Total reflection of a flare-driven quasi-periodic extreme ultraviolet wave train at a coronal hole boundary

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Received/ accepted

ABSTRACT

Context. A flare-driven quasi-periodic extreme ultraviolet wave train totally reflected at a coronal hole boundary was well imaged on both temporal and spatial scales by AIA/SDO.

Aims. We aim to investigate the driving mechanisms of the quasi-periodic wave train and demonstrate the total reflection effect at the coronal hole boundary.

Methods. The speeds of the incident and reflected wave trains are studied. The periodic correlation of the wave trains with the related flare is probed. We compare the measured incidence angle and the estimated critical angle.

Results. We find that the periods of the incident and reflected wave trains are both about 100 seconds. The excitation of the quasi-periodic wave train was possibly due to the intermittent energy release in the associated flare since its period is similar to that of the quasi-periodic pulsations in the associated flare. Our observational results show that the reflection of the wave train at the boundary of the coronal hole was a total reflection because the measured incidence and critical angles satisfy the theory of total reflection: the incidence angle is smaller than the critical angle.

Key words. shock waves – activity – corona – coronal mass ejections (CMEs) – coronal hole

1. Introduction

As a fundamental physical phenomenon, waves of any kind can infer the physical parameters of the medium supporting them and hence provide a condition for diagnosing coronal physical parameters, such as the magnetic field strength, through seismology diagnostics techniques. The coronal seismology proposed by \textit{Uchida} (1970) and \textit{Roberts et al.} (1984) is one of the most critical techniques for estimating the magnetic–field strength of the solar corona, especially in the absence of direct approaches. This technique, based on the magnetohydrodynamic (MHD) waves and oscillations in the corona, has been widely used in many articles (e.g., Liu et al. 2011, 2012b; Shen et al. 2019; Zhou et al. 2021).

Coronal waves, a ubiquitous phenomenon in the solar atmosphere, were first discovered by the Extreme ultraviolet Imaging Telescope (EIT; \textit{Delaboudinière et al.} 1995) on board the Solar and Heliospheric Observatory (SOHO; \textit{Domingo et al.} 1995) and are always accompanied with energetic eruptions such as flares and coronal mass ejections (CMEs; e.g., \textit{Vršnak & Lulić} 2000a,b). In on-disk observations, these disturbances always appear as a circular or semicircular wavefront globally propagating through the solar corona (\textit{Moses et al.} 1997; \textit{Thompson et al.} 1998). They often have a lifetime ranging from 2 to 70 minutes and are characterized by radial propagating motion with speeds of 200–1500 km s\textsuperscript{-1} (\textit{Nitta et al.} 2013). These extreme ultraviolet (EUV) waves are strongly considered to be driven by the CME. Nonetheless, without a related CME, some observations have indicated that there are some EUV waves closely associated with flares (\textit{Kumar et al.} 2016; \textit{Kumar & Innes} 2015). Early observations indicated that most of the EUV waves are single-pulse, diffuse wavefronts extending across a significant fraction of the solar corona. However, more detailed information on these waves has been gathered by the high spatio-temporal resolution Atmospheric Imaging Assembly (AIA; \textit{Lemen et al.} 2012) telescope on board the Solar Dynamics Observatory (SDO; \textit{Pesnell et al.} 2012). These new features, such as the bimodal composition with both wave and non-wave components (\textit{Zhakov & Auchère} 2004; \textit{Patsourakos & Vourlidas} 2012; \textit{Zong & Dai} 2017), allow their physical interpretations to be made from a converged view (i.e., a fast-mode magnetosonic wave component travels ahead of a non-wave component). These bimodal compositions have been predicted in the two-dimensional MHD model (e.g., \textit{Chen et al.} 2002). Three-dimensional global MHD simulations further confirm a bimodal composition of an outer, faster-mode magnetosonic wave component and an inner, CME compression front (e.g., \textit{Cohen et al.} 2009; \textit{Downs et al.} 2012). More convincing evidence comes from the off-limb events, which indicate that a faster EUV wavefront separates from a CME flank and propagates freely on the solar surface once the CME has propagated away sufficiently far from the Sun (\textit{Ma et al.} 2011; \textit{Chen & Wu} 2011; \textit{Shen & Liu} 2012b; \textit{Shen et al.} 2013, 2014; \textit{Zhou et al.} 2021), resulting in a bifurcation structure in time-distance stack plots.

