Birthplaces of Extreme Ultraviolet Waves Driven by Impingement of Solar Jets upon Coronal Loops

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Abstract

Solar extreme ultraviolet (EUV) waves are large-scale propagating disturbances in the corona. It is generally believed that a vital key to the formation of EUV waves is the rapid expansion of the loops that overlie erupting cores in solar eruptions, such as coronal mass ejections (CMEs) and solar jets. However, the details of the interaction between the erupting cores and overlying loops are not clear because the overlying loops always instantly open after energetic eruptions. Here, we present three typical jet-driven EUV waves without CMEs to study the interaction between the jets and the overlying loops that remained closed during the events. All three jets emanated from magnetic flux cancellation sites in the source regions. Interestingly, after the interactions between the jets and overlying loops, three EUV waves respectively formed ahead of the top, the near end (close to the jet source), and the far (another) end of the overlying loops. According to the magnetic field distribution of the loops extrapolated through the potential field source surface method, it is confirmed that the birthplaces of three jet-driven EUV waves were around the parts of the overlying loops with the weakest magnetic field strengths. We suggest that the jet-driven EUV waves preferentially occur at the weakest part of the overlying loops, and the location can be subject to the magnetic field intensity around the ends of the loops.

Unified Astronomy Thesaurus concepts: Solar activity (1475); Solar corona (148); Solar magnetic fields (1503); Solar coronal waves (1995)

Supporting material: animations

1. Introduction

Extreme ultraviolet (EUV) waves are spectacular propagating disturbances in the solar corona (Thompson et al. 1998). They can provide potential diagnostics on coronal magnetic field strengths and coronal plasma parameters for global coronal seismology (Kwon et al. 2013; Long et al. 2013, 2017). It is generally believed that EUV waves are best interpreted as the bimodal composition of an outer fast-mode MHD wave and an inner nonwave component of coronal mass ejections (CMEs) (Chen & Wu 2011; Zheng et al. 2013, 2014; Liu & Ofman 2014; Mei et al. 2020; Zhou et al. 2020, 2021; Chandra et al. 2021). More details about EUV waves can be found in recent reviews (Liu & Ofman 2014; Warmuth 2015; Chen 2016; Long et al. 2017).

EUV waves are associated with various successful solar eruptions, such as CMEs, solar flares, and filament eruptions, and their launch strongly depends on the rapid lateral expansion of the CME flank (Nitta et al. 2013; Liu & Ofman 2014). In addition, it has been reported that EUV waves can be generated by a failed eruption or filament activation without any eruption (Zheng et al. 2012, 2018, 2020). Hence, the formation of EUV waves is subject to the rapid expansion of the loops covering the erupting cores, whether or not associated CMEs happen. However, the interactions between the erupting cores and overlying loops are not clear, because the overlying loops are usually instantly opened by the intense eruptions.

Compared with different initial wave-front morphologies, EUV waves are categorized into two groups: flux-ropedriven waves and jet-driven waves, and it is proposed that the formation and morphology of EUV waves depend on the configuration of the overlying loops relative to the erupting cores (Zheng et al. 2019). For flux-ropedriven waves, the erupting flux ropes thrust the overlying loops outward in all directions, and therefore, the waves are generated with circular wave fronts ahead of all portions of the overlying loops. For jet-driven waves, the jets emanate from one end of the overlying loops, and the one-way movements result in arc-shaped wave fronts propagating with a limited angular extent. Note that the jet-driven waves were driven by the sudden expansion of coronal loops due to the impingement of the jet upon the loops, as has been pointed out by Shen et al. (2018b, 2018a), rather than driven by jets directly in a magnetic tube, like the work in Shen et al. (2018c).

In this article, we choose three typical jet-driven waves without any CME to study the interactions between the jets and overlying loops. Three waves all formed ahead of some special parts of the overlying loops (top part, far-end part, and near-end part, respectively) that remained closed during the eruptions. The birthplaces of the waves reveal the interaction sites between the erupting cores and overlying loops, which can shed light on the generation mechanism of EUV waves.

