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Propagating Waves Around a Coronal Null Point

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A B S T R A C T

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مقاله پژوهشی

انتشار امواج در اطراف نقطه تهی تاجی

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چکیده

We present, observational signatures of fast and slow MHD modes over an off-limb coronal X-point in AIA 171 Å passband on 2014 April 3. The X-point structure is outlined by the coronal loops. The height of the X-point is obtained to be 52 ± 2 Mm above the limb. Slow waves with speeds in the range of 2.5 to 7.2 km/s are observed to propagate in the X-point neighboring loops (close to the fan surface) from the foot points toward the loop apex, symmetrically. It looks like the slow modes over the slit 1 getting acceleration as they are moving toward the loop apex. Since, the coronal β=0 condition breaks as getting closer to the X-point, slow modes should speed up, naturally. Over the slits f, g, h, i, L, m, n, o, signatures of the fast waves and their reflections from the loop apex are visible (or the outflows getting away from the X-point) with speeds in the range of ±3.0 to 18 km/s. On the other side, the fast MHD mode with period of 5 min is observed on the slit locating close to the loop top (slits e). A Filament Eruption (FE) happens around the time step of 350 in the nearby prominence area and triggers the fast kink modes with periods of 3 to 4 minutes at a position close to the spine axis over the slits d, e, and k.

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Introduction

For almost 80 years heating of the solar atmosphere is one of the main puzzles in solar physics. Several models have been proposed to explain the heating. Among them two different classes of heating are distinguishable (based on the electromagnetic response of the corona to the input injected energy from lower layers like photosphere or chromosphere): Direct Current (DC) type, and Alternative Current (AC, or wave heating) type. First type consists of different models like reconnection, current cascade, and turbulence. Second type cover all wave heating models such as Alfvenic resonance, resonant absorption, Phase mixing, MHD turbulence, current layers, and cyclotron resonance. It seems that the heating mechanisms are different in the various regions and features of the solar atmosphere. Therefore, the mentioned models have different importance in different parts of the solar atmosphere [1, 2].

There are three types of Magnetohydrodynamic (MHD) waves: Alfven wave which is an incompressible transverse wave propagating parallel to the magnetic field lines and magnetic tension is the only restoring force for this wave. The other two are slow and Fast MHD waves which are essentially compressible. The slow mode is longitudinal and cannot propagate perpendicular to the magnetic field direction. On the other side, the fast wave is a transverse wave that is able to propagate perpendicular to the magnetic field [1, 3, 4].

Observation of Magnetohydrodynamic (MHD) waves have been reported vastly in the solar corona since 1999 using SoHo (Solar and Heliospheric Observatory) and TRACE (Transition Region and Coronal Explorer) spacecraft. For instance, slow modes are observed in the plum and inter-plume areas of polar and equatorial coronal holes and in the quiet sun areas, as well as over the legs of fan loops inside the active regions [4, 5, 6, 7]. They found to have periods between 2 to 10 minutes with speeds between 70 to 235 km/s. This speed range is close to the local sound speed [4]. Fast MHD wave propagations have been observed by Aschwanden et al. in 1999 and later by Yuan et al 2013 around a flaring region [8, 9].

Alfven waves have incompressible nature and therefore they do not have intensity and density fluctuations which made them difficult to detect. That’s why the observational signature of these waves in the solar atmosphere obtained much later than the other two modes [10, 11, 12, 13, 14].

Solar atmosphere is filled with the complicated magnetic fields structures known as the magnetic carpet. Among the magnetic field lines there are some points at those the magnetic field value is zero. These points are called the null points. There are two types of them based on their geometry (X-points and O-points). These points are important since it is expected that the magnetic energy converted to the other types energy on these points [15, 16, 17]. Figure 1, courtesy of Ashwanden 2005, shows a cartoon of a null point which is created when two dipoles get into neighboring each other. The fan surface and spine axis are demonstrated in this Figure [1].

Historically, the existence of the magnetic null points was predicted theoretically since 1947 [18, 19, 20, 15, 21] and after by the potential field extrapolating of the magnetic field of coronal regions using the photospheric measured magnetic fields obtained by magnetograms [22, 23]. Direct observation of null point has been very rare and reported for the first time by Filippov in 1999 [24]. Null points occur in different layers of the solar atmosphere. Regnier at al 2008 and Longcope and Parnell 2009 using SOT/Hinode data showed that 54%, and 44% of the null points are found to be in the vicinity of photospheric bottom boundary layer, and chromosphere, respectively. Regarding to their studies only 2% of the null points occur in corona [25, 26, 27]. This means, at any time instance, tens to thousands of magnetic null points could exist in the solar corona. On the other side, since the corona (in general) has simpler geometry respect to the photosphere and chromosphere layers, and because the coronal plasmas fill inside the coronal flux tubes, therefore, detecting and visualizing the geometry of magnetic fields and null points are easier in the solar corona [26, 27, 28].