Recently, a new type of EUV wave train with multiple wavefronts propagating across the solar surface has been reported, albeit only in sporadic cases (\textit{Liu et al.} 2012a; \textit{Kumar et al.} 2017; \textit{Shen et al.} 2019; \textit{Zhou et al.} 2021). According to the statistic from \textit{Shen et al.} (2021), these EUV wave trains travel away from the flare kernel with speeds ranging from 370–1100 km s\textsuperscript{-1}.
and with a period in the range of 36–240 seconds. Considering that the amplitude and velocity of these waves are not within the range of quasi-periodic fast propagating (QFP) wave trains channeled in open or closed loops but are similar to the classical EUV wave, Shen et al. (2021) classify these wave trains as broad wave trains and QFP wave trains as narrow wave trains. Furthermore, they can excite the oscillation of the cavity and filament, which are also widely observed in the classical EUV waves. Regarding the driving mechanism of the quasi-periodic EUV wave train, there are several possible interpretations: for example, they could be driven by downward and lateral CME compression (Liu et al. 2012a) or by the unwinding motion of the helical filament structures (Shen et al. 2019). This divergence may be caused by the limitation of the observational case, and as such it is hard to study the driving mechanisms in a detailed and comprehensive way. For detailed discussions about these two types of wave trains, we refer readers to the recent review by Shen et al. (2021).

True wave characteristics, such as refractions, reflections, and transmissions, have manifested in observations and simulations when a wave interacts with a region that exhibits a sudden density drop, such as coronal holes (CHs; Veronig et al. 2006; Schmidt & Ofman 2010; Shen & Liu 2012a; Olmedo et al. 2012; Kumar et al. 2016, 2017; Liu et al. 2018) and active regions (ARs; Ofman & Thompson 2002; Shen et al. 2013; Miao et al. 2019). Reflection evidence of an EUV wave at the boundary has even been observed in radio dynamic spectra (Mancuso et al. 2021). However, total reflection, a basic phenomenon in wave theory, had not yet been identified or detected in an EUV wave. Recently, Piantschitsch & Terradas (2021) used an extended theoretical approach, based on a linear theory that treats EUV waves as fast-mode MHD waves, to investigate the geometrical properties of secondary waves caused by the interaction between the oblique incoming waves and CHs. Their results show that the second waves’ geometrical properties depend on the incidence angle of the incoming waves to the CH boundaries and the plasma density contrasts, \( \rho_c \), between the areas inside and outside the CH. This allows us to determine whether the secondary waves are partially or totally reflected at the CH boundaries. In this paper we report, for the first time, direct observational evidence of the total reflection that occurred on 22 December 2015, in which an EUV wave train emanated from a flare kernel and was totally reflected by a remote southern polar CH. The present study focuses on the driving mechanism of the EUV wave train, its propagation, and its interaction with the CH. The used observational data are described in Sect. 2, results are presented in Sect. 3, and discussions and conclusions are given in Sect. 4.

2. Observations and data reduction

The event was recorded by the AIA (Lemen et al. 2012) onboard the SDO. During our observing time interval, AIA/SDO provided continuous full-disk observations of the solar chromosphere and corona in seven EUV channels, spanning a temperature range from approximately \( 2 \times 10^5 \) to over \( 2 \times 10^7 \) Kelvin. We mainly used the 171 Å (Fe x; characteristic temperature: \( 6.0 \times 10^5 \) K), 193 Å (Fe xii, xxiv; characteristic temperature: \( 1.6 \times 10^5, 2 \times 10^7 \) K), and 211 Å (Fe xiv; characteristic temperature: \( 2 \times 10^6 \) K) images, since the evolutionary processes are observed in these three cooler passbands but are completely absent in the other AIA channels. The time cadence and pixel size of the AIA images are 12 seconds and 0.6\′, respectively. All of the AIA images used here were calibrated with the standard procedure available in the SolarSoftWare package provided by the instrument team. The Geostationary Operational Environmental Satellite (GOES) soft X-ray 0.5–4.0 Å and 1.0–8.0 Å fluxes were used to analyze the periodicity pulsation of the flare. In addition, Large Angle and Spectrometric CORonagraph (LASCO; Brueckner et al. 1995) images were used to portray the associated CME.