2. Observation

We mainly employed the observations from two different perspectives of the Atmospheric Imaging Assembly (AIA; Lemen et al. 2012) on board the Solar Dynamics Observatory (SDO; Pesnell et al. 2012) and from the Extreme Ultraviolet Imager (EUVI; Howard et al. 2008) on board spacecraft A of
the Solar-Terrestrial Relations Observatory (STEREO). The AIA has seven EUV wave bands with a cadence of 12 s and a pixel resolution of 0°6. The EUVI images have a pixel resolution of 1°58, and their cadences are 5 or 10 minutes for 171, 195, and 304 A. The magnetic field evolution was checked by Helioseismic and Magnetic Imager (HMI; Scherrer et al. 2012) magnetograms, with a cadence of 45 s and pixel scale of 0°6. The jets and waves were better displayed in the AIA composite images. The time-slice approach was employed to analyze the dynamics of the waves and their associated jets. In addition, the coronal magnetic field lines were extrapolated with the Potential Field Source Surface (PFSS; Schrijver & De Rosa 2003) package of SolarSoftWare.

3. Results

The three events happened in the active region (AR) 12645 (∼S10W11) on 2017 April 1 (E1), AR 12671 (∼N10E47) on 2017 August 16 (E2), and AR 12498 (∼N19E50) on 2016 February 10 (E3) (the left column in Figure 1). Three source regions all involved a main negative polarity of the AR and a nearby parasitic positive polarity (red boxes in the middle column in Figure 1). In the source regions, continuous magnetic interactions existed for the main polarities and the parasitic polarities (see the animation associated with Figure 1). The magnetic flux changes of the positive (blue) and negative (red) polarities in the source regions (the right column in Figure 1) clearly show the continuous magnetic flux cancellations and emergences. Remarkably, the main AR polarities all experienced magnetic flux cancellation (red downward arrows) around the onset jets (dotted vertical lines). It indicates the intimate relationship between continuous magnetic flux cancellations and jets. For more details about the triggering and formation mechanisms of the coronal jet, refer to Shen (2021).

Before the jet onset, some brightenings (cyan arrows) appeared above the sites of magnetic cancellations between the main AR polarities (red contours) and parasitic polarities (blue contours) in the source regions (the first column of Figure 2). A few minutes later, the jets were ejected (the animation associated with Figure 2 and yellow arrows in the middle column). Note that the jets emanated from one end to the other end of the high overlying loops (blue arrows in panels (c) and (f)). Incidentally, the overlying loops in E3 were faint, but twin dimmings (black arrows in Figure 2(ii)) appeared after the jet movements, and their intensities decreased nearly simultaneously. It likely indicates that large-scale overlying loops (white dotted line in panel (i)) connecting twin dimmings in E3 existed. Moreover, the jet in E2 seems like the eruption of a mini filament toward the loops in the form of a blowout jet, like the study of Shen et al. (2017). It differs from the jets in E1 and E3 that were along the loops, but we just focus on the jet in E2 that emanated from one end of the loops to the other. Hereafter, the end of the jet sources and the other end of overlying loops are separately referred to as the “near end” and “far end.” The near ends and far ends of the overlying loops for three events are rooted in the source negative polarities and the remote positive polarities (red and blue contours in the right column).

Following the movements of jets, the overlying loops expanded outwards, which was followed by loop-like dimmings (white arrows in Figure 3). Sequentially, three EUV waves formed ahead of the expanding loops (the animation associated with Figure 3 and the pink dashed lines in the left and middle columns). Intriguingly, the overlying loops remained closed after the loop expansions, and three waves seemed to be born around different parts of the overlying loops. For E1, the wave was primarily generated ahead of the top of the overlying loops (pink dashed lines in panels (a)–(b)). For E2 and E3, the waves mainly formed around the far end and the near end of the overlying loops (dashed lines in panels (d) and (g)), respectively, which was also clearly shown by the waves and loop-like dimmings in the edge view of EUVI-A (pink and white arrows in panels (e) and (h)). Moreover, the location relationships between the waves and the overlying loops were confirmed by the wave-front curves (pink dashed lines) and PFSS-extrapolated magnetic field lines superposed on the magnetograms (right column). It is much clearer that the three waves had different birthplaces along the overlying loops relative to the jet sources.

The wave propagations in some selected slices extending from source regions (yellow dashed lines in Figure 3) are shown in time–distance plots (Figure 4). Two paths were selected in each event: one path is along the wave direction (the wave is clear in this direction), and the other path is along the other direction to ensure the wave is only generated in the above direction. Specifically, S1a and S1b passed the top and the far end of the overlying loops in E1; S2a and S2b crossed the far end and the top of the overlying loops in E2; and S3a and S3b got through the near end and the top of the overlying loops in E3. In the time–distance plots along S1a–S2a–S3a (the left column), the wave signals, which separately lasted ∼13, 10, and 10 minutes, were obvious, and their speeds were separately ∼254, 346, and 647 km s⁻¹. Moreover, the waves had a close temporal–spatial relationship with the associated jets that separately showed speeds of ∼360, 190, and 220 km s⁻¹. In the time–distance plots along S1b–S2b–S3b (the right column), only the jet in E2 and the dimmings due to the loop expansions were clear (red and blue arrows), but it is hard to distinguish the wave signals. It possibly indicates that three waves predominantly formed ahead of one section of the related overlying loops, consistent with the location relationships between the waves and overlying loops in Figure 3.