McLaughlin and Hood 2004 and 2005 investigated interaction of MHD waves with null points. They found the fast MHD waves are attracted toward null points and as they approach their wavefronts speed decrease. This phenomenon leads to accumulation of the current density at the null points and finally via Ohmic dissipation the magnetic energy transforms into the plasma heating in the vicinity of null points [29, 30, 31]. McLaughlin et al 2008 simulated a 3D MHD coronal Oscillations and found that the Alfven waves generated along the fan planes, build up along the spine [32]. Sabri et al 2020, 2021, 2022 simulated propagation of MHD waves in vicinity of a 2.5D and 3D magnetic null points and showed that the propagation of Alfven waves end up in current density excitation both in the vicinity of null point and along the spine axis. Their result show fast modes refracts around the null point but they do not accumulate along the spine axis, while, slow modes move toward the null points at fan surface [17, 28, 33, 34].

In this work, we investigate the propagation of MHD waves in vicinity of a coronal X-point.

Observations

A coronal X-point is observed in the vicinity of a solar prominence structure on the west solar limb using AIA (Atmospheric Imaging Assembly [35])/ SDO (Solar Dynamic Observatory) 171 Å bandpass starting from 13:02 UTC on the 3rd April 2014 for about 2 hours with a step cadence of 12 seconds. Using level 2 data all effects of hot pixels, cosmic rays, flat field, dark current, and the solar differential rotation effects are removed. The standard Solar Software (SSW) under Interactive Data Language (IDL) is used for data analysis. Figure 2 shows the field of view of our study. Coronal loops (with temperatures of ~ 1 MK) outlined the X-point structure.

Data Analysis and Results

Using Fig. 2, the height of the X-point is estimated to be 52 ± 2 Mm over the solar limb. As it was suggested by Nakariakov 2020 [36], to check the presence of the slow MHD waves in the vicinity of the X-point structure, four artificial curved slit positions (named as slit 1 to slit 4) are selected on the four loops around the X-point in 171 Å channel (Fig. 2). The time slice, and the running time difference images (with dt=36 time steps) for these artificial curved slits are represented in Figure 3. Each time step (cadence) is 12 seconds. Slit 1 in the upper left panel of Fig. 3 shows two pulses of brightening that propagate symmetrically from the both ends of the loops toward the loop apex. Two parabola with equations $t=-4(x-14)^2+540$ and $t=-5.9(x-13)^2+290$ are fitted to the moving path of the propagating brightening borders. These structures could be interpreted as slow modes. The borders of the propagating brightening are obtained using the Sobel edge detecting algorithm based on calculating the image intensity gradients. Both fitted curves show the brightening speed's increasing as moving toward the loop apex. Since, coronal β=0 condition breaks as getting closer to the X-point, acoustic modes should speed up, naturally [28]. The average speed is calculated to be ±2.5 km/s. The lower left panel, the running difference image for the slit 1, shows three curved and symmetrical bright pulses (cycles) with a period of 18 minutes.

Over the Slit 4 in the running time difference images, one can see three bright structure moving from the both foot points toward the apex of the loop, symmetrically. Their speeds are calculated to be ± 7.2 km/s. This phenomenon continues for about 60 minutes and after that time an opposite behavior starts with the same speeds and bright structures move away from the loop 4 apex toward its foot points. One of the possible explanation of this phenomenon could be reflection of the upward propagating waves from the loop apex. In the leg of an EUV diverging fan-like loop, Berghmans and Clette 1999, and Yuan and Nakariakov 2012 reported the existence of similar repeating structures (with slops of ±150 km/s, and ±49 km/s, respectively) and interpreted those as propagating slow MHD waves [37, 6]. Over the slits 2 and 3 also one can see some repeating pulses (represented by white arrows) but they are not very clear.

Figure 4 shows the other 15 artificial slits of our study which are selected to cross the neighboring loops of the X-point in AIA/SDO 171 Å channel. The vertical and horizontal slits are named as a, b, c, d, e, and f, g, h, i, j, and k, l, m, n, o, respectively. The spacial distance between the parallel slits is 10 pixels. Each solar X and Solar Y pixel in AIA images are 0.6 arcsec wide.