To enhance the moving feature of the wave front, we utilized the running-difference images (i.e., each image was subtracted from the previous one) to study the waves’ evolution. To visualize the obtained signatures of the wave train, we used the wavelet analysis method (Torrence & Compo 1998) to investigate the periodicity of the wave train and flare. We performed differential emission measure (DEM) analysis using the inversion code developed by Hannah & Kontar (2012) to estimate the plasma density inside and outside the CH. The DEM inversion was done at 03:22 UT, ten minutes before the incident wave trains arrived at the CH boundary. Additionally, we used the Collection of Analysis Tools for Coronal Holes (CATCH) algorithm developed by Heinemann et al. (2019), which applies the intensity gradient along the CH boundary to modulate the extraction threshold, to extract the CH boundary.

3. Results

The event occurred close to the eastern solar limb of NOAA AR 12473 on 22 December 2015. It is associated with an M 1.6 solar flare, whose start, peak, and end times were at about 03:15 UT, 03:34 UT, and 03:48 UT, respectively (see Fig. 1(e)). In addition, a jet-like CME with an average speed of \( 260 \) km s\(^{-1} \) was observed by the LASCO/C2 during the eruption (see Fig. 1(d)). An overview of the eruption source region is presented in Figs. 1(a) and 1(b). In this region there was a large southern polar CH, whose boundaries, determined using the CATCH software, are also indicated in Fig. 2 and Figs. 5 (a) and (b1). The CH regions always manifest as dark structures in the EUV and X-ray emission in comparison to the peripheral solar corona because of the reduction in density and temperature caused by plasma depletion in these regions (e.g., Heinemann et al. 2019). During the rising phase of the flare, an EUV wave train, significantly different from the classic EIT wave that manifests as a single large-scale quasi-circular propagating front, emanated from the flare kernel and interacted with the distant CH. Further distinctions between the EUV and EIT waves are discussed in the reviews by Zhukov (2011) and Liu & Ofman (2014). Recent investigations have indicated that the temperature distribution of the CH has a dominant component centered around 0.9 MK and a secondary, smaller component at 1.5–2.0 MK (Saqui et al. 2020). Some closed and open loops were present in the AR, as shown in Fig. 1(c).

3.1. Kinematics of the quasi-periodic EUV wave train

We mainly analyzed the time sequence of 193 Å running-difference images taken during the flare to show the overall evolutionary and interactional process, since the evolutionary processes are similar in the 171 Å and 211 Å images (see the animation available in the electronic supplementary material). The violent eruption launched multiple striking arc-shaped wavefronts running along the solar surface. Figure 2 displays the selected running-difference images in those 193 Å images, showing the multiple successive wavefronts during the impulsive phase. The

\[ \text{http://cdaw.gsfc.nasa.gov/CME_list} \]
A first wavefront appeared at around 03:22 UT, about 7 minutes after the onset of the flare. Following the first wavefront, at least three successive wavefronts were detected; these wavefronts are also clearly seen in the 171 Å and 211 Å running-difference images, suggesting that the responsible plasma was in the range of these three channels’ peak response temperature of 0.6–2.0 MK. If we carefully observe the animation and Fig. 2, we can see that the intensity of the wavefronts progressively decreases as the propagation distance increases. After arriving at the CH boundary, they showed a significant reflection feature. The deflection is with respect to the initial propagation direction (and it would be around 90°; see the animation available in the electronic supplementary material and Figs. 2(d)–(f)).

To reveal the speeds of the wave train, we selected sectors S1 and S2, as shown in Fig. 1(b), in the AIA 211 Å channels. Sectors S1 (width 20°) and S2 (width 8°) were placed respectively over the incident and reflected wave train tracks, and they were selected in almost the exact directions of the corresponding wave trains. The time-distance stack plots are displayed in Fig. 3, in which one can see that the incident and reflected wave trains propagated at speeds of 730 km s\(^{-1}\) and 560 km s\(^{-1}\), respectively. Obviously, the wave train speeds are close to that of classical EUV waves but are significantly lower than that of the QFP wave train (around 2000 km s\(^{-1}\), as reported by Liu et al. 2011). This may reflect the difference of the fast magnetosonic speed in the quiet-Sun (as shown in the present paper) and in funnel-like magnetic structures stemming from ARs (as reported by Liu et al. 2011). Therefore, the wave train under investigation in this paper should be classified as a broad wave train, according to the classification of Shen et al. (2021). We estimated the error by making the fit ten times, placing two points along the front and deriving the average velocity (Olmedo et al. 2012). It is worth noting that only the first, strongest wavefront can be tracked from the erupting origin to the CH boundary, and there was no significant wave signal indicating that the wavefront intrudes into the CH, in contrast to what was reported by Veronig et al. (2006). The first wavefront encountered the CH boundary at about 3:32 UT (see the black arrow in Fig. 3(a)). Almost at the same time, the first reflected wavefront appeared (see the black arrow in Fig. 3(e)), followed by a series of wavefronts at the time-distance stack plot. The trailing wavefronts are so weak that they are not discernable from the time-distance stack plots in Fig. 3 after a propagation of about 200 Mm, but they can be discerned in the animation. From the time-distance stack plots, there is no significant signal of a reflected wave train in the AIA 211 Å channel, indicating that the energy of the wave train dissipates during its impingement and long-distance propagation.