To understand the three waves that formed at different places of the overlying loops, we first focus on the magnetic field intensity surrounding two ends of the overlying loops (Figure 5). For each event, two boxes with the same area enclosed two ends of the extrapolated field lines (yellow boxes in the left column). Because the extrapolated field lines are anchored in a single polarity patch on the one side in the PFSS method, which is also the dominant polarity around the ends of the extrapolated field lines, the dominant flux in the box is taken to perform further calculations. In a period of 2 hr covering each event, the magnetic flux change of the dominant polarities in the boxes was first calculated (red and blue curves in the right column), and then the average magnetic flux of the dominant polarities in the near end (B̅_near) and far end (B̅_far) were obtained, and finally the ratio of (B̅_near) to (B̅_far) was obtained. The ratios for the three events were ∼0.99, 11.1, and 0.65, respectively. The ratio numbers representing the magnetic field intensity in the near end were nearly equal to those in the far end for E1, were much stronger than those in the far end for E2, and were weaker than those in the far end for E3, respectively. Furthermore, the magnetic field strength (|B|) at each point of the extrapolated loops was first calculated through
the extrapolated three-dimensional field \( (B_r, B_\theta, B_z) \) in the PFSS method, and then superimposed on the loops with different colors (refer to the color bars). For each loop, the weakest point and the weakest part were searched, represented by the “X” symbol and pink curve, respectively. It is seen that the range of 0–3 G defining the “weakest part” covered well the birthplace of the wave (pink dashed line) in each event. Accordingly, the weakest part was in the top for E1 and offset to the weak end for E2 and E3, which indicates the good spatial relationship between the birthplace of the waves and the weakest part of the loops.

4. Conclusions and Discussion

In this article, we present three jet-driven waves without any CME. Before the jet onset, there existed continuous magnetic flux cancellations in the source regions (Figure 1). Subsequently, there appeared some brightenings in the upper
atmosphere, and the jets were ejected and moved along the large-scale overlying loops (Figure 2). Because of the interactions between the jets and overlying loops, three jet-driven EUV waves formed with speeds in the range of $\sim 346-647$ km s$^{-1}$ and lifetimes of more than 10 minutes. As discussed by Su et al. (2015) and Shen et al. (2017, 2018c), jet-driven waves have a relatively shorter lifetime than those associated with CMEs. This is reasonable because the CME can provide a continuous driver to the wave, and the three waves fit this pattern. Intriguingly, the overlying loops remained closed, and the birthplaces of these three waves were predominantly around the top, the far end, and the near end of the overlying loops (Figures 3 and 4).

It is very interesting that the birthplaces of the three waves were inconsistent, though three jets emanated from similar near ends. One question that arises is what condition determines the
The birthplaces of jet-driven waves. The first focus is the magnetic field intensity in the two ends of the overlying loops (Figure 5). Incidentally, we assumed that two ends had similar inclination angles in each event, due to the short distance between the two ends. Therefore, the longitudinal magnetic field data used in the ratio measurements of the average magnetic flux can be comparable to that of the three-dimensional magnetic field. By comparing with the magnetic flux of the dominant polarity around two ends of overlying loops, the birthplaces of the waves appeared around the top and weak end of the overlying loops. Therefore, we deduced that the wave may form around the part of the overlying loops with the weakest magnetic field strength. Further, the magnetic field strength along the loops was calculated and superimposed on the loops. It is confirmed that the birthplace of the waves formed around the weakest part of the loops.