Fig. 5 top, middle, and below panels show the time slice, gradient of the time slice, and the time running difference (with dt=36 time steps) over the horizontal slits a to e. This structure is used in plotting Fig. 6 and 7, as well. Figure 5 seems to represent slow propagating disturbances with periods of about 5 minutes over the slit j locating on the apex of the loop structure. The parallel dark and bright wavefronts are marked by white arrows over the running difference map of slit j. They propagate in the direction of the magnetic field (the loop axis). This finding pattern is similar to what Yuan et al 2013 observed as propagating wave trains with periods of 3 minutes [38]. Over the slit i in Fig. 5 running difference plot, one would see multiple symmetric diagonal pattern with slops of ±3.0 km/s and ±7.2 km/s creating hexagonal shapes. It seems that, these are the fast mode waves propagating upward from the both foot point toward the loop apex (with a non-zero angle with the magnetic field direction along the loop) and then reflecting back. The reflection signatures are visible over the slits f, g, and h, as well. Reflection of the fast mode waves was predicted in the simulations performed by Provornikova et al. 2018 in the vicinity of a magnetic reconnection region [39].

In Fig. 6, over the slit e running difference image, 5-minute fast wave train propagating oscillations are visible (green arrow). A Filament Eruption (FE) happens around the time step of 350 in the nearby prominence area toward the solar North direction. After this time, if we look at running difference images over the slits e and d (at the position showed by white arrows, which is close to the position of the spine axis), some fast kink oscillations with periods of 3 to 4 minutes are visible. Cross section of the bright loop (parallel to spine axis) moves toward the right and left directions periodically. Since the direction of the oscillation is perpendicular to the loop direction (= magnetic field direction), the wave mode identified to be fast kink wave.

It looks that the EF is responsible to trigger this wave mode. As going away from the X-point along the spine axis (going from slits e to a), the fast kink wave gets fainter and less visible. The white arrows in the time slice plots shows a bright structure moving away from the X-point (first, it appears over the slit e, close to the X-point, and by passing time it moves toward the farther slits d, to a, respectively.). This could be another signature of the fast mode reflection from the null point.

Running difference image over the slit k in the Fig. 7 also captures the mentioned fast kink modes (after the FE event) but with periods of 5 min. Slit k is placed perpendicular to the loop structure. On the m, n and l slits some opposite diagonal pattern with velocities of ±3.6 km/s to ±18 km/s is observed over the running difference images which all are manifestations of fast propagating waves with reflection behavior. It seems that the amount of the velocities decreases by getting distance from the location of the X-point (from ±9 km/s to ±3.6 km/s). This behavior is expected and seen over the slit 1, as well (due to increasing plasma-β parameter as getting away from the X-point, acoustic speeds decrease.). A summary of the all measured oscillatory waves are listed in Table 1.

Fillipov 2018 studied the coronal loop dynamics near the null point above AR NOAA 2666 [40]. He obtained velocities in the range of 2.3 to 5.5 km/s. Sun et al. 2016 obtained velocities of 1-10 km/s in a null point associated with an erupting event [41]. The speed obtained in this work is in the range of the mentioned studies. This quiet slow speeds could be an indication of a slow magnetic reconnection process occurring in the place of the X-point [40].

Table 1. List of the observed oscillatory modes and their properties

Slit name	Slit direction (respect to loop axis)	Slit position (respect to X-point)	Period (min)	Speed (km/s)	Wave mode	Extra explanations (RF: Reflection Signatures)
1	parallel	Lower left	18	±2.5	slow	-
2	parallel	Upper left	not clear	not clear	not clear	-
3	parallel	Upper right	not clear	not clear	not clear	-
4	parallel	Lower right	13	±7.2	slow	RF
a	perpendicular	most distant	-	-		--
b	perpendicular	-	-	-	--	-
c	perpendicular	-	-	-	-	
d	perpendicular	-	3 to 4	-	fast kink	visible after FE
e	perpendicular	Closest, the loop apex	5 3 to 4	-	fast fast kink	- visible after FE
f	perpendicular	most distant	-	-	-	RF
g	perpendicular	-	-	-	-	RF
h	perpendicular	-	-	-	-	RF
i	perpendicular	-	-	±3 to ±7.2	-	RF
j	perpendicular	closest, the loop apex	5	-	fast	-
k	perpendicular	closest	5	-	Fast kink	visible after FE
L	perpendicular	-	-	±9	slow	RF
m	perpendicular	-	-	±7.2,+9,-18	slow	RF
n	perpendicular	-	-	±5.4	slow	RF
o	perpendicular	most distant	-	±3.6	slow	RF