To study the origin of the EUV wave train, we applied the Morlet wavelet analysis (Torrence & Compo 1998) to analyze the periodicities of the associated impulsive M 1.6 flare and the wave train. Since the Reuven Ramaty High-Energy Solar Spectroscopic Imager (RHESSI) had a data gap during the flare, a temporal derivative of GOES soft X-ray 0.5–4.0 Å and 1.0–8.0 Å fluxes were used as a proxy of the corresponding hard X-rays to analyze the periodicity of the flare according to the Neupert effect (Neupert 1968; Veronig et al. 2005; Ning & Cao 2010). Figure 4(a1) displays the GOES 0.5–4.0 Å soft X-ray flux. Its temporal-derivative curve (black) is shown in Fig. 4(a2). After subtracting a smoothed 100-second curve (red) from the temporal-derivative curve, we get the detrended signal, and the result is overlaid in Fig. 4(a3) (see the yellow curve). Using the same method, we obtained the detrended, temporal-derivative curve of GOES 1.0–8.0 Å, and the result is overlaid in Fig. 4(a4). Using such a detrended temporal-derivative curve as input, we could see that the period of the flare is about 100 seconds (see Figs. 4(a3)–(a4)).

For the periodicities of the wave train, we analyzed the intensity profile extracted along the white horizontal lines marked in Fig. 2. Evolutions of the incident wave trains (top) and reflected wave trains (bottom) in 193 Å running-difference images. In each panel the red and blue lines depict the wavefronts of the incident and reflected EUV wave trains, respectively, while the green lines mark the location of the CH boundary.
We moved and projected S1 and S2 on the disk center, taking the projection effect on this limb event, as shown in Fig. 5(a), into consideration. Considering the facts that the incidence angle equals the reflected angle (i.e., $\theta_i = \theta_r$) and the angle between the incident and reflected wave trains (two red axes of sectors S1 and S2) is about $115^\circ$, we determine that the incidence angle, $\theta_i$, is about $33^\circ$, as shown in the inset in the upper-left corner of Fig. 5(a). According to Piantschitsch & Terradas (2021), the critical angle, $\theta_c$, depends only on the density contrast (i.e., $\theta_c = \cos^{-1}(\sqrt{\rho_c})$, in which $\rho_c = \rho_i/\rho_o$ is the density contrast between the interior and exterior of the CH. To estimate the density contrast, we followed the method provided by Saqri et al. (2020) to perform DEM analysis for the CH; one example is shown in Fig. 5(b1). All of the AIA images used for the DEM analysis were binned by $8 \times 8$ pixels to enhance the signal-to-noise ratio and then further deconvolved with the instrument point spread function (PSF) provided by the aia_calc_psf.pro routine to reduce the effect of instrument stray light. The plasma density can be derived from the formula $\hat{\rho} = \sqrt{EM/h}$, where EM, the emission measure, is the integration result of the DEM over the temperature range and $h$ is the column height of the emitting plasma along the line of sight (taken here as 42 Mm and 90 Mm for the CH and the quiet-Sun region, respectively; cf. Saqri et al. 2020; Long et al. 2019). We selected ten successive segments along the CH boundary near the wave-CH interaction location and estimated the densities in the patches outside and inside the CH boundary of each individual segment. Figure 5 (b2) shows that the plasma densities inside and outside the CH boundary are in the range of $1.5 - 2.0 \times 10^3 \text{ cm}^{-3}$ and $2.5 - 3.0 \times 10^3 \text{ cm}^{-3}$, respectively, which are slightly lower than that reported by Saqri et al. (2020), who studied low-latitude CHs. This slight divergence is likely the result of the projection effect. The density contrast for ten segments inside and outside the CH are plotted in Fig. 5(b3). From the density contrast distribution, we find that the average density contrast, $\rho_c$, is about 0.62. Based on the critical angle $\theta_c = \cos^{-1}(\sqrt{\rho_c})$ (Piantschitsch & Terradas 2021), we determine the critical angle, $\theta_c$, to be about $38^\circ$, which is larger than the incidence angle, $\theta_i (33^\circ)$. This suggests that the incident wave train was totally reflected at the CH boundary, resulting in the secondary wave train. According to the theoretical analysis by Piantschitsch & Terradas (2021), the phase inversion angle is defined as $\theta_p = \cos^{-1}\left[\frac{\rho_i + \rho_o}{2\rho_o}\right]$. Here, we took the density contrast $\rho_c$ = 0.62 and thus determined the phase inversion angle to be $\theta_p = 31^\circ$, which is in the range of $0 < \theta_i < \theta_p$. This result further confirms that the incident wave train was totally reflected at the CH boundary.

