeds in Figures 4(c)–(d) are overestimates due to the wave from the S-CH approaching the cuts sideways.

The rest of the on-disk wave fronts comprise reflected and refracted secondary waves from the two polar CHs that travel equatorward (Figures 1(f)–(h)) and are well captured by the polar sector cuts (Figure 4, bottom). They emerge from the poles at \( \sim 1800 \text{ km s}^{-1} \), again, comparable to the off-limb wave speeds, and decelerate down to 200–400 km s\(^{-1}\), within the expected range of quiet-Sun fast-mode speeds. Eventually, the two equatorward waves collide near BP2 around 16:40 UT, as marked by the plus signs, and produce extra intensity enhancements at 193/211 \( \AA \) followed by long-lasting C-shaped dimming (brightening at 171 \( \AA \)) that expands toward the southeast (Figure 1(i)). Such interactions of counter-propagating waves (e.g., Ofman & Liu 2018) can result in plasma heating, e.g., by turbulence generation and dissipation.

3.4. Thermal Response of the Global Corona

As alluded earlier, the EUV wave generally causes substantial intensity decreases in cool channels (e.g., 171 \( \AA \)) and increases in warm channels (e.g., 193/211 \( \AA \), with slight delays at 211 \( \AA \). This implies plasma heating across these channels’ characteristic temperatures, from \( \log T = 5.9 \) (\( T = 0.8 \text{ MK} \)) to 6.2 (1.6 MK) and then 6.3 (2.0 MK). This is usually followed by an opposite change, suggestive of cooling. In composite running-ratio images (Figure 1), heating (cooling) corresponds to yellow/red (blue). Such variations can be understood as wave-produced adiabatic compressional heating followed by rarefractional cooling (e.g., Downs et al. 2012; Liu et al. 2012).

Figures 5(a)–(c) show an example of such anti-correlated intensity variations off the northwest limb. Within the N-CH at \( s_0 = 1.1 R_\odot \) from the eruption, the 211 \( \AA \) emission brightens by \( \times 3 \) from its pre-event level, while the 171 \( \AA \) intensity drops by 40\%. At \( s_1 = 0.7 R_\odot \) in the northern peripheral of AR 12674/12679, such changes are \( +50\% \) and \( -80\% \), respectively. These numbers dwarf those in mild EUV waves, e.g., \( \lesssim 20\% \) in a C3.3 flare (Liu et al. 2012) and \( \lesssim 80\% \) in an

![Figure 3. Height dependence and off-limb to on-disk wave transition. (a) Context AIA 171 \( \AA \) image overlaid with selected vertical cuts in white. (b)–(i) Corresponding space–time plots in base-ratio at 211 \( \AA \) in (b) and running-ratio at 171/193 \( \AA \) in the other panels. The horizontal dotted line marks the limb position, above which the original intensity is shown in (f). The portion within the four white brackets (on-disk N-CH) here in (d) and those in Figures 4(g)–(i) shows 171 \( \AA \) data to highlight the EUV wave there. Cyan dotted lines in (b) and (f) are parabolic fits (not shifted in time), labeled with average \( \langle v \rangle \) and final speeds \( v_f \).](image-url)
M1.0 flare (Downs et al. 2012). Such intensity variations can occur repeatedly involving multiple heating–cooling cycles, e.g., at $500^\circ < s < 800^\circ$ around $s_1$, which are associated with damped (by leakage and/or dissipation) kink oscillations of coronal loops, $\Delta s(t) = A_0 \exp(-t/\tau_A) \sin(2\pi t/P)$, at a typical period $P = (23 \pm 2)$ minutes, damping time $\tau_A = (3.5 \pm 0.6)$ $P$, and initial displacement and velocity amplitudes of $A_0 = (11 \pm 1)$ Mm and $v_0 = (49 \pm 6)$ km s$^{-1}$.

To tease out wave-caused subtle thermal changes, we performed differential emission measure (DEM) inversion (Cheung et al. 2015), which is generally underused for EUV waves (Vanninathan et al. 2015). We focused on the off-limb corona and constructed space–time plots at selected temperatures from DEM maps. As shown in Figures 5(d)-(g) for azimuthal Cut A0, the EUV wave, marked by white arrows, is well captured. Similar to the intensity variations noted above, the DEM generally decreases at lower temperatures (e.g., $\log T = 6.0$) and increases at higher temperatures (e.g., $\log T = 6.2$), indicating plasma heating, followed by an opposite change, indicating recovery cooling. The exact change varies, depending on the distance from the eruption (thus wave or compression amplitude) and the initial local DEM distribution. For example, as shown in Figures 5(h)-(i), at $s_2 = -1.2 R_\odot$ inside the S-CH where the plasma is initially cool, the wave causes substantial, prompt (within ~10 minutes) DEM increases at $\log T \geq 6.1$ by $\lesssim 40\%$ and decreases at lower temperatures by $\lesssim 30\%$, with the DEM peak shifted from

Figure 4. On-disk wave propagation. (a) Context AIA 193 Å image, overlaid with spherical sector cuts in white to obtain (b)–(i) space–time plots. The other sector cuts used are labeled in black, but not shown. The horizontal dotted lines in (e)–(i) mark the N-CH and D-CH boundaries.
log $T = 5.9$ to 6.1. Further away at $s_3 = 2.3R_\odot$ in the quiet-Sun coronal cavity where the plasma is warm, the heating is gentle and gradual, with the DEM at log $T \geq 6.2$ increased by \(\leq 20\%\) and the peak temperature shifted from log $T = 6.1$ to 6.2.

4. Conclusion

We have presented SDO/AIA observations of an extraordinary global EUV wave associated with the X8.2+ flare-CME on 2017 September 10. Major findings include the following.

1. This truly global EUV wave and a cascade of its secondary waves were observed, for the first time, to traverse the entire visible solar disk and off-limb corona.
2. In addition to commonly observed reflections, there are strong transmissions into both polar CHs at elevated speeds, which are then refracted out of the CHs toward the equator and eventually collide head-on.
3. The wave causes large-amplitude thermal perturbations and structural oscillations, some lasting for hours,
signifying its profound impact on the global coronal plasma.

These remarkable characteristics have opened a new window for utilizing EUV waves of such magnitudes to probe the solar corona on global scales. This allows for global coronal seismology, an area yet to be fully exploited, to perform a variety of diagnostics to infer the physical conditions of the entire corona. For example, wave reflections and transmissions at polar CHs offer clues to the fast-mode speed and thus magnetic-field strength in the polar regions, an important but poorly observed quantity. Using the measured EUV wave speeds and DEM-inferred density, we obtained preliminary $B = 9–12$ G in the polar CHs and 3–6 G on the quiet-Sun at the Cut A1 height (0.12 $R_\odot$). Such analyses, together with numerical modeling providing direct comparison with observations, will be presented in future publications (M. Jin et al., in preparation).

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