Discussion and Conclusion

Propagation of MHD waves are studied close-by a coronal X-point structure using AIA 171 Å bandpass. The obtained results could be summarized as:

1) The results show the presence of slow waves over the slits 1, 4, and j with speeds in the range of 2.5 to 7.2 km/s. The speeds are in the agreement with findings of Sun et al. 2016 and Filippov 2018 [40, 41].

2) The slow wave speed increasing as it propagates upward through the coronal loop. Since, the coronal β=0 condition breaks as getting closer to the X-point, slow modes should speed up, naturally. This was predicted by Sabri et al 2020 as their first conclusion out of the simulations of Alfven wave induced MHD wave propagation around a 2.5D magnetic null-point [28]. Our observational results confirm this phenomenon.

3) The slow mode speeds in this work is less than the findings of Berghmans and Clette 1999 and Yuan and Nakariakov 2012 [37, 6]. However, one should keep in mind that their measurements were done over the open fan-like loop structures, while this work is measuring the slow mode speeds in the closed loops nearby an X-point structure. On the other side, similar velocities are obtained by Sun et al. 2016 and Filippov 2018 in the vicinity of null point. The slow speeds could be an indication of slow magnetic reconnection near the X-point location [40, 41].
4) Fast MHD modes with speeds in the range of ±3.0 to 18.0 km/s are observed over the slits e, I, k, L, m, n, and o.
5) Another interesting observed fact is the reflection of the fast waves from the loop top (apex, close to X-point) toward the loop foot points over the slits f, g, h, I, L, m, and o. One can interpret them as outgoing waves getting away from the null point. Sabri et al. 2020 called them outflows. They found simultaneous signatures of both induced inflows and outflows in the x and y directions of their simulations at the vicinity of the magnetic X-point, which could contribute in the jet formation, around the null point position [28].
6) A filament Eruption (FE) happens at the time step of about 350 in a province structure nearby the null point which triggers the fast kink modes with periods 3 to 4 minutes at a position close to the spine axis of the X-point, over the slits d, e, and k.

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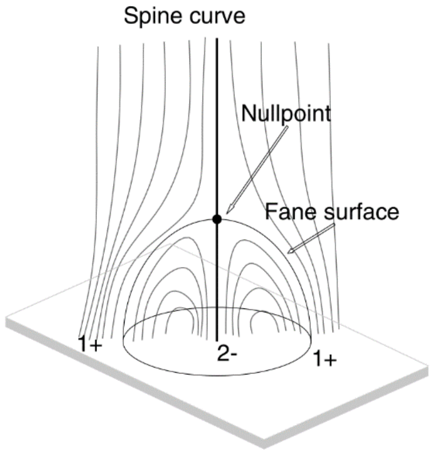

Figure 1: Manifestation of an X-point (courtesy of Ashwanden 2005 [1])

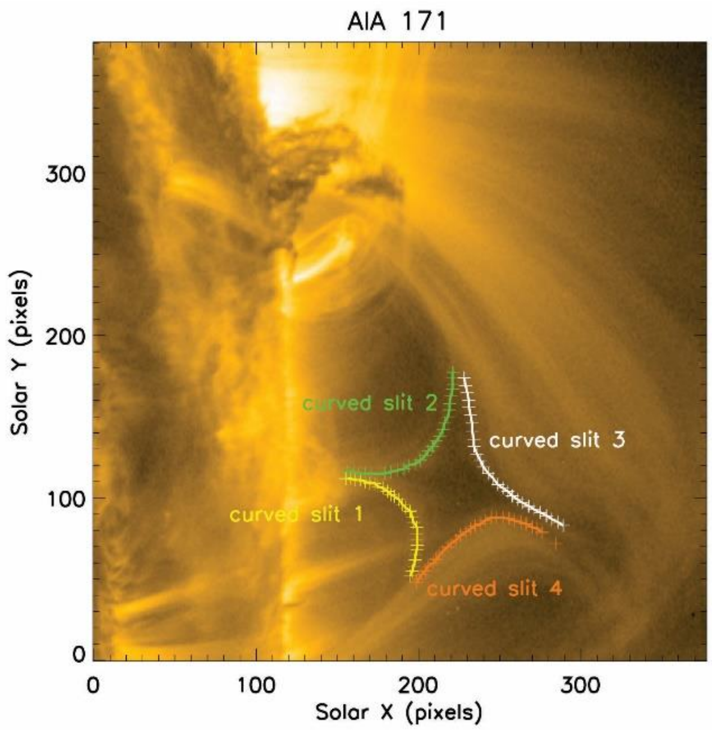

Figure 2: The studied X-point over the solar west limb is shown in AIA/SDO 171 Å channel. The curved artificial slits 1, 2, 3, and 4 are over plotted.