4. Discussion and conclusions

Using high spatio-temporal resolution imaging observations from AIA/SDO, we have presented a rare observation of a series of wavefront interactions with the southern polar CH that occurred on 22 December 2015 in NOAA AR 12473. This event is associated with an M1.6 flare and a jet-like CME. The wave train launched from the flare kernel, propagated along the solar surface, eventually reflected at the CH boundary. The speeds of the incident and reflected wave trains are 730 km s$^{-1}$ and 560 km s$^{-1}$, respectively. Their period is about 100 seconds, which is similar to that of the pulsation flare. Thus, we propose that the wave train was initiated by the intermittent energy-release process in the flare, at least in this event. The observed evolutionary process together with the fact that the incidence angle is less than...
3.8 The cross-hatched regions in panels (a3)-(c2) indicate the cone of influence region due to the edge $e_1$ and $e_2$ of the horizontal dashed white lines labeled “L1” and “L2” in Fig. 3, and their corresponding wavelet power spectra are displayed in each panel. The cross-hatched regions in panels (a3)-(c2) indicate the cone of influence region due to the edge effect of the data, while the dotted and horizontal dashed red lines mark the 95% confidence level and the period, respectively.

Fig. 4. Periodicity analysis for the wave train and the associated flare pulsation. Panels (a1) and (a2) show the GOES 0.5−4.0 Å soft X-ray flux and its temporal derivative (black curve in (a2)), respectively. The detrended intensity profile (yellow curve in panel (a3)) is obtained from the temporal derivative in panel (a2) by subtracting its smoothed intensity profile (red curve in (a2)). The smooth and detrended derivative signal of the GOES 1.0−8.0 Å soft X-ray flux is overlaid in panel (a4). The yellow curves in panels (b1)–(c2) are smooth and detrended intensity profiles of the horizontal dashed white lines labeled “L1” and “L2” in Fig. 3, and their corresponding wavelet power spectra are displayed in each panel. The cross-hatched regions in panels (a3)-(c2) indicate the cone of influence region due to the edge effect of the data, while the dotted and horizontal dashed red lines mark the 95% confidence level and the period, respectively.

the critical angle (i.e., $\theta_i < \theta_c$) suggests that the flare-initiated, quasi-periodic wave train was totally reflected at the CH boundary.