For EUV waves associated with violent eruptions, it is difficult to study the interactions between the erupting cores and overlying loops, because the impulsive flux ropes or energetic jets always instantly destroyed the overlying loops.
That is why we selected these typical jet-driven waves to study the interactions between the jets and overlying loops. Naturally, the jets have to move along the overlying loops (E1 and E3) when their energy was not enough to get rid of the confinements. However, the jets were searching for weaknesses in the overlying loops. Finally, when the jets successfully found and interacted with the weakest part of the overlying loops, it resulted in the waves ahead of the interaction sites. As a result, the birthplaces of jet-driven waves were around the weakest part of the overlying loops. On the other hand, it is also suitable for ejecting plasma under the loops (E2). They also likely have a preference for searching and interacting with the

Figure 4. The time–distance plots of the running-ratio-difference images in AIA 193 Å along the selected paths (yellow dashed lines in Figure 3). The green dotted lines indicate the signals of the waves. The blue and red arrows separately indicate the jets and the dimmings. The speeds of the waves and the jets are provided.
weakest part of the overlying loops as the confinement is weakest in this direction.

In summary, the different birthplaces of three jet-driven waves in E1–E3 were subject to the magnetic field distribution of the overlying loops. We suggest that jet-driven waves prefer to be generated ahead of the weakest part of the overlying loops. Further observations are necessary to verify the results and suggestions.

Figure 5. The magnetic field distribution of the loops and the comparisons of the magnetic field intensities around two ends of the overlying loops. In the left column, the magnetic field strength was superimposed on the loops with different colors (refer to the color bars). The green “X” symbols indicate the weakest point of the loops, and the pink curves indicate the weakest part of the loops. The yellow boxes with the same area in each panel enclose two ends of the PFSS-extrapolated field lines superimposed on the HMI magnetograms, and the pink dashed lines represent the waves. In the right column, the red and blue curves indicate the magnetic flux changes of the dominant polarities in the left yellow box. The ratios of the average magnetic flux in the near end to that in the far end are listed.
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References

Chandra, R., Chen, P. F., Devi, P., et al. 2021, ApJ, 919, 9
Chen, P. F. 2016, in Low-Frequency Waves in Space Plasmas, ed. A. Keiling et al. (Washington, DC: American Geophysical Union), 381
Chen, P. F., & Wu, Y. 2011, ApJL, 732, L20
Howard, R. A., Moses, J. D., Vourlidas, A., et al. 2008, SSRv, 136, 67
Kwon, R.-Y., Kramar, M., Wang, T., et al. 2013, ApJ, 776, 55
Lemen, J. R., Title, A. M., Akin, D. J., et al. 2012, SoPh, 275, 17

Liu, W., & Ofman, L. 2014, SoPh, 289, 3233
Long, D. M., Bloomfield, D. S., Chen, P. F., et al. 2017, SoPh, 292, 7
Long, D. M., Williams, D. R., Régnier, S., et al. 2013, SoPh, 288, 567
Mei, Z. X., Keppens, R., Cai, Q. W., et al. 2020, MNRAS, 493, 4816
Nitta, N. V., Schrijver, C. J., Title, A. M., et al. 2013, ApJ, 776, 58
Pesnell, W. D., Thompson, B. J., & Chamberlin, P. C. 2012, SoPh, 275, 3
Scherrer, P. H., Schou, J., Bush, R. I., et al. 2012, SoPh, 275, 207
Schrijver, C. J., & De Rosa, M. L. 2003, SoPh, 212, 165
Shen, Y. 2021, RSPSA, 477, 217
Shen, Y., Liu, Y., Liu, Y. D., et al. 2018c, ApJ, 861, 105
Shen, Y., Liu, Y., Tian, Z., et al. 2017, ApJ, 851, 101
Shen, Y., Tang, Z., Li, H., et al. 2018a, MNRAS, 480, L63
Shen, Y., Tang, Z., Miao, Y., et al. 2018b, ApJL, 860, L8
Su, W., Cheng, X., Ding, M. D., et al. 2015, ApJ, 804, 88
Thompson, B. J., Plunkett, S. P., Gurman, J. B., et al. 1998, GeoRL, 25, 2465
Warmath, A. 2015, LRSP, 12, 3
Zheng, R., Chen, Y., Feng, S., et al. 2018, ApJL, 858, L1
Zheng, R., Chen, Y., Wang, B., et al. 2020, ApJ, 894, 139
Zheng, R., Jiang, Y., Yang, J., et al. 2012, A&A, 541, A49
Zheng, R., Jiang, Y., Yang, J., et al. 2013, ApJ, 764, 70
Zheng, R., Jiang, Y., Yang, J., et al. 2014, MNRAS, 444, 1119
Zheng, R., Xue, Z., Chen, Y., et al. 2019, ApJ, 871, 232
Zhou, G., Gao, G., Wang, J., et al. 2020, ApJ, 905, 150
Zhou, X., Shen, Y., Su, J., et al. 2021, SoPh, 296, 169