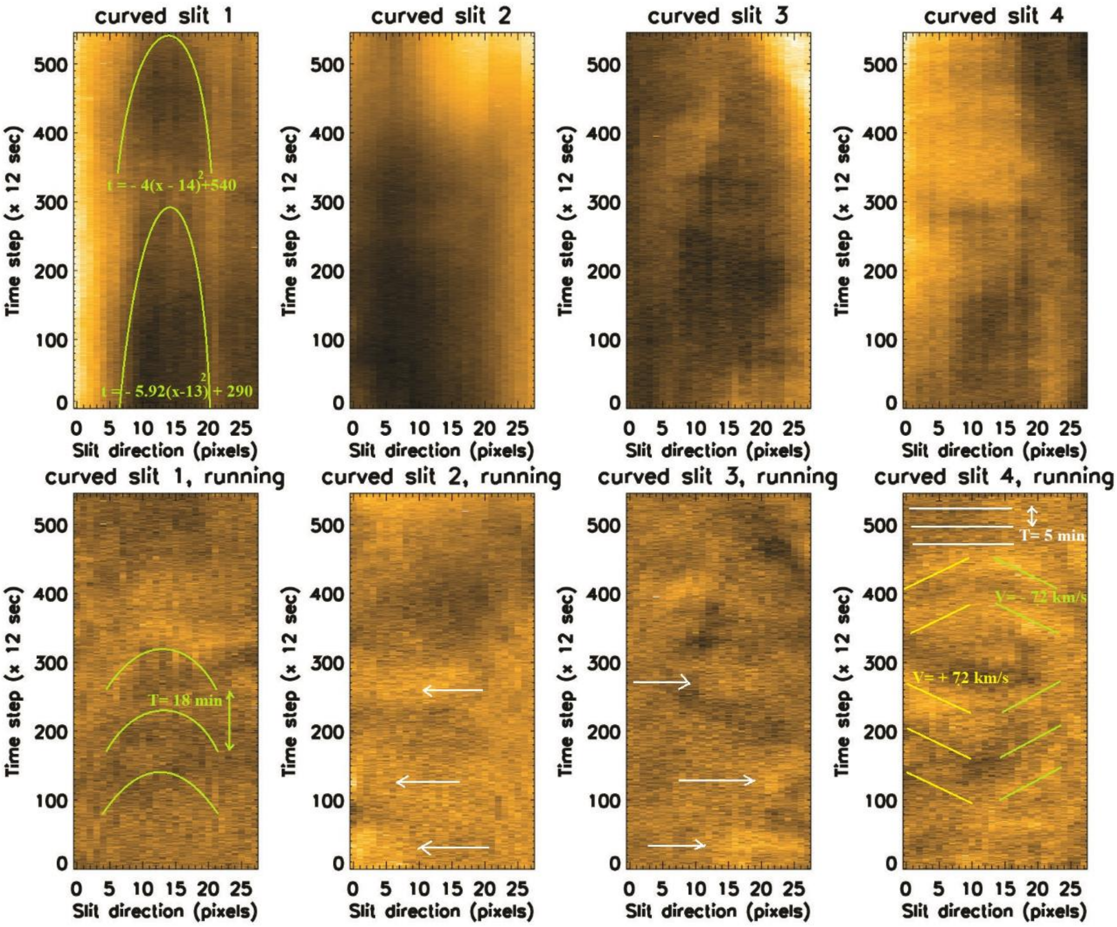

Figure 3: Top row demonstrates the time slices of the curved slits 1 to 4 in AIA/SDO 171 Å channel. Bottom row shows the running time difference plots (dt=36-time step) over the slits 1 to 4 with the time running upward in all plots. Each time step is 12 second.