It is worth noting that most related studies have revealed that EUV waves are tightly associated with CMEs and that their relationship with flares is very weak (e.g., Veronig et al. 2008, 2010; Liu et al. 2014, 2018; Downs et al. 2021). At the same time, a considerable amount of observational evidence shows that these waves always exhibit a single diffuse wavefront. Another feature is the appearance of multiple wavefronts in a single eruption; however, such a phenomenon has only rarely been observed. According to the statistics in Shen et al. (2021), only three EUV wave trains have been reported. These wave trains have multiple wavefronts, such as the one propagating along the solar surface in the current event, and are significantly different from the narrow QFP magnetosonic wave trains (Liu et al. 2011). The main dominant difference between the broad and narrow trains is their propagating medium: the former runs along the solar surface, whereas the latter is constrained in closed or open loops. The narrow QFP wave trains are mainly detected in the AIA 171 Å wavelengths, and sometimes in the 193 Å wavelengths. In contrast, the quasi-periodic EUV wave trains, such as classical EUV waves, are visible in AIA 171 Å, 193 Å, and 211 Å wavelengths, suggesting different temperature ranges. More detailed information about these two types of wave trains can be found in a recent review (Shen et al. 2021, and references therein). These differences indicate that the observed wave train in the current event is a rare quasi-periodic wave train. In the scenario of a piston-driven shock, the wavefront should decouple from the driver, resulting in a single wavefront propagating freely on the solar surface. A single erupting jet-like CME as a driver cannot excite multiple successive wavefronts, meaning it is unlikely that the observed EUV wave train was launched by a jet-like CME. Due to the similar period of the flare pulsations and the wave train, we are inclined to believe that it was initiated by the quasi-periodic pressure pulses launched by the intermittent energy-releasing process in the flare. As we have already mentioned, EUV waves, characterized by a single wavefront, are usually initiated by a CME and generally have a weak connection with flares. The present study has shown strong evidence that EUV waves can also be excited impulsively by the quasi-periodicity of a flare. Recently, Zhou et al. (2021) reported a similar example: multiple consecutive wavefronts propagating continuously inside a CME bubble that had already attained developmental completion. This event is also hard to explain using CME expansion. The appearance of the first wavefront in the event analyzed here has a delay of several minutes relative to the onset time of the flare. A possible explanation is that the wave needs time to build up a large amplitude or shock to be observed.

Observational studies of the interaction of EUV waves with CHs are scarce, but the appearance of the secondary waves is found to be a pretty frequent phenomenon when the waves interact with CHs or ARs (Wang 2000; Gopalswamy et al. 2009; Liu et al. 2019). These observational findings were verified via numerical simulation (Piantschitsch et al. 2017, 2018a,b; Afanasyev & Zhukov 2018). In accordance with these observational and simulation-wave-like features, we can confidently confirm the interpretation that it is a fast-mode MHD wave. However, as we have already mentioned, a totally reflected wave train is a basic behavior of waves and has hardly ever been observed in the solar corona. Studying the wave-CH interaction and its secondary waves can provide a great deal of information about the CHs themselves, particularly their boundaries. Because of that, (i) the observed CH areas are well correlated with the solar wind speed measured in situ at 1 AU, which is of crucial importance for space weather forecasting models, and (ii)
The corresponding critical angle, $\theta$, the range 0.1-0.6 (Saqri et al. 2020; Heinemann et al. 2019) and been shown that the density contrast at the CH boundary is in the range 0.1-0.6 (Piantschitsch & Terradas 2021). Recently, based on a few statistical studies, it has been shown that the density contrast surrounding the CH boundary, of which ten are inside the CH and ten are outside. (b2) Density inside and outside the CH shown by, respectively, the green and red lines. (b3) Plasma density contrast between the inside and outside CH regions.

The wave-CH interactions allow us to study the influence of the CH on wave parameters, such as the velocity and the amplitude. There were relatively rough and of low quality. Therefore, studying more clearly captured examples of wave-CH interactions can help us deepen our understanding of the influence of CHs on coronal waves and gather more information about CHs.

Acknowledgements. We want to thank the anonymous referee for his/her many valuable suggestions and comments for improving the quality of this article. We also thank Prof. Dr. Astrid M. Veronig and Dr. Stephan G. Heinemann for data processing and useful suggestions. Moreover, the authors want to acknowledge SDO/AIA, GOES, and SOHO/LASCO science teams for providing the data. This work is supported by the Natural Science Foundation of China (12173083,11922307,11773068,11633008), the Yunnan Science Foundation for Distinguished Young Scholars (2021YAJ04005000), and the West Light Foundation of Chinese Academy of Sciences.

Fig. 5. Geometrical properties of the wave trains and the density contrast surrounding the CH boundary. (a) AIA 211Å full-disk images. The green outline represents the CH boundary extracted with the CATCH, and the sectors located on the central disk show the S1 and S2 translocation and projection results. (b1) Plasma total emission measure in the 1.2-1.4 MK temperature range. Twenty patches were selected to estimate the density contrast surrounding the CH boundary, of which ten are inside the CH and ten are outside. (b2) Density inside and outside the CH shown by, respectively, the green and red lines. (b3) Plasma density contrast between the inside and outside CH regions.

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