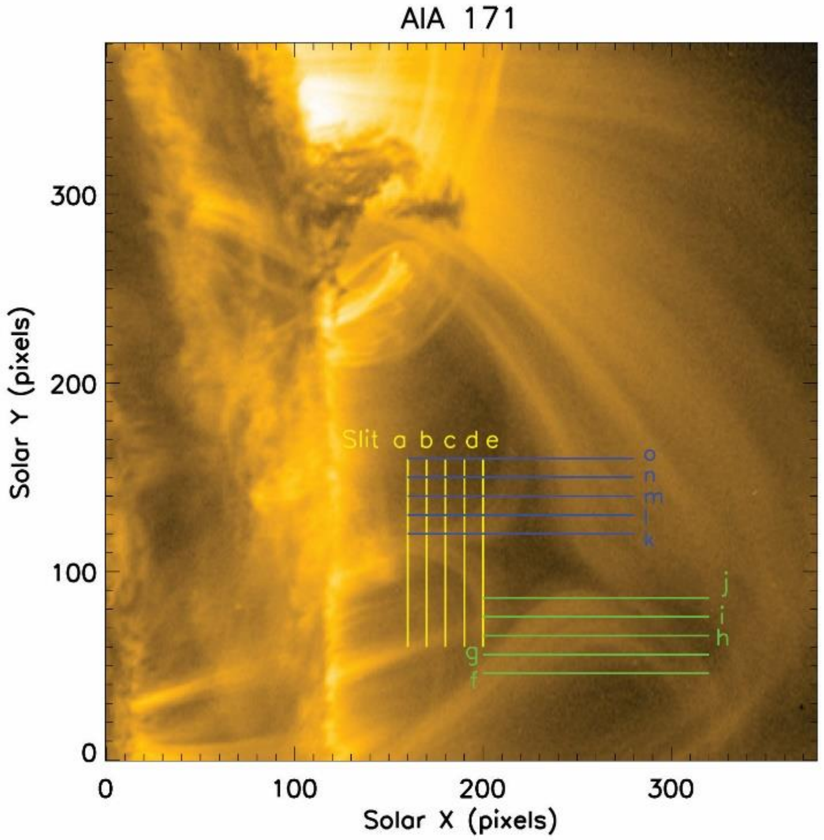

Figure 4: The studied X-point over the solar west limb is shown in AIA/SDO 171 Å channel. The vertical slits a, b, c, d, and e, along with the horizontal slits f, g, h, I, j and k, l, m, n, o crossing the neighboring X-point loops are shown. The special distance between the parallel slits is 10 pixels.

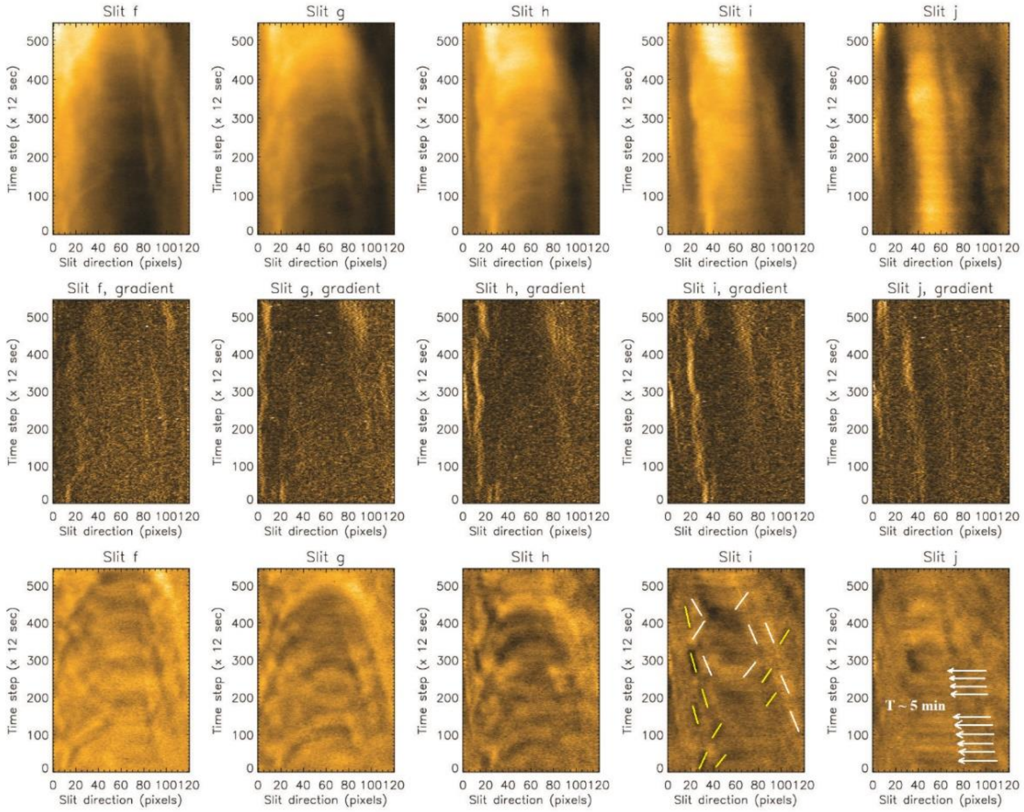

Figure 5: Top, middle, and below panels show the time slice, gradient of the time slice, and the time running difference (with dt=36 time steps) over the horizontal slits f to J. Lower right panel seems to represent the fast propagating disturbances with periods of about 5 minutes over the slit j locating on the apex of the loop structure. The parallel dark and bright wavefronts are marked by white arrows over the running difference map of slit j. They propagate perpendicular to the direction of the magnetic field (the loop axis). Over the slit i running difference plot, one would see multiple symmetric diagonal pattern with slops of ±3 km/s and ±7.2 km/s creating hexagonal shapes. It seems that, these are slow mode waves which are propagating upward from the both footpoint toward the loop apex and then reflecting back.

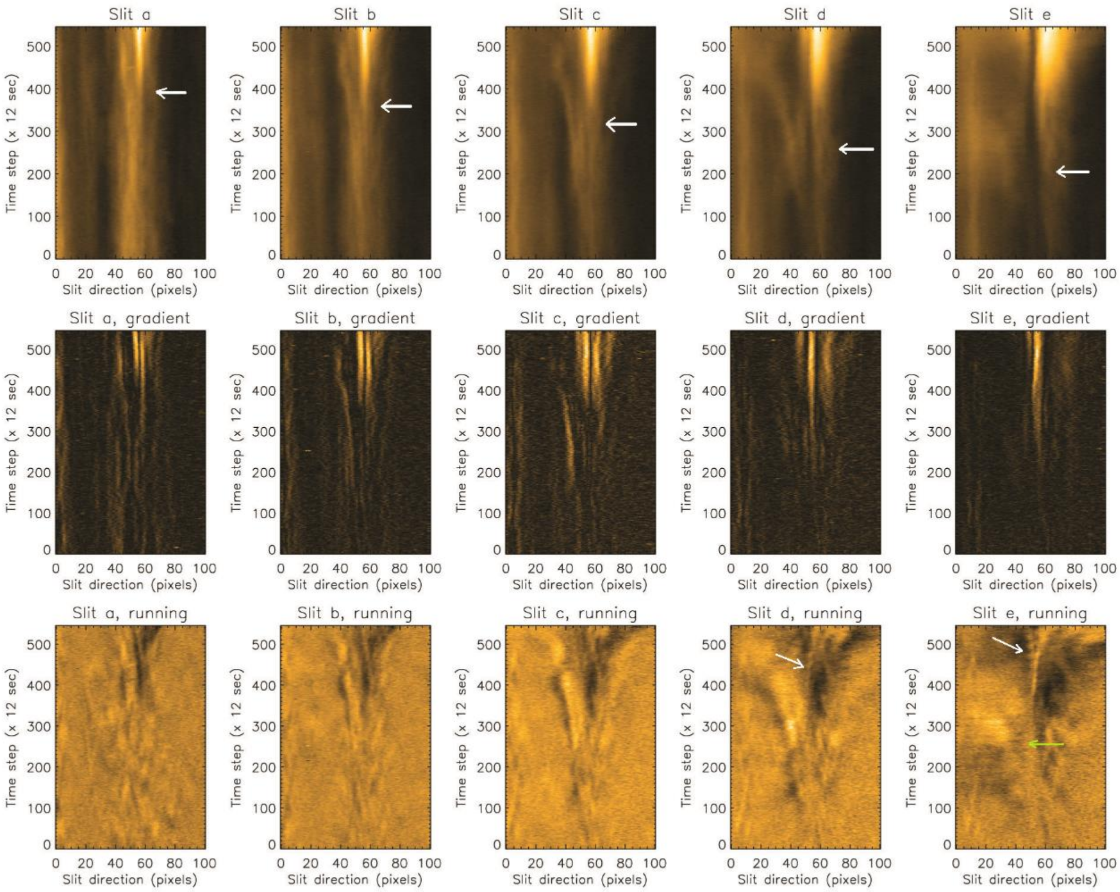

Figure 6: Top, middle, and below panels show the time slice, gradient of the time slice, and the time running difference (with dt=36 time steps) over the horizontal slits a to e. 5-minute fast wave train propagating oscillations are visible (green arrow) over the slit e running difference image. A Filament Eruption (FE) happens around the time step of 350 in the nearby prominence area toward the solar North direction. In the running difference images over the slits e and d (at the position showed by white arrows, which is close to the position of the spine axis), some fast kink oscillations with periods of 3 to 4 minutes are visible. As going away from the X-point along the spine axis (going from slits e to a), the fast kink wave gets fainter and less visible. The white arrows in the time slice plots shows a bright structure moving away from the X-point.

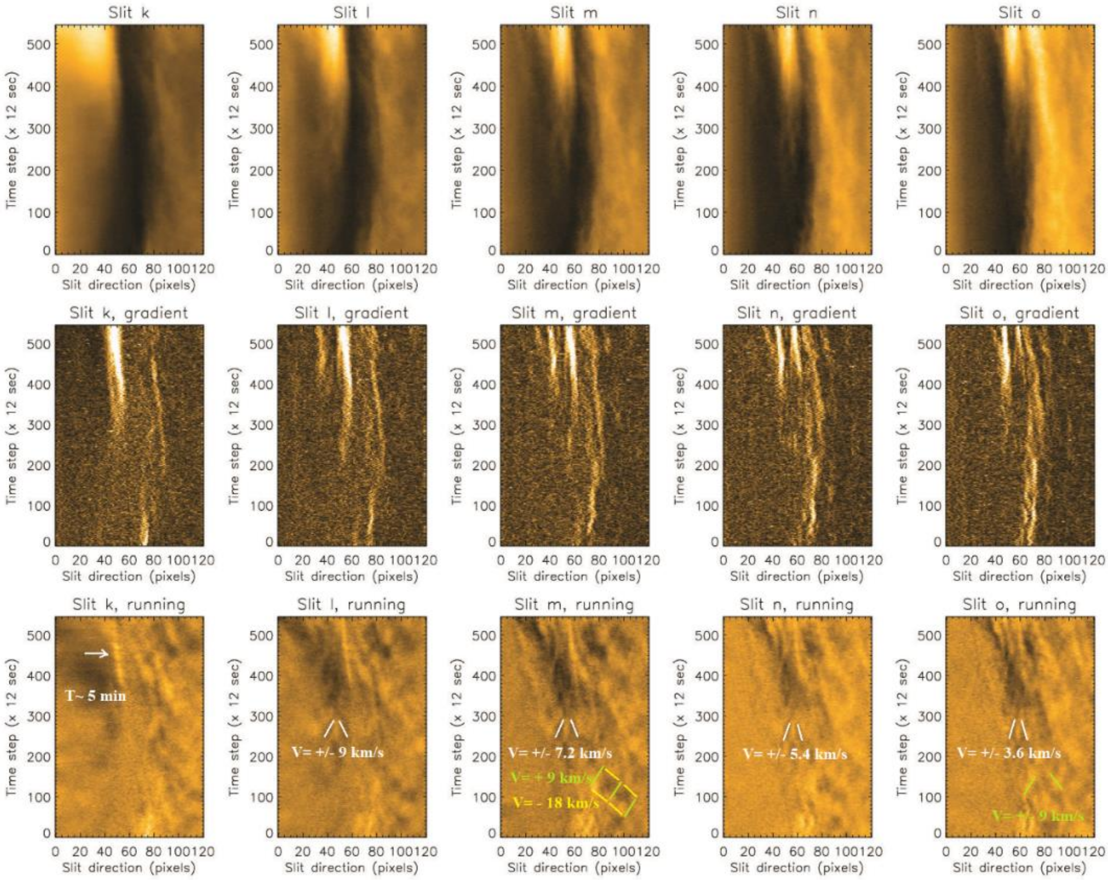

Figure 7: Top, middle, and below panels show the time slice, gradient of the time slice, and the time running difference (with dt=36 time steps) over the horizontal slits k to o. 5 minute oscillations are visible in the top of the slit k running difference image. The diagonal features in the bottom row have velocities in the range of ±3.6 km/s to ±18 km/s. It seems that the amount of the velocities decreases by getting distance from the location of the X-point (from ±9 km/s to ±3.6 km/s).